Original Research

Which Tests Predict 6-Month Isokinetic Quadriceps Strength After ACL Reconstruction? An Examination of Isometric Quadriceps Strength and Functional Tests at 3 Months

Nicholas Giampetruzzi[1], Adam P Weaver[1a], Dylan P Roman[1], Joshua A Cleland[2], Brandon M Ness[2]

[1] Sports Physical Therapy, Connecticut Children's Medical Center, [2] Doctor of Physical Therapy Program, Tufts University

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Background

Restoration of quadriceps strength after anterior ligament reconstruction (ACLR) is a persistent challenge for patients and clinicians. Inadequate recovery of quadriceps strength has been linked to increase risk of re-injury. Developing methods of early identification of strength deficits is essential to allow clinicians to provide more individualized interventions early in the rehabilitation process.

Purpose

To determine whether 3-month isometric quadriceps strength, the Y-Balance Test (YBT), and the anterior step-down test are predictive of isokinetic quadriceps strength at six months in adolescents after ACLR.

Design

Retrospective cohort

Methods

Thirty-six adolescent patients with primary ACLR (58% female, 36% with concomitant meniscal repair, age: 15.7 ± 1.6 years). At three months post-operative, isometric quadriceps strength via isokinetic dynamometer, YBT-Lower Quarter, and anterior step-down tests were completed. At six months post-operative, an isokinetic knee strength assessment was completed. Regression analysis was used to evaluate the predictive relationship between 3-month isometric tests and 6-month isokinetic knee extension tests.

Results

Three-month post operative isometric quadriceps peak torque predicted isokinetic quadriceps peak torque at 6 months, $F(1,34) = 19.61$, $p < 0.001$. Three-month isometric quadriceps peak torque accounted for 36.6% of the variance in normalized isokinetic quadriceps peak torque at 6 months with adjusted $R^2 = 34.7\%$. Including YBT anterior reach ($\beta = 0.157$, $p = 0.318$) in regression added 1.9% of variance when predicting 6-month isokinetic quadriceps peak torque, $F(2,33) = 10.32$, $p < 0.001$, $R^2 = 0.385$, $\Delta R^2 = 0.019$.

a Corresponding Author:
Adam P. Weaver, PT, DPT
Connecticut Children's Sports Physical Therapy
399 Farmington Ave
Farmington, CT 06032
Email: Aweaver@connecticutchildrens.org
Phone: (860) 284-0246

Conclusion

At three months post-ACLR, isometric strength testing appears more optimal than other functional tests in predicting isokinetic quadriceps peak torque in later stages of rehabilitation for adolescents. Clinicians should use tests at three months that measure quadriceps strength if aiming to predict isokinetic quadriceps peak torque at six months post-ACLR, rather than using functional tests such as the YBT-LQ or anterior step-down.

Level of Evidence

Level 3

INTRODUCTION

One of the primary rehabilitation goals after anterior cruciate ligament reconstruction (ACLR) is to restore quadriceps strength. Quadriceps strength after ACLR typically improves over time,[1] yet strength deficits can exceed 20% at six months post-ACLR[2] and these deficits may last even longer.[3,4] This is crucial, as limitations in quadriceps strength after ACLR have been linked to anterior cruciate ligament (ACL) re-injury,[5] altered running and landing biomechanics, poor self-reported outcomes,[6,7] and post-traumatic osteoarthritis.[3,8,9] Functionally, quadriceps strength plays an important role in running[10] and hopping[11] tasks and persistent quadriceps weakness can lead to alterations in movement patterns up to two years after ACLR.[12,13]

Obtaining valid, reliable strength measurements during ACLR rehabilitation provides valuable feedback on patient progress and is used in clinical decision making for return to activity/sport. Several options exist for objective strength assessment after ACLR including isometric dynamometry or handheld dynamometry, repetition-maximum testing,[14] or isokinetic dynamometry. The current gold standard device for quadriceps strength testing is an isokinetic dynamometer. In instances where access to an isokinetic dynamometer is limited, isometric dynamometry can be performed using devices that are offer increased clinical accessibility (i.e., cost, space) while maintaining acceptable levels of validity and reliability.[15] Gaining further insight into isometric quadriceps strength in adolescents would be valuable, given the wide reaching impact of quadriceps strength on patient outcomes after ACLR.

The timing of clinical measures, including knee strength testing, can vary after ACLR due to factors such as graft type,[16] however, early strength measures appear to be an indicator of late strength outcomes (i.e., time of return to play). Hannon et al.[17] reported isokinetic quadriceps peak torque 12 weeks postoperatively was a strong predictor (47% of the variance) of isokinetic quadriceps peak torque at time of return to play in adolescent athletes following primary bone-patellar tendon-bone autograft ACLR. Similarly, the isokinetic quadriceps peak torque limb symmetry index at three months postoperatively predicted nearly 35% of the variance for the same measure at six months in young adults following primary ACLR with hamstring autograft.[18] It is currently unknown whether early isometric quadriceps strength is associated with isokinetic late-stage quadriceps strength in adolescents after ACLR.

It would be incorrect to assume that most clinicians are using a handheld or isokinetic dynamometer to evaluate knee strength after ACLR. Recent trends in knee strength assessment after ACLR among physical therapists have been somewhat concerning. In a survey of those making return to sport decisions, 80.6% of respondents indicated using manual muscle testing results to make decisions to initiate jogging and modified sports activity.[19] Further, 56.1% of respondents reported using manual muscle testing as the only method of strength assessment.[19] In the absence of using a device to objectively assess isolated quadriceps strength after ACLR, clinicians will at times utilize other functional tests as a proxy for strength assessment. However, it must be recognized that such tests may not accurately measure maximum strength of a specific muscle or group, but rather reflect a different construct or require contributions from other muscle groups. Two such tests include the Y-Balance Test (YBT) and the anterior step-down test, which can often be performed at three months post-ACLR. The YBT is used to measure single limb dynamic balance, where asymmetries of greater than four centimeters have been shown to identify those individuals after ACLR that were unable to achieve 90% or greater limb symmetry on hop tests,[20] as well as correlate to higher scores on patient-reported outcomes.[21] Finally, the anterior step-down test has been linked to patient reported outcomes and running, and has a stronger relationship to knee mechanics and patient-reported knee function than the YBT.[22] It has yet to be determined whether early performance on the YBT and/or anterior step-down test have an association with late-stage quadriceps strength after ACLR.

It appears that early isokinetic quadriceps strength measures have predictive value for determining late-stage isokinetic quadriceps strength. However, it is unknown if early isometric strength and other functional measures are predictive of late-stage isokinetic quadriceps strength in adolescents. Therefore, the purpose of this study was to determine whether 3-month isometric quadriceps strength, YBT, and the anterior step-down test are predictive of isokinetic quadriceps strength at six months in adolescents after ACLR. It was hypothesized that isometric quadriceps strength at 3-months would be a better predictor of isokinetic strength at six months when compared to the YBT and the anterior step-down test.

METHODS

DESIGN

This study was approved by the Institutional Review Board at Connecticut Children's. A retrospective chart review of patients undergoing ACLR at the organization between January 2013 and November 2021 was performed. Information pertaining to demographics, surgical procedure, and clinical outcome measures were collected. Only those patients with a full data set were included in the study.

PATIENTS

To be eligible for this study, patients had to satisfy the following inclusion criteria: 1) were 12-18 years of age when surgery was performed, 2) had undergone primary ACLR using hamstring autograft, with or without meniscal injury, and 3) had completed the organization's standard testing procedures in full at both "early-stage" testing as well as "late-stage" testing post-operatively. "Early-stage" was defined as two to four months (60-122 days) while "late-stage" was defined as 5.6-9.6 months (171-294 days) post-operatively. The gap of nearly two months between early- and late-stage testing was chosen with the aim to create more distinct testing timeframes, as it was reported that it may take upwards of two months to observe clinically meaningful quadriceps strength gains after ACLR.[1]

Patients undergoing concurrent meniscus repair, chondroplasty, or anterolateral ligament reconstruction were eligible. Patients were included if they completed strength testing at both rehabilitation time points and complete data was available for all outcomes of interest. Patients were excluded if they underwent bony deformity correction surgery, multi-ligament reconstruction, ACL revision, posterolateral corner reconstruction, or experienced post-operative complications (re-injury, arthrofibrosis or nerve injury). Demographic data including age, height, mass, and sex, at time of surgery were extracted. Surgical procedure information including ACLR surgical technique, and concomitant pathology were also recorded.

Patients treated by five different orthopedic sports medicine surgeons at Connecticut Children's and patients completing physical therapy at Connecticut Children's were included in this sample. All patients were provided with a standardized postoperative rehabilitation protocol (Appendix A) with recommendations for attaining supervised rehabilitation. Patients attended physical therapy at a variety of locations, both within and independent of the host organization. All clinical tests were completed at Connecticut Children's.

EARLY-STAGE 3-MONTH TESTING

All patients undergoing ACLR at Connecticut Children's were scheduled for a follow up examination with the orthopedic surgeon at approximately three months following ACLR. At this time, a battery of tests and measures were completed to assess the patient's progress. This included range of motion (hip, knee, and ankle), isometric strength (knee extension, knee flexion, hip extension), dynamic balance (YBT Lower Quarter), functional testing (anterior step down and single-leg bridge), and patient reported outcome measures (Pedi International Knee Documentation Committee Subjective Knee Evaluation Form and Anterior Cruciate Ligament Return to Sport after Injury). All testing was performed and evaluated by a Connecticut Children's sports physical therapist.

The YBT Lower Quarter (YBT-LQ) (Functional Movement System, Chatham, VA) has shown to be reliable when measuring dynamic balance in adolescent athletes.[23] Patients were instructed to stand on the center footplate barefoot with the distal tip of the tested foot at the marked starting line. Patients maintained single leg stance while reaching with the free limb in the anterior, posteromedial, and posterolateral directions by pushing the indicator box as far as possible. Three practice trials were performed prior to administration of three test trials on each limb. Three successful test trials were recorded in each direction. A trial was deemed unsuccessful if the patient did one or more of the following: kicking the indicator box, not returning to the staring position under control, touching down with upper or lower extremities during reach, or placing their foot on top of the indicator box. The uninvolved limb was tested first, followed by the involved lower limb. The mean distance of the three recorded trials in each direction, normalized to height, were used for analysis.

Patients began the anterior step-down test[22] by standing on a firm 12-inch step without shoes. They were instructed to attain single leg stance on the test limb and descend with their free limb lowering towards a 1.5-inch scale on top of a 1.5-inch box positioned anterior to the step. A successful trial was tallied if the patient contacted the scale with their heel without transferring more than 10% of their body mass onto the scale. Patients completed as many repetitions as possible in 60 seconds. Repetitions were excluded if the patient did not contact the scale, exceeded 10% of body mass transfer, or failed to return to the starting position. The uninvolved limb was tested prior to the involved limb.

Isometric quadriceps peak torque was evaluated using an isokinetic dynamometer (Humac CSMI USA, Stoughton, MA, USA). Patients were positioned in sitting with 90 degrees of hip flexion, their trunk and thigh supported with straps, and dynamometer arm secured proximal to the ankle joint. Isometric peak torque was measured with the knee joint positioned at 60 degrees of knee flexion. After one practice trial, patients performed three maximal effort test trials lasting five seconds each with five seconds of rest between each trial. Verbal encouragement was provided throughout the test to encourage maximal effort. The highest peak torque measurement was recorded in newton-meters (Nm) and normalized to the patient's body mass (Nm/kg). The uninvolved limb's quadriceps and hamstring strength were tested first, followed by the involved limb. Patients were given verbal encouragement throughout the test to provide maximal effort. Using an isokinetic dynamometer in this manner has been shown to be a reliable method to quantify quadriceps and hamstring torque in adults[24,25] and children.[26]

LATE-STAGE 6-MONTH TESTING

The organizational standard for a late-stage testing battery included knee range of motion, KT1000 arthrometry, isometric and isokinetic knee strength, single-leg hop tests, drop vertical jump assessment, and other functional strength measures. Of these late-stage tests, only the isokinetic knee strength measurements were included for analysis in this study.

Isokinetic knee strength testing replicated the initial set up as previously described for early-stage isometric knee strength testing. Isokinetic quadriceps and hamstring torque was assessed through a knee range of motion from 0-90 degrees with gravity correction applied.[27] A practice trial of two repetitions and a testing trial of five repetitions were completed at 60°/sec, with 10 seconds of rest between trials. Patients were provided with verbal encouragement to provide maximal effort through the full knee range of motion. The highest peak torque measurement of the testing trial was recorded in newton-meters (Nm) and normalized to the patient's body mass (Nm/kg). The uninvolved limb's quadriceps and hamstring strength were measured first, followed by the involved limb. Patients were given verbal encouragement throughout the test to provide maximal effort.

STATISTICAL ANALYSIS

Descriptive statistics were calculated for demographic and all outcome data for the involved lower limb including normalized quadriceps peak torque, normalized YBT-LQ reach distance, and the number of anterior step-down repetitions. Pearson-product-moment correlation coefficients were calculated between outcomes. Of the 3-month clinical measures that were shown to be significantly correlated with 6-month isokinetic quadriceps peak torque, a regression analysis was used to evaluate their predictive value. Hence, a hierarchical regression analysis was used to evaluate the predictive relationship between 3-month isometric quadriceps peak torque and 6-month isokinetic quadriceps peak torque (step 1). Then, normalized YBT-LQ anterior reach was added in step two of the regression. Data were assessed for violations of the assumptions for regression analysis at each step including independence of residuals, linearity, homoscedasticity, and multicollinearity. Visual inspection of histograms and normal predicted probability (P-P) plots revealed normal distribution of the standardized residuals. Alpha level was set to 0.05. SPSS version 26.0 (IBM Corp, Armonk, NY, USA) was used to conduct the statistical analyses.

RESULTS

Thirty-six patients were included in the study (58% female, 36% with concomitant medial and/or lateral meniscal repair, age: 15.7 ± 1.6 years, height: 168.2 ± 9.6 cm, mass: 65.1 ± 13.6 kg). Descriptive statistics are presented in Table 1.

A significant positive correlation was identified between 3-month isometric quadriceps peak torque and 6-month isokinetic quadriceps peak torque ($r = 0.605$, $p < 0.01$), in addition to YBT-LQ anterior reach and 6-month isokinetic quadriceps peak torque ($r = 0.405$, $p < 0.05$) (Table 2). No other clinical measures had significant correlation with 6-month isokinetic quadriceps peak torque, thus were not included in the regression.

The regression analysis (Table 3) revealed 3-month isometric quadriceps peak torque significantly predicted isokinetic quadriceps peak torque at 6 months, $F(1,34) = 19.61$, $p < 0.001$. Three-month isometric quadriceps peak torque accounted for 36.6% of the variance in normalized isokinetic quadriceps peak torque at 6 months with adjusted $R^2 = 34.7\%$. In the second step when YBT-LQ anterior reach ($\beta = 0.157$, $p = 0.318$) was included in the regression, this added only 1.9% of variance when predicting 6-month isokinetic quadriceps peak torque, $F(2,33) = 10.32$, $p < 0.001$, $R^2 = 0.385$, $\Delta R^2 = 0.019$.

DISCUSSION

The purpose of this study was to determine whether 3-month isometric quadriceps strength, YBT, and the anterior step-down test were predictive of isokinetic quadriceps strength in adolescents six months after ACLR. Normalized isometric quadriceps peak torque and YBT-LQ anterior reach during early-stage testing were significantly associated with normalized isokinetic quadriceps peak torque during late-stage testing. Early-stage isometric quadriceps peak torque accounted for 36.6% of the variance in isokinetic quadriceps peak torque during late-stage testing, while YBT-LQ anterior reach only added an additional 1.9% of variance. No significant correlations were observed between YBT-LQ posterolateral reach, posteromedial reach, or anterior step-down relative to 6-month isokinetic quadriceps peak torque.

In comparison to the current findings, Hannon et al[17] reported isokinetic quadriceps peak torque at 12 weeks post-ACLR accounted for greater variance (47%) in the same measure at time of return to sport. Although their study population was similar in age (16.1 ± 1.4 years) and gender distribution (54% female), a bone-patellar tendon-bone autograft was used and return to sport testing occurred later (7.3 ± 1.3 months). Additionally, Mitomo et al[18] examined the three- and six-month limb symmetry index of isokinetic quadriceps peak torque in young adults following primary ACLR with hamstring autograft. Despite the current study's examination of normalized quadriceps peak torque, three-month isokinetic quadriceps limb symmetry index accounted for a similar level of variance (34.9%) in limb symmetry index at six months, comaparitively.[18] While limb symmetry indices are commonly used to establish desired performance thresholds after ACLR, the uninvolved limb may experience deterioration in function leading to an overestimation of strength and function for the injured limb.[28-30] It has also been reported that isometric quadriceps strength, when normalized to body mass, was a better predictor of high self-reported function (subjective International Knee Documentation Committee index ⩾ 90%) after ACLR when compared to the quadriceps strength limb symmetry index.[31] Hence, it would seem plausible to advocate for reporting torque measurements normalized to body mass in future investigations.

The three-month functional tests included in the study were the YBT-LQ and anterior step-down test. The only functional test that had significant correlation with six-

Table 1. Descriptive Statistics for 3- and 6-Month Testing after ACL Reconstruction

3-month testing timeframe (days since surgery)	92.8 ± 10.7 (89.2, 96.4)
Isometric quadriceps peak torque – Involved (Nm)	109.5 ± 31.8 (98.8, 120.3)
Normalized to body mass (Nm/kg)	1.71 ± 0.43 (1.56, 1.85)
Y-Balance Test Lower Quarter – normalized to height	
Anterior reach (cm)	36.5 ± 4.2 (35.1, 38.0)
Posteromedial reach (cm)	58.3 ± 5.8 (56.3, 60.2)
Posterolateral reach (cm)	56.9 ± 5.6 (55.0, 58.8)
Anterior step down (repetitions completed)	22.5 ± 9.9 (19.2, 25.9)
6-month testing timeframe (days since surgery)	197.6 ± 26.5 (188.6, 206.6)
Isokinetic quadriceps peak torque at 60 degrees/sec– Involved (Nm)	116.3 ± 33.8 (104.9, 127.7)
Normalized to body mass (Nm/kg)	1.80 ± 0.45 (1.65, 1.96)

[a]Values are expressed as mean ± SD, (95% confidence interval)

Table 2. Pearson correlations between 3-month clinical measures and 6-month isokinetic quadriceps peak torque

	6-month normalized isokinetic quadriceps peak torque	**3-month normalized isometric quadriceps peak torque**	**YBT-LQ anterior reach**	**YBT-LQ posteromedial reach**	**YBT-LQ posterolateral reach**	**Anterior step down**
6-month normalized isokinetic quadriceps peak torque	--	**.605***	**.405***	.155	.173	.187
3-month normalized isometric quadriceps peak torque	**.605***	--	**.468***	.211	.239	.217
YBT-LQ anterior reach	**.405***	**.468***	--	**.688***	**.571***	**.506***
YBT-LQ posteromedial reach	.155	.211	**.688***	--	**.831***	**.349***
YBT-LQ posterolateral reach	.173	.239	**.571***	**.831***	--	.288
Anterior Step down	.187	.217	**.506***	**.349***	.288	--

YBT-LQ, Y Balance Test Lower Quarter, * with bolded text indicates significant correlation ($p < 0.05$)

month isokinetic quadriceps peak torque was the YBT-LQ anterior reach. The anterior reach task generally requires increased contributions from the quadriceps relative to other reach directions in healthy individuals,[32,33] but is not always the case.[34] In those recovering from ACL-R., isokinetic quadriceps peak torque on the involved ACL-R limb had the greatest correlation with anterior reach performance (r= 0.591) compared to the posteromedial (r = 0.498) and posterolateral (r = 0.294) reach directions.[35] Moderate correlations of YBT-LQ reach distance and quadriceps peak

Table 3. Hierarchical regression analysis results of 3-month clinical measures relative to 6-month normalized isokinetic quadriceps peak torque

	B (constant)	R^2	ΔR^2	*B*	β	*p*
Step 1						
3-month normalized isometric quadriceps peak torque		.366		.624	.605	<0.001*
Step 2		.385	0.019			<0.001
3-month normalized isometric quadriceps peak torque				.548	.532	0.002*
3-month normalized anterior reach (YBT- LQ)				.017	.157	0.318

YBT-LQ, Y Balance Test Lower Quarter

torque may be partially explained by the electromyographic activity of the vastus medialis only reaching 69-79% maximum voluntary isometric contraction (MVIC) in healthy participants during the YBT-LQ during various reach directions.[34] By comparison, although examining the rectus femoris and using a shorter step height (mean of 8.6-9.3 inches), an anterior step-down task required only 12-13% MVIC.[36] Given that the YBT-LQ does not appear to require maximum muscle activation to complete the reaching task, it may partly explain the relatively low amount of variance (1.9%) when YBT-LQ anterior reach was added to the regression to predict 6-month isokinetic quadriceps peak torque. Additionally, both the YBT-LQ and anterior step-down are multi-joint tasks, which may allow for compensations or offloading during these closed chain movements. The study findings suggest the YBT-LQ and anterior step-down are weak predictors of isokinetic quadriceps strength at six months postoperatively.

LIMITATIONS

The retrospective design limits the strength and applicability of the results of this study. The study did not include participant activity/sport level, rates of return to sport after surgery, or secondary injuries. Also, the testing methods used in the study may have impacted isometric quadriceps strength and anterior step-down test outcomes and limit the generalizability of the findings. During maximal strength testing, the limited rest period may not have allowed for full recovery between trials. Further, the knee joint angle for isometric testing was set at 60° using an isokinetic dynamometer, which differs from 90° of knee flexion when using more clinically available devices such as a handheld dynamometer. It should also be noted that isometric strength outcomes may differ between testing devices (i.e., isokinetic versus handheld dynamometry). For the anterior step-down test, the box height used was 12 inches which did not allow for standardized knee flexion angles between patients of different limb lengths. Lastly, the generalizability is limited to adolescent patients who underwent ACLR with a hamstring autograft over a relatively short term (6.5 ± 0.9 months) follow up period.

CONCLUSION

Three-month isometric quadriceps peak torque significantly predicted isokinetic quadriceps peak torque at six months after ACLR in adolescents with hamstring autograft and accounted for 36.6% of the variance. The 3-month functional tests were limited in predictive value, with the YBT-LQ anterior reach only accounting for a small proportion of the variance (1.9%). At three months post-ACLR, isometric strength testing appears to be more appropriate than using other functional tests for predicting isokinetic quadriceps peak torque in later stages of rehabilitation for adolescents. Clinicians should use objective measures of strength at three months if aiming to predict isokinetic quadriceps peak torque at six months post-ACLR, rather than using functional tests such as the YBT-LQ or anterior step-down.

DECLARATIONS OF INTEREST

The authors declare no conflicts of interest.

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SUPPLEMENTARY MATERIALS

Appendix 1

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