Original Article

Deficits in Contralateral Limb Strength Can Overestimate Limb Symmetry Index After Anterior Cruciate Ligament Reconstruction

Thomas E. Moran, M.D., Anthony J. Ignozzi, B.S., Zachary Burnett, M.D., Stephan Bodkin, Ph.D., Joseph M. Hart, Ph.D., and Brian C. Werner, M.D.

Purpose: To evaluate whether contralateral limb strength represents a dynamic, rather than static, data point after anterior cruciate ligament reconstruction (ACL-R). **Methods:** Patients who underwent isolated ACL-R at a single institution were identified. Patients completed an institutional Lower-Extremity Assessment Protocol (LEAP) testing protocol at 6 and 9 months postoperatively. Extension strength and flexion strength of the ipsilateral and contralateral limbs and limb symmetry index (LSI) were compared between the 6- and 9-month testing outcomes. Subgroup analysis compared patients demonstrating less than or greater than 10% change in contralateral limb flexion and extension strength between 6 and 9 months postoperatively. **Results:** A total of 144 subjects were included in this study. On average, contralateral limb flexion and extension strength increased 2-4% between 6 and 9 months postoperatively. However, the contralateral limb increased >10% from 6 to 9 months in extension and flexion strength in 35/144 (24.3%) and 55/144 (38.2%) of patients, respectively. The cohort with >10% change between 6 and 9 months had significantly weaker contralateral extension and flexion strength at 6 months compared to the cohort that demonstrated <10% change (extension: 2.00 vs 2.39; $P < .001$; flexion: 0.84 vs 1.08; $P < .001$), but similar ipsilateral limb performance. Therefore, the >10% change cohort had a significantly greater LSI at 6 months compared to the <10% change cohort (67.3% vs 59.4%; $P = .006$). No demographic or operative factors correlated with which patients demonstrated >10% flexion or extension strength changes of the contralateral limb. **Conclusion:** A large percentage of patients demonstrate significant changes in their contralateral limb flexion and extension strength between 6 and 9 months postoperatively that result from an initial contralateral limb strength deficit. This may limit the utility of the contralateral limb as a control for comparison to the operative extremity during return to sport assessment.

Introduction

Anterior cruciate ligament (ACL) reconstruction is one of the most commonly performed orthopaedic knee surgeries, with an estimated 200,000-350,000 procedures being performed annually in the United States.[1-3] Given its prevalence, especially within the athletic community, extensive research has been performed examining the preoperative, intraoperative, and postoperative factors that influence one's ability to return to competitive athletics.[1,4] Significant advances in preoperative management, surgical technique, and postoperative rehabilitation have led to improved outcomes following surgery and greater ability to return to sport after injury.[1] There remains, however, a paucity of literature clearly defining objective criteria and formal guidelines about when athletes are able to return to sport without increasing their risk of graft rupture.[1,3,5-7] Most surgeons currently employ a

From the University of Virginia Medical Center, Department of Orthopaedic SurgeryCharlottesville, Virginia, U.S.A.

The authors report the following potential conflicts of interest or sources of funding: J.M.H. reports personal fees from Elsevier, research support from DJ Orthopaedics, and stock options from Springbok, outside the submitted work; he is an editorial or board member of Journal of Athletic Training, Journal of Sports Rehabilitation, *and* Athletic Training, *and* Sports Healthcare, *and he is a committee member of the NATA Foundation. B.C.W. is a paid consultant for Arthrex; and has received research support from Biomet, Exactech, and Flexion Therapeutics, outside the submitted work He is a board or committee member of AAOS, AOSSM, and American Shoulder and Elbow Surgeons. Full ICMJE author disclosure forms are available for this article online, as supplementary material.*

Received February 23, 2022; accepted June 25, 2022.

Address correspondence to Brian C. Werner, M.D., 515 Ray C. Hunt Dr., Suite 1100, Charlottesville, VA, 22903, U.S.A. E-mail: bcw4x@virginia.edu

2666-061X/22256

https://doi.org/10.1016/j.asmr.2022.06.018

multifactorial functional testing algorithm that includes quantitative measurements designed at detecting impairment in the operative limb that could place the athlete at risk of reinjury.[1,3,8,9] Although differences exist between the exact criteria used, many surgeons have adopted protocols that compare function and quadriceps muscle strength between the operative extremity and the contralateral, uninjured leg.[10-17]

General guidelines based on studies examining knee mechanics and reinjury rates have led to researchers advocating that patients be cleared for return to sport once quadriceps strength is at least 90% of the contralateral, uninjured limb.[10,12,14,15,18-20] While considerable effort has been dedicated to examining the impact of ACL injuries, subsequent reconstruction, and postoperative recovery on strength and performance in the injured leg,[10,21-23] there remains a lack of understanding regarding whether strength and performance are concomitantly affected in the contralateral, uninjured leg.

Some evidence suggests that strength deficits and functional impairment of the contralateral, uninjured leg occurs following ACL injury.[24-26] Deconditioning and central nervous system inhibition have been proposed as possible etiologies for these findings, although the occurrence of possible bilateral functional deficits is not yet well understood.[27,28] Given the emergence of these findings and the contralateral, uninjured limb presently being used as a control for rehabilitation endpoint, further study is necessary to define these effects and their progression over time in the postoperative period. Bilateral functional deficits would suggest less validity for the use of the contralateral limb as a control in side-to-side limb strength and functional performance comparisons in considering clearance to return to sport. The purpose of this study was to evaluate whether contralateral limb strength represents a dynamic, rather than static, data point after ACL-R.[1] We hypothesized that contralateral limb strength and functional testing represent a dynamic, rather than static, data point for the evaluation of safety to return to sport after ACL reconstruction.

Materials and Methods

This study was assessed and approved by the Institutional Review Board (IRB-HSR 173999) of the Health Sciences Research of the University of Virginia prior to data collection. Consecutive patients were evaluated for inclusion in the study if they underwent ACL reconstruction after an acute ACL tear at a single academic institution by 6 fellowship-trained, orthopaedic sports medicine surgeons between March 2013 and August 2018. Patients undergoing revision ACL-R or undergoing additional ligamentous reconstruction were excluded. In all cases, primary ACL-R was performed using arthroscopic assistance with either bone-patella tendon-bone autograft, quadriceps autograft, or hamstring autograft, using modern surgical technique with independent femoral tunnel creation. Included patients must have completed at least 2 postoperative follow-up visits during which they completed the Lower-Extremity Assessment Protocol (LEAP) testing to provide sufficient data for evaluation of contralateral limb strength over time. Follow-up LEAP testing was scheduled and completed at ∼6 and 9 months postoperatively for all included patients. LEAP testing included objective functional outcome metrics that are described in further detail in “LEAP Procedures”. LEAP testing was conducted according to institutional standards by a group of 3 trained doctoral students (S.G.B., A.B., X.T.), and directly overseen by one of the authors (J.M.H.). Patients were able to return to sport at 6 months only if the LSI were greater than 90% or based on patient and sport-specific factors. Retrospective chart review was performed to identify and record patient demographic factors, including age, sex, BMI, and limb dominance. Operative notes were evaluated to identify various intraoperative factors, the specific ACL graft type used, and any performance of concomitant meniscectomy or meniscal repair procedures.

Lower Extremity Assessment Protocol (LEAP) Procedures

Knee Strength During Flexion and Extension

Knee extension and flexion strength was measured bilaterally using a Biodex Systems 4 multimode dynamometer (Biodex Medical Systems, Shirley, NY) at a speed of 90°/s. This testing was performed with isokinetic and concentric movements. Testing was performed on the contralateral limb and then followed by the ipsilateral limb. Participants completed practice trials on each limb for familiarization prior to measurements being recorded. The participants provided maximal effort through their full range of motion for a total of 8 trials. The peak torque was measured, for both knee extension and flexion, via Biodex software. Peak torque was normalized to the participant’s body mass (Nm/kg). The LSI was calculated as the ipsilateral limb measurement divided by the contralateral limb measurement. A value of 100% indicated perfect symmetry.

Dynamic Hop Testing

Four, single-leg hopping trial were performed on each limb. The hop tests included the following: 1) a single hop for maximal distance where participants were instructed to hop straight forward as far as possible with a balanced landing on one limb (single hop), 2) three consecutive hops in a straight line for maximal distance (triple hop), and 3) a timed hop where subjects were instructed to hop as quickly as possible for 6 meters (timed hop). Distances were measured in centimeters,

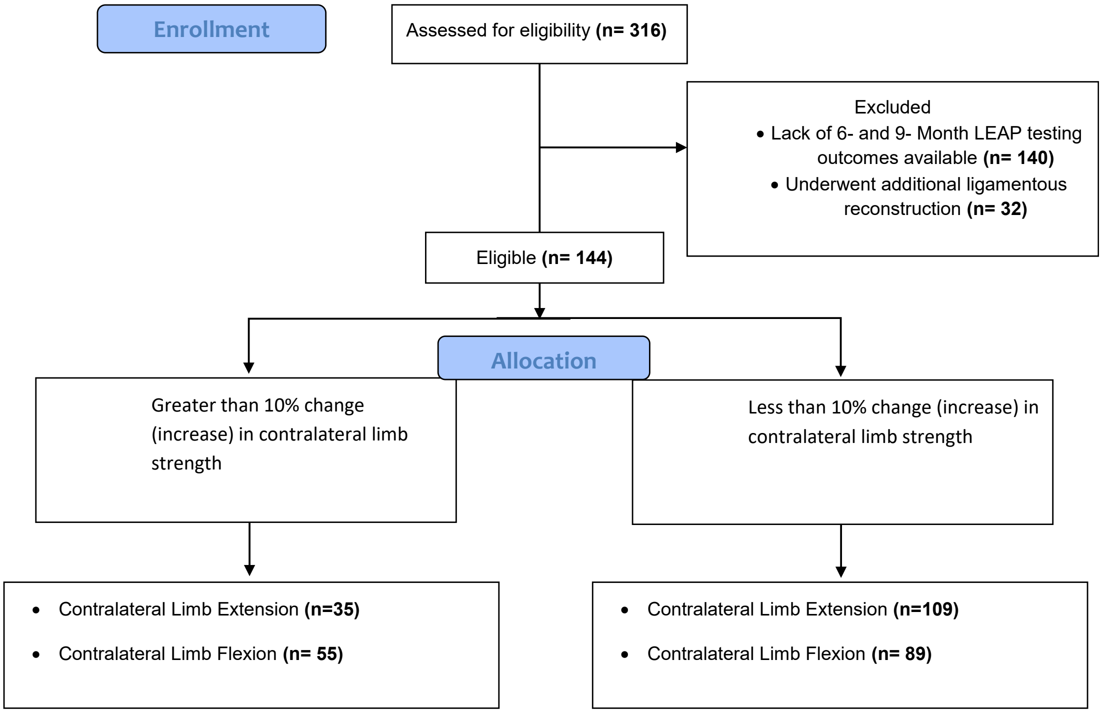

Fig 1. 144 patients were identified for inclusion from a population of 316 potentially eligible patients. LEAP, Lower-Extremity Assessment Protocol.

time in seconds, and symmetry was expressed as a percentage of the contralateral limb as described above.

Statistical Analyses

Statistical analyses were performed using IBM SPSS Statistics 26 (International Business Machines Corporation, Armonk, NY). Descriptive statistics, including mean and standard deviation, were calculated for all quantitative variables. Extension strength, flexion strength, LSI, and hop tests of ipsilateral and contralateral limbs were compared between the 6- and 9-month LEAP testing outcomes using a paired Student's *t*-test. With an alpha of 0.05 and power of 0.80, a sample size of at least 52 would be required to detect a difference of 8% in LSI.

Further subanalysis of cohorts demonstrating less than and greater than 10% change in contralateral limb flexion, and extension strength was performed using an independent Student's *t*-test. The contralateral extension and flexion performance had a resulting power of 0.83 and 0.91, respectively, to determine LSI differences of 8% with an alpha of 0.05. Multivariable binary logistic regression was used to evaluate demographic and operative risk factors for developing greater than 10% change to contralateral limb strength including age, sex, BMI, graft type, limb injured, meniscectomy, and meniscal repair. For all comparisons, $P < .05$ was considered statistically significant.

Table 1. Cohort Characteristics

N (Number of Patients)	144
Age (years, means ± SD, range)	21.6 ± 8.1 (14–56)
Sex (*n*, % female)	75 (52.1%)
BMI (kg/m^2, means ± SD, range)	25.4 ± 4.4 (18.1–39.4)
Graft type (BPTB:HS:Quad)	99:43:2
Limb (*n*, % dominant)	72 (50.0%)
Meniscectomy (*n*, %)	46 (31.9%)
Meniscus repair (*n*, %)	62 (43.1%)

BMI, body mass index; BPTB, bone patella tendon bone; HS, hamstring; Quad, quadricep; SD, standard deviation.

Results

144 patients were identified for inclusion from a population of 316 potentially eligible patients (Fig 1). Cohort demographics and surgical characteristics are reported in Table 1. Mean functional outcome testing metrics for the ipsilateral (operative) limb and contralateral (nonoperative) limb, as well as determination of limb symmetry, are reported at both 6 and 9 months postoperatively in Table 2. A statistically significant difference was seen in all testable metrics of flexion, extension, and hop testing for both the ipsilateral limb, contralateral limb, and quantified limb symmetry indices between 6 and 9 months (Table 2). However, ipsilateral limb strength had an average increase of 14-25%, whereas contralateral limb strength had an average increase of 2-4%. The contralateral limb extension and flexion strength demonstrated an increase of >10% between 6 to 9 months postoperatively

Table 2. LEAP Outcomes in Patients with Two LEAP Follow-Up Assessments (n = 144)

	First Follow-up	Second Follow-Up	*P* Value
LEAP Follow-up Time (months)	6.08 ± 1.55	9.60 ± 2.31	
Extension Measures			*P*
Ipsilateral norm peak ext torq 90° (Nm/kg)	1.41 ± 0.41	1.76 ± 0.43	<.001
Contralateral norm peak ext torq 90° (Nm/kg)	2.30 ± 0.45	2.35 ± 0.43	.043
LSI ext (%)	62.2% ± 16.9%	75.5% ± 14.6%	<.001
Flexion Measures			*P*
Ipsilateral norm peak flex torq 90° (Nm/kg)	0.90 ± 0.27	1.03 ± 0.28	<.001
Contralateral norm peak flex torq 90° (Nm/kg)	0.99 ± 0.28	1.03 ± 0.24	.009
LSI flexion (%)	92.0% ± 19.9%	100% ± 20.5%	<.001
Single Hop Tests			*P*
Ipsilateral single hop (cm)	109.1 ± 33.3	125.5 ± 31.0	<.001
Contralateral single hop (cm)	124.1 ± 31.9	131.8 ± 27.7	<.001
LSI single hop (%)	88.0% ± 12.5%	95.0% ± 10.0%	<.001
Triple Hop Tests			
Ipsilateral triple hop (cm)	392.0 ± 103.8	438.1 ± 98.8	<.001
Contralateral triple hop (cm)	436.4 ± 102.3	458.0 ± 90.4	<.001
LSI triple hop (%)	89.0% ± 13.5%	95.0% ± 8.5%	<.001
Timed Hop Tests			
Ipsilateral timed hop (seconds)	2.54 ± 0.67	2.35 ± 0.56	<.001
Contralateral timed hop (seconds)	2.34 ± 0.512	2.23 ± 0.41	.001
LSI timed hop (%)	108.0% ± 13.8%	105.0% ± 9.8%	.001

in 35/144 (24.3%) and 55/144 (38.2%) of patients, respectively (Table 2). Further subgroup analysis was performed between cohorts demonstrating less than and greater than 10% change in contralateral limb extension and flexion strength between 6 and 9 months postoperatively (Tables 3 and 4).

Patients with >10% change in contralateral limb extension strength between 6 and 9 months postoperatively had significantly weaker contralateral extension strength at 6 months compared to the cohort that demonstrated <10% change (2.00 vs 2.39; $P < .001$). However, ipsilateral limb extension strength at 6 months was similar between groups (1.41 vs 1.42; $P = .872$). The cohort demonstrating >10% contralateral limb strength change between 6 and 9 months, therefore, had a significantly greater LSI at 6 months compared to the <10% change group (67.3% vs 59.4%; $P = .006$). At 9 months postoperatively, both groups showed no difference in contralateral limb strength, ipsilateral limb strength, or LSI (Table 3). No demographic or operative factors were identified that correlated with which patients demonstrated >10% change in contralateral limb extension strength (Table 3).

Patients with >10% change in flexion strength between 6 and 9 months postoperatively had significantly weaker contralateral flexion strength at 6 months than the cohort that demonstrated <10% change (0.84 vs 1.08; $P < .001$). Ipsilateral flexion strength was also different between groups at this time point (0.78 vs 0.97; $P < .001$). Limb symmetry comparison between groups demonstrating >10% change and <10% change did not significantly differ (93.9% vs 90.9%; $P = .379$). At 9 months postoperatively, both groups showed no difference in contralateral limb strength or ipsilateral limb strength (Table 4). A significant difference in LSI was seen between groups; however, there existed a small absolute or percentage difference in LSI (Table 4). No demographic or operative risk factors were identified that correlated with which patients demonstrated >10% change in contralateral limb flexion strength (Table 4).

Discussion

The primary finding of this study is that a large percentage of patients demonstrate significant changes in

Table 3. Contralateral Extension Performance

Percent Improvement	>10%	<10%	*P* Value
N (number of patients)	35 (24.31%)	109 (75.69%)	
6 Month Follow-Up			
Ipsilateral norm peak ext torq 90° (Nm/kg)	1.41 ± 0.47	1.42 ± 0.38	.872
Contralateral norm peak ext torq 90° (Nm/kg)	2.00 ± 0.46	2.39 ± 0.40	**<.001**
LSI (%)	67.3% ± 18.2%	59.4% ± 12.9%	**.006**
9 Month Follow-Up			
Ipsilateral norm peak ext torq 90° (Nm/kg)	1.84 ± 0.49	1.74 ± 0.41	.252
Contralateral norm peak ext torq 90° (Nm/kg)	2.43 ± 0.49	2.32 ± 0.40	.187
LSI (%)	75.7% ± 14.1%	75.5% ± 14.8%	.937
Characteristics			
LSI percent improvement	13.0 ± 26.4	30.5 ± 28.1	.001
Age (means ± SD, years)	20.1 ± 7.2	20.84 ± 8.5	.197
Sex (*n*, % female)	20 (57.1%)	55 (50.5%)	.660
BMI (means ± SD, kg/m^2)	25.6 ± 4.8	25.3 ± 4.3	.319
Limb (*n*, % dominant)	20 (57.1%)	52 (47.7%)	.604
Graft type (*n*, BPTB%)	19 (55.9%)	80 (74.1%)	.129
Meniscectomy (*n*, %)	11 (31.4%)	35 (32.1%)	.687
Meniscus repair (*n*, %)	15 (42.9%)	47 (43.1%)	.634

Bolded values indicate significant differences. BMI, body mass index; BPTB, bone patella tendon bone; ext, extension, deviation; flex, flexion; LSI, limb symmetry index; Norm, normalized; SD, standard deviation; torq, torque.

Table 4. Contralateral Flexion Performance

Percent Improvement	>10%	<10%	*P* Value
N (number of patients)	55 (38.19%)	89 (61.81%)	-
6 Month Follow-Up			
Ipsilateral norm peak ext torq 90° (Nm/kg)	0.78 ± 0.24	0.97 ± 0.27	<.001
Contralateral norm peak ext torq 90° (Nm/kg)	0.84 ± 0.23	1.08 ± 0.27	<.001
LSI (%)	93.9% ± 21.6%	90.9% ± 18.8%	.379
9 Month Follow-Up			
Ipsilateral norm peak ext torq 90° (Nm/kg)	1.00 ± 0.30	1.05 ± 0.27	.249
Contralateral norm peak ext torq 90° (Nm/kg)	1.06 ± 0.26	1.02 ± 0.22	.420
LSI (%)	94.5% ± 16.9%	104% ± 21.8%	.006
Characteristics			
LSI percent improvement	4.1 ± 21.5	17.9 ± 29.1	.003
Age (means ± SD, years)	22.1 ± 8.4	19.8 ± 8.0	.246
Sex (*n*, % female)	26 (47.3%)	49 (55.1%)	.778
BMI (means ± SD, kg/m^2)	26.3 ± 4.8	24.8 ± 4.1	.082
Limb (*n*, % dominant)	25 (45.5%)	47 (52.8%)	.476
Graft type (*n*, BPTB%)	36 (65.5%)	63 (70.8%)	.961
Meniscectomy (*n*, %)	16 (29.1%)	30 (33.7%)	.302
Meniscus repair (*n*, %)	22 (40.0%)	40 (44.9%)	.571

Bolded values indicate significant difference. BMI, body mass index; BPTB, bone patella tendon bone; Ext, extension; Flex, flexion; LSI, limb symmetry index; Norm, normalized; SD, standard deviation; torq, torque.

their contralateral limb flexion and extension strength between 6 and 9 months postoperatively that result from an initial contralateral limb strength deficit. This may limit the utility of the contralateral limb as a control for comparison to the operative extremity during return to sport assessment. Notably, this study did not identify characteristics that help to reliably distinguish which patients will demonstrate these initial deficits and experience greater change in contralateral limb strength during recovery following ACL-R.

The present study suggests that the significant changes in contralateral limb extension and flexion strength seen at 6 months postoperatively in certain patients is representative of a relative performance deficit in comparison to peers, as comparable strength exists at 9 months postoperatively. Several previous studies have also identified the potential for impairment of the contralateral, nonsurgical limb after ACL reconstruction.[24-27,29] Chung et al. compared the performance of the contralateral limb in a cohort of 75 patients who underwent primary, unilateral ACL reconstruction to a matched, healthy cohort and suggested that functional deficits, particularly extension strength, existed in the population undergoing ACL reconstruction.[26] The relative deficits in extension strength were even demonstrated by 24-month final follow-up.[26] However, this study found this strength deficit to be resolved by 9 months.

Another study by Hiemstra et al. compared flexion and extension strength of the ipsilateral and contralateral limbs of 12 patients undergoing ACL reconstruction using a hamstring tendon graft, as well as to that of 30 healthy controls.[24] The authors found that in the patients undergoing surgery, knee extension normalized to within 10% of the contralateral, nonoperative limb, but that some deficits in flexion strength >10% persisted. However, when compared to limbs of the healthy control group, 13.5-26.8% of the deficits were demonstrated in knee flexion and extension of both the ACL-reconstructed and noninjured limbs.[24] Both of the aforementioned studies questioned the validity of the use of the contralateral limb as a control group in side-to-side limb strength and functional performance comparisons.[24,26] In comparison, a systematic review and meta-analysis by Brown et al. examining the quadriceps strength of the contralateral, uninjured leg of patients undergoing ACL reconstruction in comparison to a healthy, matched control group reported that the differences in extension strength were small.[13] In another systematic review and meta-analysis, Lisee et al. also did not observe a significant difference between the contralateral, uninjured limb and the limb of a control group.[30] Both of these reviews contained a relatively small number of studies examining this finding.[13,30]

In the context of this prior literature, the findings of our study also offer some mixed support to the use of the contralateral limb as a control for performance comparisons of the operative limb. Findings from the present study support that, as a general rule, the contralateral limb serves as a valid comparison, but that exceptions to this principle may exist in a proportion of patients that demonstrate more notable contralateral limb deficits at initial assessment. It would be ideal to be able to predict which patients would be the exceptions; however, the present analysis was unable to identify factors that correlate with which patients will manifest these findings. Considering that around one-fourth of patients in this study had extension strength changes of >10% between 6 and 9 months, physicians must be wary that 6-month limb symmetry tests may overestimate ipsilateral limb strength recovery. Thus, the strength recovery of both ipsilateral and contralateral limbs should be closely monitored at sequential follow-up assessments to truly evaluate the normality of the ipsilateral limb and account for potential deficits previously present in the contralateral limb. Collectively, the results of our study in the context of the prior literature are relevant given the lack of consensus in the literature regarding the use of the contralateral limb as a control for comparison during LSI calculations after ACL reconstruction. The present study suggests that in a significant proportion of patients, there may be limited validity to the use of the contralateral limb as a control group in side-to-side limb strength and functional performance comparisons when assessing a patient's return to sport. Although further investigation is needed, comparing the operative extremity to a patient's own preinjury measures or a large, population-based, matched, uninjured, control group may be more ideal.

Limitations

There are several limitations of note. Patients with meniscectomy and meniscal repair were both included. At the institution where the present study was conducted, the postoperative protocol is different for ACL reconstruction with concomitant meniscectomy and meniscal repair, which may have affected contralateral limb strength recovery. However, our analysis did not identify either as a predictive factor for the development of contralateral limb differences. Given the retrospective nature of the study, it remains possible that other confounding variables may have impacted the results. These include, but are not limited to, the timing between injury and surgery, degree of chondromalacia or meniscal injury, and preoperative strength deficits. Although LSI differences were adequately powered, certain subanalysis with large standard deviations may be underpowered. Unfortunately, no preinjury LEAP testing was performed in any patients. Comparison between these data and the postoperative LEAP data may have revealed baseline differences between cohorts. Physical therapy duration and adherence were also unable to be accounted for and may contribute to contralateral limb strength deficits. Additionally, there was no LEAP testing data beyond 9 months that could reveal further changes in contralateral limb strength.

Conclusions

A large percentage of patients demonstrate significant changes in their contralateral limb flexion and extension strength between 6 and 9 months postoperatively that result from an initial contralateral limb strength deficit. This may limit the utility of the contralateral limb as a control for comparison to the operative extremity during return to sport assessment.

References

1. Ellman MB, Sherman SL, Forsythe B, LaPrade RF, Cole BJ, Bach BR Jr. Return to play following anterior cruciate ligament reconstruction. *J Am Acad Orthop Surg* 2015;23:283-296.
2. Raines BT, Naclerio E, Sherman SL. Management of anterior cruciate ligament injury: What's in and what's out? *Indian J Orthop* 2017;51:563-575.
3. Davies GJ, McCarty E, Provencher M, Manske RC. ACL Return to sport guidelines and criteria. *Curr Rev Musculoskelet Med* 2017;10:307-314.
4. Nwachukwu BU, Adjei J, Rauck RC, et al. How much do psychological factors affect lack of return to play after anterior cruciate ligament reconstruction? A systematic review. *Orthop J Sports Med* 2019;7:2325967119845313.
5. van Melick N, van Cingel RE, Brooijmans F, et al. Evidence-based clinical practice update: Practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *Br J Sports Med* 2016;50:1506-1515.
6. Cheney S, Chiaia TA, de Mille P, Boyle C, Ling D. Readiness to return to sport after ACL reconstruction: A combination of physical and psychological factors. *Sports Med Arthrosc Rev* 2020;28:66-70.
7. Flagg KY, Karavatas SG, Thompson S Jr, Bennett C. Current criteria for return to play after anterior cruciate ligament reconstruction: an evidence-based literature review. *Ann Transl Med* 2019;7:S252 (Suppl 7).
8. Webster KE, Feller JA. Who passes return-to-sport tests, and which tests are most strongly associated with return to play after anterior cruciate ligament reconstruction? *Orthop J Sports Med* 2020;8:2325967120969425.
9. Della Villa F, Straub RK, Mandelbaum B, Powers CM. Confidence to return to play after anterior cruciate ligament reconstruction is influenced by quadriceps strength symmetry and injury mechanism. *Sports Health* 2021;13:304-309.
10. Lepley LK. Deficits in quadriceps strength and patient-oriented outcomes at return to activity after ACL reconstruction: A review of the current literature. *Sports Health* 2015;7:231-238.
11. Glattke KE, Tummala SV, Chhabra A. Anterior cruciate ligament reconstruction recovery and rehabilitation: A systematic review. *J Bone Joint Surg Am* 2022;104:739-754.
12. Di Stasi SL, Logerstedt D, Gardinier ES, Snyder-Mackler L. Gait patterns differ between ACL-reconstructed athletes who pass return-to-sport criteria and those who fail. *Am J Sports Med* 2013;41:1310-1318.
13. Brown C, Marinko L, LaValley MP, Kumar D. Quadriceps strength after anterior cruciate ligament reconstruction compared with uninjured matched controls: A systematic review and meta-analysis. *Orthop J Sports Med* 2021;9:2325967121991534.

14. Arhos EK, Capin JJ, Buchanan TS, Snyder-Mackler L. Quadriceps strength symmetry does not modify gait mechanics after anterior cruciate ligament reconstruction, rehabilitation, and return-to-sport training. *Am J Sports Med* 2021;49:417-425.
15. Zwolski C, Schmitt LC, Thomas S, Hewett TE, Paterno MV. The utility of limb symmetry indices in return-to-sport assessment in patients with bilateral anterior cruciate ligament reconstruction. *Am J Sports Med* 2016;44:2030-2038.
16. Johnston PT, McClelland JA, Feller JA, Webster KE. Knee muscle strength after quadriceps tendon autograft anterior cruciate ligament reconstruction: Systematic review and meta-analysis. *Knee Surg Sports Traumatol Arthrosc* 2021;29:2918-2933.
17. Ithurburn MP, Altenburger AR, Thomas S, Hewett TE, Paterno MV, Schmitt LC. Young athletes after ACL reconstruction with quadriceps strength asymmetry at the time of return-to-sport demonstrate decreased knee function 1 year later. *Knee Surg Sports Traumatol Arthrosc* 2018;26:426-433.
18. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: A criterion-based rehabilitation progression. *J Orthop Sports Phys Ther* 2012;42:601-614.
19. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 2012;42:750-759.
20. Wellsandt E, Failla MJ, Snyder-Mackler L. Limb symmetry indexes can overestimate knee function after anterior cruciate ligament injury. *J Orthop Sports Phys Ther* 2017;47:334-338.
21. Anderson JL, Lamb SE, Barker KL, Davies S, Dodd CA, Beard DJ. Changes in muscle torque following anterior cruciate ligament reconstruction: a comparison between hamstrings and patella tendon graft procedures on 45 patients. *Acta Orthop Scand* 2002;73:546-552.
22. Bizzini M, Gorelick M, Munzinger U, Drobny T. Joint laxity and isokinetic thigh muscle strength characteristics after anterior cruciate ligament reconstruction: Bone patellar tendon bone versus quadrupled hamstring autografts. *Clin J Sport Med* 2006;16:4-9.
23. Cardone C, Menegassi Z, Emygdio R. Isokinetic assessment of muscle strength following anterior cruciate ligament reconstruction. *Isokinet Exer Sci* 2004;Jan:173-177.
24. Hiemstra LA, Webber S, MacDonald PB, Kriellaars DJ. Contralateral limb strength deficits after anterior cruciate ligament reconstruction using a hamstring tendon graft. *Clin Biomech (Bristol, Avon)* 2007;22:543-550.
25. Mirkov DM, Knezevic OM, Maffiuletti NA, Kadija M, Nedeljkovic A, Jaric S. Contralateral limb deficit after ACL-reconstruction: an analysis of early and late phase of rate of force development. *J Sports Sci* 2017;35:435-440.
26. Chung KS, Ha JK, Yeom CH, et al. Are muscle strength and function of the uninjured lower limb weakened after anterior cruciate ligament injury? Two-year follow-up after reconstruction. *Am J Sports Med* 2015;43:3013-3021.
27. Rice DA, McNair PJ. Quadriceps arthrogenic muscle inhibition: neural mechanisms and treatment perspectives. *Semin Arthritis Rheum* 2010;40:250-266.
28. Urbach D, Awiszus F. Impaired ability of voluntary quadriceps activation bilaterally interferes with function testing after knee injuries. A twitch interpolation study. *Int J Sports Med* 2002;23:231-236.
29. Patterson BE, Crossley KM, Perraton LG, et al. Limb symmetry index on a functional test battery improves between one and five years after anterior cruciate ligament reconstruction, primarily due to worsening contralateral limb function. *Phys Ther Sport* 2020;44:67-74.
30. Lisee C, Lepley AS, Birchmeier T, O'Hagan K, Kuenze C. Quadriceps strength and volitional activation after anterior cruciate ligament reconstruction: A systematic review and meta-analysis. *Sports Health* 2019;11:163-179.