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Research Article

Knee Extension Rate of Torque Development Deficit Is Not Captured by Standard Functional Performance Measures Post-Anterior Cruciate Ligament Reconstruction

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Abstract

Background

Criteria for full recovery following anterior cruciate ligament reconstruction (ACL-R) include the ability to achieve >90% limb symmetry in maximal quadriceps strength (QI) and functional hop tests. Additionally, knee extension rate of torque development (RTD) is an important performance metric post-ACL-R. This study investigated the rate of recovery of these performance metrics in a recreationally athletic population.

Purpose

To investigate RTD at 30% (RTD30), 50% (RTD50), and 90% (RTD90) of maximal voluntary isometric contraction (MVIC) recovery rate compared to knee extension peak torque and hop test performance post ACL-R.

Study Design

Descriptive, prospective, cross-sectional single-cohort study.

Methods

Subjects between five months and two years post-primary ACL-R were included from three medical centers. The primary outcomes were QI, RTD30, RTD50, RTD90, and Noyes Hop Test symmetry. Secondary outcome measure was The International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form. All outcomes were performed as part of the standard of care for late-stage ACL-R rehabilitation.

Results

19 subjects (13 male) with a mean age of 27.6 years were included. Subjects were, on average, 37-week (9.5 months) post-ACL-R.The pooled QI and hop tests were 88.8 ± 7% and 86.5±13.5%, respectively. In contrast, the LSI of RTD30, RTD50, and RTD90 values were 76±24%, 65±35%, and 49±33%, respectively. The LSI for RTD50 and RTD90 demonstrated statistical significantly different from LSI of all hop tests ($P<0.005$) and QI ($P<0.05$).

Conclusion

Despite the near recovery of MVIC torque and hop performance symmetry, there is still significant deficits in RTD at 9 months post-ACL-R. These results suggest that, following ACL-R, traditional functional performance tests that are used for return to sport and activity decision making are insufficient at capturing significant deficits in knee extension RTD in a recreational athletic population.

Levels of Evidence: 2B

Clinical Relevance

Traditional return to sport criteria of quadriceps MVIC and hop testing appear to overlook deficits

in knee extension RTD. This may lead to patients being cleared for return to sport prematurely, and subsequently increase the risk of re-injury. Knee extension RTD testing is recommended prior to return to sport.

Abbreviations

6m, 6 meter single leg hop;
3x Hop, triple single leg hop;
ACL, Anterior cruciate ligament;
ACL-R, anterior cruciate ligament reconstruction;
BMI, body mass index;
cm, centimeter;
BTB, Bone patellar tendon bone graft;
Crx Hop, triple cross over hop;
EMR, electronic medical record;
F, female;
HS, hamstring;
IKDC, 2000 International knee documentation committee score;
kg, kilogram;
M, male;
ms, milliseconds;
MVIC, max volitional isometric contraction;
Nm, newton-meters;
Post-op, post-operative;
ROM, range of motion;
rpm, revolutions per minute;
RTD, rate of torque development;
RTS, return to sport;
s, seconds;
QI, quadriceps index;
QT, quad torque;
W/kg, watts per kilogram;
yr, year.

What Is Known about the Subject?

To date, RTD has been used in elite and professional level sports as a performance measure as well as a return to sport (RTS) functional performance measure. It has been shown that RTD lags behind other functional performance tests following ACL-R. However, there is limited evidence demonstrating RTD in a recreational athletic population and to what extent current RTS tests capture RTD recovery.

What This Study Adds?

This study investigates how limb symmetry of RTD recovers compared to other standard RTS functional performance tests. Additionally, the investigation extends the scope of RTD research to recreational athletic populations, which makes up a much larger percentage of individuals who participating in athletics compared to the elite and professional populations.

Introduction

As the anterior cruciate ligament (ACL) the most commonly injured ligament in the knee among athletes [1], extensive literature has focused on the optimal recovery and rehabilitation of athletes following ACL injuries and ACL-R [2]. Despite the breadth of ACL-R research initiatives, functional outcomes are still inadequate with only 44% successfully return to competitive sport after long term follow up [3]. Per Ardern *et al.*, [4], 90% of athletes may be rated at or near normal on return to sport (RTS) functional performance tests. Despite the pass rates, 9-25% of athletes may retear their ACL-R [5]. The subsequent re-tear rates and increased risk of contralateral knee injuries call into question the current outcome measures utilized for RTS testing.

As an objective measure post-ACL-R, the Quadriceps Strength Index or Symmetry (QI) is the gold standard measure for return to play and discharge from rehabilitation [6-9]. QI is predictive of functional performance [9], patient IKDC (International Knee Documentation Committee Subjective Knee Form) scores [8], and risk of second injury [10]. Criteria measures for RTS often include a QI >90% (or higher) [11]. The QI only provides a relative maximum force production of the quadriceps, while neglecting to account for the time component, and thus, QI may overestimate RTS readiness following ACL-R [12].

The speed at which force is produced is often more important for athletic movements, rather than maximal force produced [13]. RTD commonly used as a metric to predict an athlete's ability to acceleration, deceleration, and change direction [14]. Despite attaining a >90% QI, significant deficits in RTD have been demonstrated in athletes at 6 months post-ACL-R [15]. Further research has demonstrated that the speed of activation is more important than absolute strength for predicting IKDC scores [16]. In many of the current rehabilitation programs, deficits in RTD have continued to be reported in athletes post-ACL-R, yet they are cleared for RTS due to passing scores on the QI and other functional performance tests [17].

The Noyes Hop Tests are consistently used in determining RTS readiness due to the ease of set up, similarity to sport-specific movements, and proven reliability [18,19]. The hop test battery includes a single-leg hop for distance, triple hop for distance, 6-meter timed hop, and the triple cross-over hop for distance. Knee extensor strength and single-limb hop testing have been found to have a weak association [20], further suggesting a gap in RTS testing when only the QI is assessed. Consistent with these findings, research demonstrates that patients commonly lag in leg symmetry during hop tests despite having higher ratings for maximal quadriceps strength [12].

The use of knee extension RTD as a standard RTS functional test battery is not a part of standard clinical practice [15]. A majority of the current RTD literature has focused on elite or professional athletes [15,21].

The equipment required to measure RTD is also expensive and may not be found in most clinical settings. Other valid and reliable ways to measure RTD and functional outcomes in patients need to be established. Additional research is needed to investigate the validity and reliability of measuring RTD in the clinical setting. This will provide greater insight into functional deficits that need to be addressed to further improve RTS both in the short and long term. Further research is needed on recreational athletes commonly seen in the rehabilitation setting, to expand beyond the focus on elite athletes in the current literature.

The present study was designed to investigate (1) the recovery of knee extension RTD post ACL-R as measured by LSI and (2) how this recovery compares to that of standard RTS functional performance tests (QT and Noyes hop test battery). We hypothesized that knee extension RTD would have significantly greater limb asymmetry when compared to concurrent QT and Noyes hop testing LSI. This investigation intends to determine RTD's potential usefulness as an adjunct parameter of functional recovery for a safe return to activity in a recreational athlete demographic.

Methods

Study Design

Descriptive, prospective, cross-sectional single-cohort study.

Setting

Four hospital-based outpatient physical therapy departments in Los Angeles, CA.

Participants

Electronic medical records (EMR) databases of four large medical centers were prospectively scoured for patients who had undergone a primary ACL-R between August 1, 2018, to January 31, 2019. Participants identified as having primary, unilateral ACL-R were included if they met the following inclusion criteria [22-25].

- Older than 14 years of age
- No baseline pain or edema/effusion
- Full knee ROM (compared to the non-involved knee)
- 20 weeks to 2 years post-surgery
- Non-antalgic gait
- Currently in return to sport/activity rehabilitation phase
- Undergone isokinetic muscle performance testing for quadriceps
- Performed the Noyes Hop test with documented results within the EMR.

Participants Were Excluded if They

- had a history of low back pain or lower extremity injury in the last year that required medical attention [9]

- skeletally immature (as identified by an ACL-R procedure that was modified due to open epiphyseal plates in the tibia or femur) [9]

- pregnant at the time of testing (all medical history was taken on a subjective basis by treating therapist) [26]

- had a concomitant ligament injury requiring surgical intervention

Bone-tendon-bone patellar tendon, hamstring tendon, and allograft tissue graft types were considered for inclusion, as well as concomitant meniscus repair or partial meniscectomy. All eligible participants were taken through an informed consent form that specified the overview of the study, the risks and the benefits of participating. Each participant was informed that they could opt out of participation without any punitive repercussions. The study protocol was approved by the Southern California Kaiser Permanente Institutional Review Board.

Consistent with the recommendations for the type of study a priori power analysis for an appropriate number of subjects was not conducted. The number of patients was limited by the number of eligible participants that were available during the specified time frame of recruitment.

Outcome Measures

Completed International Knee Documentation Committee (IKDC) scores of the identified subjects were extracted from the EMR [27,28]. As part of their standard ACL-R rehabilitation in the medical center health care system, patients underwent functional performance testing to determine current rehabilitation progress and improve decision making for return to activity. The outcome data of bilateral QT and RTD using an isokinetic dynamometer, as well as the Noyes hop test battery were taken directly from the EMR system. Testing of the MVIC and RTD is performed no sooner than 20 weeks (~ 5 months) post-ACL-R. The following sub-sections describe the standard practices for functional performance testing post ACL-R within the medical center health care system. Licensed physical therapists conducting the testing testified, and the EMR documentation reflected that all functional performance testing was conducted according to the following protocols.

Functional Performance Testing

All functional test measures were obtained during the same session by attending physical therapists at one of two medical centers. The order of the isolated muscle performance tests (i.e. QT and RTD) was randomized for each patient using the Microsoft Excel '=RANDBETWEEN (1,2)' function. The numerals one and two were conventionally allocated to QT and RTD, respectively. The test order was randomized to reduce the risk of fatigue, influencing the second test results. The results were then used to inform clinical staff at the respective medical centers to which aspects of knee extension performance, power or strength, needed to be emphasized within the group rehabilitation classes. The isolated muscle performance tests preceded the hop tests. For each functional performance test, the non-surgical limb (healthy limb) was tested before the surgical limb (ACL-R limb). The standardized order of the tests and assessments is summarized in Table 1.

Table 1: *Data collection sequence*

Functional performance test protocol
1. Patient arrival to test location
2. One on one consultation describing and signing consent form
3. IKDC 2000 results submitted
4. Height and weight taken
5. Warm-up
6. Isolated muscles performance tests on BTE Primus RS isokinetic dynamometer NOTE: *The order of max torque test and rate of torque development test were randomized for each subject. The order was the same for each limb.* a. Healthy Limb Testing i. Knee extension isometric max torque test ii. Knee extension rate of torque development b. ACL Limb Testing i. Knee extension isometric max torque test ii. Knee extension rate of torque development
7. 10-minute rest period
8. Noyes Hop Test

Note. ACL, anterior cruciate ligament; IKDC, 2000 International knee documentation committee score

Warm-up

During the functional performance test session, all participants began with a four-minute warm up on a cycle ergometer (SportsArt Fitness® C532u Cycle), at an intensity of 1 W/kg of body weight, maintaining 70-80rpm. This warm-up has previously been described when comparing quadriceps strength to hop test performance [29].

Isokinetic Dynamometer Set Up

Isolated muscle performance testing was conducted using an isokinetic dynamometer (BTE PrimusRS, BTE technology Greenwood Village, CO) during a maximum voluntary isometric contraction (MVIC). In accordance with the BTE PrimusRS manual, the isokinetic dynamometer is calibrated every week before testing, using the 'Calibration' function within the BTE software. The subjects were placed in a sitting position and securely strapped into the test chair. Extraneous movement of the upper body was limited per manufacturer's instructions using straps (across the chest and the proximal one-third of both thighs) [9,13,30-33]. The trunk-thigh angle was 90°. [9,13,32-34]. The lateral femoral epicondyle of the testing leg was visually aligned with the axis of rotation of the dynamometer, and the lever arm was attached to the shank by a strap [29,35]. Subjects sat in the dynamometer with the trunk fully supported, the hips flexed to approximately 90°, and the knee flexed to 60°. The subject was asked to relax his/her leg so that the passive determination of the effects of gravity on the limb and lever arm could be carried out. The knee joint was set at 60° (0° = full extension) as this has been the position at which maximal isometric knee extension torque is attained [9,35-41]. A rigid leg cuff was mounted on the lower leg ~3 cm above the medial malleolus on the anterior aspect of the distal shank [42]. For all isolated muscle performance tests, the subject was instructed not to hold back any effort for subsequent contractions [30]. The testing investigator (one at each test site) provided real-time standardized verbal commands and encouragement, as well as visual feedback, was available on a monitor positioned in front of the dynamometer seat, as an output guide [9,26,30,34].

Knee Extension Isometric Torque Index

This procedure has been used to quantify QT in individuals with ACL deficit and reconstruction and has yielded reliable measurements [9,43-47]. Subjects were told to push "hard and fast" with an emphasis on 'hard' [13,42,48,49]. After two practice trials, 5 recorded maximum-effort trials (5 seconds in duration, separated by 20 seconds of rest) were completed for each knee. As the patient profiles are created directly on the BTE PrimusRS software, the raw data of the QT was taken directly from the BTE PrimusRS computer to ensure the accuracy of the data being extracted. The three trials with the highest peak torque were used for statistical analysis. The uninvolved side was always tested first. The three highest peak torque values in Newton-meters (Nm) were averaged. Isometric QT values are routinely used to calculate asymmetry between the involved and uninvolved limbs [9,43-47]. The average peak torque value for each limb was used for further analysis and calculation of the quadriceps index (QI), as calculated with Equation 1 shown below.

Equation 1: QI = [ACL-R Limb QT MVIC/Health Limb QT MVIC] x 100%

Knee Extension Rate of Torque Development

Quadriceps rate of torque development isometric knee extension (RTD) was quantified during a quick (2.0 second) contraction. For familiarization of the test, subjects performed up to two trials of isometric repetitions (the first practice repetition was recommended at 50%, and the second repetition at 75%) [26,43-48]. The subjects were instructed to extend their knee "as fast and as hard as possible" [9,34,35,44], with an emphasis on "fast" [9,40,44]. Subjects were instructed to avoid any prior countermovement of the limb, and the resting force level was displayed on a sensitive scale to provide biofeedback on whether any countermovement or pre-tension had occurred [32,40,44,50].

Subjects then performed 5 maximal contractions with short duration (2.0 second) contractions interspersed by short rest periods (20 sec) [44,45,50,51]. Of the 5 maximal contractions, the 3 trials with the greatest MVIC, and without an unstable baseline (i.e. any evidence of muscle pre-tension &/or counter-movements), were selected. The three selected MVIC's were averaged [44,45,50,51].

As the patient profiles are created directly on the BTE PrimusRS software, the raw data of the RTD was taken directly from the BTE PrimusRS computer to ensure the accuracy of the data being extracted. The RTD was calculated for a certain percentage of peak torque. The RTD values were selected at 30%

(RTD30%), 50% (RTD50%), and 90% (RTD90%) of peak torque as these have previously been described in the ACL-R population [15]. For each RTD trial, 30%, 50%, and 90% of the peak torque (Nm) reached was determined. The closest data point to the respective percentage point was identified, and the slope of the torque-velocity curve at that point was determined using the immediately preceding data point. The slope represented Nm/s at that specific point and was identified as the RTD. The highest RTD at each of the respective percentages of peak (30, 50, and 90%) across the three trials was recorded.

The LSI for RTD30%, RTD50%, and RTD 90% was calculated by dividing each respective ACL-R limb value by that of the Healthy limb and multiplying by 100 to provide percentage between limbs. The equation for RTD is detailed by Equation 2 below:

Equation 2: LSI RTD30% = [ACL-R Limb max RTD30%]/[Health Limb max RTD30%] x 100%

Noyes Hop Test Procedure

The standard practices for assessing hop performance testing post ACL-R within the Medical Center was carried out for each of the subjects included within the study and are described below. The series of four hop tests were administered consistent with the protocols outlined by Noyes *et al*., Barber *et al*, and Daniel *et al*., [52-54]. The four hop tests included: a single hop for distance (1hop), a 6-meter timed hop (6mHop), a triple hop for distance (3Hop), and a crossover hop for distance (CrxHop). The tests were performed in that order according to the original description by Noyes *et al,* [52]. The course consisted of a 6-meter-long × 15-cm-wide marking placed on the floor.

For each hop test, the participant was allowed one practice trial, followed by two recorded trials. No warm-up activity was allowed other than that described above. A trial was recorded when a subject was able to maintain single limb landing for a minimum of two seconds without touching the floor with their contralateral leg or either upper extremity, and without taking an additional hop upon landing. If a trial was unsuccessful, the participant was reminded of requirements for landing and the hop was repeated until two successful trials were performed.

The distance hopped, measured at the level of the great toe, was measured and recorded to the nearest centimeter from a standard tape measure that was permanently affixed to the floor. For the 6mHop, the built-in manufactory stopwatch app on an iPhone 7 was used to record time. The stopwatch was started when a subject's heel lifted from the starting position and was stopped the moment that the tested foot passed the finish line. Measurements were recorded to the nearest 10th of a second.18 Participants began with the nonoperative limb. A rest period of up to 2 minutes was offered between types of hops, and up to 30seconds between individual hop trials.

Control of Bias

All physical performance measures taken were administered by the same member of the research team. A prior to initiation of the testing a formal script of instruction was agreed upon as specified above. None of the participants were informed of the study hypothesis and were informed to perform their very best on each of the physical performance measures with each leg. This was to avoid participants tailoring their performance to a presumed or preferred outcome.

Statistical Analysis

The D'Agostino's (modified Shapiro-Wilk) normality test was used to determine normality of distribution of the data. Data was found to be normally distributed, allowing the use of parametric tests. Data was reported as a group mean ± SD.

A paired t-test was used to compare the average RTD30%, RTD50%, RTD90%, QI, 1Hop, 6mHop, 3Hop, and CrxHop between the healthy and ACL-R limbs. An alpha level of 0.05 was deemed statistically significant.

The relationships between RTD30%, RTD50%, RTD90%, and MVIC and IKDC were calculated using the Pearson correlation coefficient, and interpreted as follows: 0.00 to 0.19, very weak correlation; 0.20 to 0.39, weak correlation; 0.40 to 0.69, moderate correlation; 0.70 to 0.89, strong correlation; and 0.90 to 1.0, very strong correlation [55]. All analyses were conducted using Microsoft Excel 2016 Inferential Statistic Template. An alpha level of 0.05 was considered to be statistically significant.

Results

Participants

Nineteen appropriate subjects, 13 males and 6 females, were prospectively identified across three medical centers within the specified period. Participant demographic characteristics are shown in Table 2a and 2b. On average, the participants were 36.9±18.0 weeks (~9.2 months) post-surgery when tested and had 27.4±9.4 treatment sessions.

Regarding surgical procedures, the majority of ACL-R limbs were reconstructed with bone- patellar tendon-bone autograft (n=9, 47%) and had a subsequent procedure performed on the meniscus (n=9, 47%). Other graft types included hamstring autograft (n=8, 42%), quadriceps tendon autograft (n=2, 11%), bone-patellar tendon-bone allograft (n=1, 5%).

Table 2a: *Summarized subject demographics*

Cohort	n	Age (yr)	Height (m)	Weight (kg)	BMI	IKDC Score	# of Treatment Sessions	Weeks Post-op
Males	13	29.1	1.7	77.2	25.3	74.8	27.8	31.0
Females	6	24.3	1.6	61.6	22.7	85.8	26.4	49.9
Aggregate	19	27.6	1.7	72.3	24.5	78.3	27.4	37.0

Note. BMI, body mass index; IKDC, 2000 International knee documentation committee score; yr, year

Table 2b: *Subject Demographics*

St	Age (yr)	Gender	Height (m)	Weight (kg)	BMI	Involved Side	Graft Type	Surgical Procedure(s)	IKDC Score	# of Treatment Sessions	Weeks Post-Op
1	31	Male	1.88	89.0	25.19	Right	BTB autograft	None	81.61	22	41.1
2	25	Female	1.63	69.9	26.45	Left	HS autograft	Arthroscopy and manipulation under anesthesia 3/22/18	86.20	47	74.0
3	30	Male	1.77	95.1	30.53	Left	Quad tendon autograft	Medial meniscus repair & partial lateral meniscectomy	66.70	43	26.0
4	36	Male	1.83	89.7	26.81	Left	BTB autograft	Lateral meniscus repair	64.40	14	23.3
5	37	Female	1.74	60.8	20.08	Right	HS autograft	Medial meniscus repair	88.50	19	23.1
6	41	Male	1.78	82.8	26.19	Left	BTB allograft	None	71.60	38	23.0
7	15	Male	1.59	68.0	26.98	Left	HS autograft	None	94.30	33	27.0
8	31	Male	1.68	72.0	25.62	Left	BTB autograft	Partial medial meniscectomy and lateral meniscus repair	86.20	22	25.7
9	18	Female	1.69	68.0	23.83	Left	HS autograft	None	78.20	28	65.9
10	30	Male	1.73	84.8	28.18	Left	HS autograft	Partial medial meniscus debridement	80.50	25	32.7
11	30	Female	1.57	47.2	19.03	Left	BTB autograft	Lateral meniscus repair	82.50		56.1

12	16	Male	1.73	68.2	22.86	Right	BTB autograft	None	70.10	19	76.1
13	18	Female	1.63	71.8	27.17	Left	BTB autograft	Medial meniscus repair, partial lateral meniscectomy	94.30	20	43.0
14	28	Male	1.71	74.0	25.25	Left	HS autograft	Lateral meniscus repair	78.20	32	20.9
15	18	Female	1.63	51.8	19.60	Right	BTB autograft	None	85.10	18	37.4
16	30	Male	1.70	77.1	26.62	Left	HS autograft	Lateral meniscus repair	62.10	31	29.0
17	29	Male	1.75	68.2	22.20	Right	HS autograft	None	69.00	18	24.7
18	33	Male	1.77	63.0	20.22	Left	Quad tendon autograft	None	65.50	29	20.9
19	28	Male	1.77	71.4	22.75	Left	BTB autograft	None	82.80	36	32.1

Note. BMI, body mass index; BTB, Bone patellar tendon bone graft; HS, hamstring; IKDC, 2000 International knee documentation committee score; Kg, kilograms; m, meters; yr, year.

IKDC Scores

The mean IKDC score was 78.3±10.0. Seven (37%) individuals rated their knee function <75% as determined by the IKDC score, two (11%) subjects rated their knee function as near normal (>90%), and the remaining eleven (58%) fell in the moderate range, knee function 75-90%.

Knee Extension Peak Torque Index

QT data is summarized in Table 3. The quad index (QI) was stratified into 'high' (>90%), 'moderate' (85-90%), 'low' (<85%). In the table, these are represented by green, yellow, and red cells, respectively. The mean QI was 'moderate' at 88.8 ± 7%. Ten subjects (53%) demonstrated 'high' QI, three subjects demonstrated 'moderate', and six subjects demonstrated 'low' QI score.

Table 3: *Knee extension peak torque data*

Subject	Health Limb Torque Values		ACL-R Limb Torque Values		Quad Index
	Average Torque (Nm)	Avg Torque to Body Weight (Nm/kg)	Average Torque (Nm)	Avg Torque to Body Weight (Nm/kg)	(ACL-R Limb Avg Torque/Health Limb Avg Torque)
1	167.67	1.88	149.50	1.68	89%
2	129.03	1.85	114.03	1.63	88%
3	127.33	1.34	101.90	1.07	80%
4	161.23	1.80	135.37	1.51	84%
5	123.17	2.03	98.60	1.62	80%
6	125.10	1.51	112.70	1.36	90%
7	101.67	1.50	98.27	1.45	97%
8	138.53	1.92	144.57	2.01	104%
9	122.87	1.81	110.67	1.63	90%
10	186.43	2.20	149.63	1.76	80%
11	89.03	1.89	82.53	1.75	93%
12	156.29	2.29	145.28	2.13	93%
13	178.37	2.48	149.70	2.08	84%
14	167.87	2.27	147.83	2.00	88%
15	124.00	2.39	115.95	2.24	94%
16	122.07	1.58	112.43	1.46	92%
17	168.02	2.46	161.55	2.37	96%
18	127.03	2.02	94.73	1.50	75%
19	126.10	1.77	113.67	1.59	90%
				Average	89%

Note. ACL-R, anterior cruciate ligament reconstruction; Avg: average

Knee Extension Rate of Torque Development

The RTD data is summarized in Table 4. The LSI for RTD30%, RTD50%, and RTD 90%, like the QI scores, were stratified into 'high' (>90%), 'moderate' (70-90%), 'low' (<70%). In the table, these are represented by green, yellow, and red cells, respectively. The mean values of LSI for RTD30%, RTD50%, and RTD90% were 76±24%, 65±35%, and 49±33%, respectively. Across all RTD LSI values, only 12 (21%) were in the 'high' range. Seven LSI values were in the 'moderate' (12%) range, and the remaining 38 (67%) were 'low.'

Table 4: *Knee extension rate of torque development*

Subject	Health Limb Rate of Torque Development (Nm/s)			ACL-R Limb Rate of Torque Development (Nm/s)			Limb Symmetry Index (LSI)		
	30% Peak	50% Peak	90% Peak	30% Peak	50% Peak	90% Peak	LSI 30% Peak	LSI 50% Peak	LSI 90% Peak
1	1809	1238	1010	2267	2147	568	125%	173%	56%
2	1576	1585	364	1064	674	327	68%	43%	90%
3	1476	1343	601	1189	574	416	81%	43%	69%
4	1514	1020	676	957	406	227	63%	40%	34%
5	595	559	127	466	224	39	78%	40%	31%
6	1614	1481	660	325	294	86	20%	20%	13%
7	1407	1028	404	920	581	106	65%	57%	26%
8	1089	1469	310	694	716	151	64%	49%	49%
9	1469	800	256	1288	524	84	88%	65%	33%
10	2000	1865	436	1852	981	97	93%	53%	22%
11	994	692	167	635	509	107	64%	74%	64%
12	983	1065	416	1028	1141	525	105%	107%	126%
13	1885	2204	820	2048	1537	133	109%	70%	16%
14	2374	2459	1027	1630	1358	283	69%	55%	28%
15	911	934	337	552	617	93	61%	66%	28%
16	561	393	197	386	407	199	69%	104%	101%
17	1899	1521	569	1400	1141	559	74%	75%	98%
18	1134	816	380	1164	629	81	103%	77%	21%
19	1562	1374	572	760	396	149	49%	29%	26%
						Average	74%	62%	44%

Note. 3x Hop, triple single leg hop; 6m: 6-meter single leg hop; Crx Hop, triple cross over hop.

Noyes Hop Tests

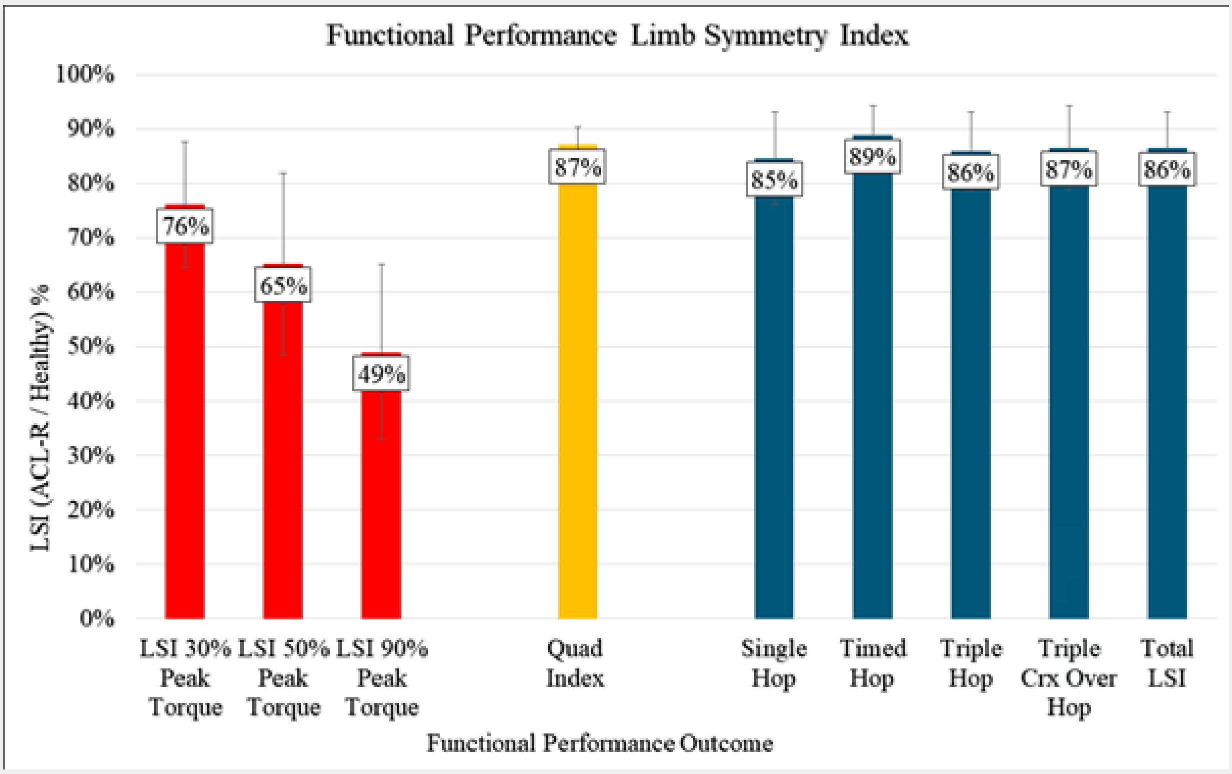
The Noyes Hop Test results are represented in Table 5. The LSI for each of the hop tests were stratified into 'high' (>90%), 'moderate' (85-90%) and 'low' (<85%). The mean for LSI for all hop tests, including the composite LSI, demonstrated 'moderate' performance. No individual hop test result significantly differed from the others. When considering the composite LSI, 10 (53%) subjects achieved 'good' performance, one (5%) subject achieved 'moderate' performance, and 8 (42%) subjects demonstrated 'poor' performance on their ACL-R limb compared to the healthy limb.

Table 5: *Noyes hop test results*

Subject	Health Limb (cm)				ACL-R Limb (cm)				Limb Symmetry Index (LSI)				
	Single Hop	6m Hop (s)	3x Hop	Crx Hop	Single Hop	6m Hop (s)	3x Hop	Crx Hop	Single Hop	6m Hop	3x Hop	Crx Hop	Total
1	174	1.92	431	389	162	2.01	428	360	93%	96%	99%	92%	95%
2	118	2.32	331	249	117	2.25	331	261	100%	103%	100%	105%	102%
3	130	1.96	404	370	101	2.09	336	315	78%	94%	83%	85%	85%
4	215	1.48	642	563	141	1.91	488	359	66%	77%	76%	64%	71%
5	103	2.15	363	278	98	2.57	359	300	95%	84%	99%	108%	96%
6	158	2.17	438	411	75	2.73	236	222	47%	79%	54%	54%	59%
7	136	1.80	380	386	143	1.80	384	377	105%	100%	101%	98%	101%
8	149	2.56	422	366	130	4.03	385	298	87%	63%	91%	81%	81%
9	163	2.28	439	345	131	2.41	335	277	81%	95%	76%	80%	83%
10	160	1.78	458	401	149	1.87	415	355	93%	95%	91%	88%	92%
11	143	2.27	389	290	132	2.39	342	303	93%	95%	88%	105%	95%
12	162	1.92	432	398	164	1.97	418	377	101%	97%	97%	95%	98%
13	142	1.83	422	401	150	1.83	434	427	106%	100%	103%	106%	104%
14	184	1.77	457	415	91	2.59	282	264	49%	68%	62%	64%	61%
15	159	2.36	401	358	142	2.33	379	345	89%	101%	95%	96%	95%
16	172	2.04	500	437	125	2.49	376	309	73%	82%	75%	71%	75%
17	175	1.63	581	526	183	1.86	590	525	105%	88%	101%	100%	98%
18	199	1.54	602	500	147	1.74	420	375	74%	88%	70%	75%	77%
19	183	1.67	531	496	130	2.05	380	382	71%	82%	72%	77%	75%
							Average		85%	89%	86%	87%	86%

Note. 3x Hop, triple single leg hop; 6m, 6 meter single leg hop; Crx Hop, triple cross over hop.

A summary of each of the functional performance LSI outcomes are summarized in Figure 1. There were no missing outcome data points for any of the participants in this study.



Note: ACL-R, anterior cruciate ligament reconstruction limb outcomes. Crx, cross over hop; LSI, limb symmetry index.

Figure 1: *Functional performance limb symmetry index summary*

Discussion

The primary purpose of this study was to investigate the recovery of knee extension RTD in subjects between 20 weeks and two years post-ACL-R. The results show that the reconstructed limb had significantly lower RTD of the quadriceps as compared to the non-reconstructed limb at 30%, 50%, and 90% of peak torque. These results suggest that significant deficits in the speed of quadriceps isometric torque production post-ACL-R persist beyond restoration of QT and hop performance.

The reductions in RTD of the quadriceps post-ACL-R are consistent with previous reports that showed decreased quadriceps RTD within the same post-operative time frame [15,16,21,56-59]. The deficit in quadriceps RTD in the current study was highly dependent on the percent of peak torque that was considered. The deficits were 76%±24%, 65±35%, and 49±33% at RTD30, RTD50, and RTD90, respectively. The magnitude of percent reduction is comparable to that of previous findings [16,21,56,57,59]. However, the results of other studies cannot be directly compared as the rate of torque development was captured using a leg press maneuver rather than seated knee extension [15].

It is also important to note that there is heterogeneity in the methodology of calculating and reporting RTD. Prior studies have reported peak torque achieved (Nm/s) [16,21,58,59], average rate of torque development [16,21,57,59], and peak torque normalized the body weight (Nm/s/kg) [16,57,58]. The current study considered the rate of torque development at specific time points as determined by a percentage of the peak torque achieved. These time points were selected in accordance with previously described methods of RTD [15].

The rationale in choosing specific RTD data points as a percentage of peak torque allowed for direct comparison between the limbs at relevant points of force production. Had peak torque alone been utilized, it is possible that the moment of peak torque may have occurred at significantly different time points for each limb (i.e., 30ms, 50ms, 100ms, 150ms, 200ms). Additionally, measuring RTD as a percentage of peak torque allowed for evaluation of the rate of torque development throughout the contraction to better identify where the most substantial discrepancy in limb symmetry index existed. The results demonstrated that there is a significant difference in the rate of torque development at each of the intervals considered, and the higher the percentage of force that is required, the greater the deficit in RTD.

The physiological components that directly influence the rate of torque development performance have been motor unit recruitment and muscle fiber composition [13,60]. It is likely that a combination of deficits in both physiological components played a role in the significant discrepancies in RTD limb symmetry performance found in this study. First, considering muscle fiber type, it is well documented that there is muscle atrophy of the quadriceps post-ACL-R [61], due to the quadricep arthro-genic inhibition and disuse secondary to postoperative precautions. In such settings, it is also known that fast-twitch glycolytic fibers are more vulnerable than slow-twitch oxidative fibers under such atrophic conditions [62]. Additionally, the alterations in neural drive that persist after ACL-R [63-66], likely play a factor in motor unit recruitment resulting in impaired speed of contraction and RTD [13,21].

The second part of the study was to investigate recovery of RTD compared to that of standard RTS functional performance tests, QT and Noyes Hop test performance. With standard timelines of RTS post-ACL-R being 6 to 12-months, and primarily when greater than 90% of limb symmetry index has been achieved for quad strength and Noyes hop test, it can be argued that the cohort included in this study were very close to being cleared for RTS based upon these criteria [3,65,67]. The mean duration post ACL-R at the time of testing for this cohort was 8.6 months, with a mean QI of 89% and mean Noyes Hop test composite score of 86% (see Table 5). The significant difference between QI and RTD LSI may partly be due to the fact that the peak torque measurement used to calculate QI is not as sensitive to motor unit recruitment or the loss of type II fibers during muscle atrophy as the metric of RTD. The performance on the Noyes hop test, on the other hand, does correlate with quadricep performance post-ACL-R [68]. The hop tasks do not isolate the quadriceps to the extent that the isometric/isokinetic quadriceps assessments do, and thus deficits in quadriceps performance can be overcome with the utilization of other muscle groups, prior experience, and neuromuscular strategies.

It is critically important to recognize that the study's cohort had nearly met standard discharge and RTS criteria on common and recommended functional performance tests and that the limb symmetry performance on these tests did not capture the significant deficits of RTD LSI. The inability of RTS tests to detect such large deficits in RTD is a considerable concern given the fact that it is within ~50ms of the foot hitting the ground that non-contact ACL injuries occur [69]. It does not matter how much force can be produced over a five-second torque test if the injury is likely to occur in a fraction of that time, therefore RTD has been identified as more important for injury risk reduction and safe RTS [69,70]. As many as 30% of active young patients who undergo reconstruction suffer a second ACL rupture in the first few years after surgery [71,72]. It is apparent that more rigorous functional performance measures must be considered when clearing athletes to return to their sport. Beyond injury prevention, RTD has consistently proven to be more influential in athletic performance than peak torque alone [70]. Neuromuscular function during sporting activities such as sprinting, jumping, and punching have all been shown to have a stronger correlation to RTD than peak force production in isolation [33,73]. Based upon the findings of the current study, as well as the protective and performance based merits of RTD, the recommendations of prior investigators [15,16,21,56-59], are reinforced that RTD should be considered as part of the functional performance test battery when returning recreational athletes to competition post-ACL-R.

An additional interpretation of these results is that current rehabilitation post-ACL-R requires specific interventions in order to adequately restore RTD to preinjury levels. Prior investigators have described up to 20 weeks of training emphasizing RTD improvements before full recovery of RTD is achieved [15]. During the return to sport phase of rehabilitation, as the athlete reintegrates back into sports specific strength and conditioning programs, it is necessary to incorporate heavy resistance training (>70% 1RM) along with an emphasis on speed of multi-joint athletic-based movements, lower extremity plyometrics and agility training as each of these components have been shown to improve RTD [17,21,33,70,73]. Further research is needed to identify the most effective methods of RTD restoration following ACL-R.

Limitations

This study had several limitations. To improve the generalizability of our findings, we had a relatively heterogeneous sample. The patient's age ranged from 15-41 years old, with 13 male and 6 female participants. Quadriceps function and development may differ based upon the age of the patient [74]. The sample size as a whole was limited, and only 31.6% of our sample was female, despite the higher incidence of ACL injuries reported in females [75,76]. By using a recreational athlete population, athletic experience and ability was diverse, though previous studies that investigated elite athletes have recommended that this population be assessed [15]. As subjects' data was captured at various stages of their respective rehabilitation timelines, there was variability in the time since surgery (20.9 - 76.9 weeks) and the number of rehab sessions that each subject had completed. Time since surgery and number of rehab sessions completed inherently affect limb symmetry in muscle performance post ACL-R [77], yet it is difficult to avoid this issue as strength deficits have been reported to persist as late as 20 years following ACL-R [78]. While the full range of time since surgery makes our results more generalizable, it restricts the ability to apply our findings to a specific time point in the ACL-R rehabilitation process. We did not take into account the time interval between ACL injury and reconstructive surgery, though this has been shown to have some influence on surgery outcome [79].

Four different graft types were included in our sample; patellar tendon autograft (8), patellar tendon allograft (1), hamstring autograft (8), and quadriceps tendon autograft (2). Graft type can have a significant effect on quadriceps function - strength deficits are higher following patellar tendon autograft compared to hamstring autograft [80]. Harvesting an ipsilateral bone-patellar-bone autograft, or quadriceps tendon autograft may impair the quadriceps differently to an allograft or hamstring graft due to pain and structural changes. Previous research has indicated that using the contralateral side can lead to improved limb symmetry for quadriceps strength and knee range of motion [81,82]. The graft harvest site has been indicated to play a role in torque production of the quadriceps independent of the presence of an ACL reconstruction [21]. Though we included subjects with varying graft types, we were able to validate the details of each surgical procedure via the database, rather than rely on self-report as previous studies have had to do [57].

Due to the nature of testing, subjects were not blinded during the assessments, though verbal instructions were standardized. We could not assess the longitudinal changes in RTD, QI, or hop performance as subjects included had only undergone one testing session. The generalizability of these results is limited to hospital-based outpatient physical therapy departments. It is possible that in other outpatient rehabilitation settings that frequency, duration, and type of care for patients may differ and resultant outcomes may differ from the results shown here.

Conclusion

Despite the near recovery of peak quadriceps torque and hop performance symmetry, there were still significant deficits in RTD at 9 months post-ACL-R. These results suggest that, following ACL-R, traditional functional performance tests that are used for return to sport and activity decision making are insufficient at capturing significant deficits in knee extension RTD. It appears that additional focus should be placed on restoring normal quadriceps RTD before clearing a patient to return to sport. Previous research has found that normal RTD can be achieved at 12 months following ACL-R [15]. Future studies should investigate interventions aimed at normalizing knee extensor RTD following ACL-R at a rate comparable to the recovery of peak knee extensor torque and hop performance. It would also be beneficial to perform a long term follow up to compare individuals post-ACL-R with normal RTD to those with impaired RTD to assess the role of quadriceps RTD on return to functional activities/sport and potential reinjury rates.

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