


Quality of Movement for Athletes 6 Months After ACL Reconstruction

Polly deMille,^{*†} RN, MA, ACSM-CEP, CSCS, Cara L. Lewis,[‡] PT, PhD, Joseph T. Nguyen,[†] MPH , Allison M. Brown,[§] PhD, PT, Jo A. Hannafin,[†] MD, PhD, and Theresa Chiaia,[†] PT, DPT

Investigation performed at the Hospital for Special Surgery, New York, New York, USA

Background: Anterior cruciate ligament (ACL) injury prevention programs address quality of movement to identify and correct high-risk movement patterns. However, return-to-play decisions after ACL reconstruction (ACLR) are often based on non-sport related quantitative measures such as isokinetic tests, jump testing, and/or time from surgery, with 6 to 9 months a common expectation for progressing to sport-specific training and return to play.

Purpose: To identify the presence in each limb of movement patterns associated with ACL injury in athletes 6 months post-ACLR using a quality-of-movement assessment.

Study Design: Cross-sectional study; Level of evidence: 3.

Methods: A quality-of-movement assessment including 10 dynamic tasks progressing from double- to single-limb and vertical to horizontal movements was administered to 148 athletes at 6 months after ACLR. Tasks were viewed live from the frontal and sagittal planes by a physical therapist and certified strength and conditioning specialist. Movements were evaluated for strategy, depth, alignment, symmetry, and control. The proportion of patients exhibiting faulty movement patterns for each task was assessed in the involved and uninvolved leg and between sex, meniscal injury status, and age. To examine the differences in age, patients were divided into age groups based on their age at the time of surgery (<14 years, 14-18, 19-25, 26-34, and ≥35 years).

Results: Mean time of testing was 6.4 months after ACLR. All patients exhibited faulty movement patterns for ≥1 task on the involved leg. On the involved leg, the proportion of patients demonstrating faulty movement patterns for a task ranged from 52% to 95%. Forward stepdown ($P < .001$), single-leg squat ($P = .03$), side-to-side jump ($P = .03$), and hop to opposite ($P = .04$) demonstrated higher frequency of faulty movement patterns in the involved versus the uninvolved leg. Rates of faulty movement patterns were not different between sex or meniscal injury status. Single-leg stance on the involved leg ($P = .05$) and single-leg bridge (uninvolved leg) ($P = .02$) differed between age groups.

Conclusion: Athletes demonstrated multiple faulty movement patterns that have been associated with both initial and second noncontact ACL injury. Faulty movement patterns were evident in tasks as simple as single-leg stance. The rates of faulty movement were similar in both male and female patients, as well as in the involved and uninvolved limb.

Keywords: anterior cruciate ligament; return to play; reinjury; movement quality

Anterior cruciate ligament (ACL) injuries have been identified as the single largest problem in orthopedic sports medicine.⁴⁸ ACL reconstruction (ACLR) is the standard of care for injured athletes who wish to return to their previous level of play.^{36,39} The incidence of ACL injury and ACLR have both been shown to increase over recent years.⁵⁰ In the United States alone, 200,000 primary ACLR are performed annually.⁴⁷ Historically, an athlete

who underwent ACLR typically expected to return to play (RTP) at his/her previous level at 6 months after surgery,⁴ an expectation that was consistent with the RTP time frames documented by the orthopaedic community.^{4,20,46} Current research, however, has shown that this time frame is not realistic.^{3,9,38} Several studies have highlighted the low rate of athletes who RTP and the high rate of subsequent ACL injury.^{3,43,44,49} In a meta-analysis, Ardern² reported that only 1 in 3 athletes returns to the previous level of play and 1 in 2 returns to competition. In addition, athletes who RTP after ACLR are vulnerable to sustaining a second ACL tear occurring on either their ipsilateral or their contralateral limb; second injuries

have been reported in 8% to 30% of athletes who RTP at any time point after ACLR.^{28,30,49} Laboute and colleagues³³ reported that if an athlete returns to one's sport within the first 7 months, there is a 3-fold increase in reinjury. Furthermore, athletes evaluated for 2 years after ACLR were found to have as much as a 15 times higher risk of suffering a second injury.^{43,44} Nonetheless, athletes are initiating return to sport-specific activities—for example, running, jumping, and cutting drills—at 6 months postoperatively.

The rationale for ACL injury prevention programs is to address an athlete's quality of movement during sport-specific tasks for the purpose of identifying and modifying movement patterns known to put an athlete at risk for ACL injury. In contrast, RTP decisions after ACLR are often based on non-sport related quantitative measures such as isokinetic tests, clinical diagnostic tests (ie, Lachman test), single-leg (SL) hop tests, and/or time from surgery.^{5,20,46} The athlete is often deemed ready to return when he or she achieves an 85% to 90% limb symmetry index (LSI) with various performance measures.¹ Recent studies question the usefulness of the LSI as a tool in RTP decision making.^{19,34,40,56,60} Bilateral strength deficits exist after ACLR; thus, LSI may overestimate function by failing to account for the decrease in muscle strength in the uninvolved leg.^{51,56} Postoperative ACL rehabilitation guidelines have largely promoted early RTP by focusing on reducing pain and swelling and restoring range of motion, strength, and neuromuscular control while protecting the "new" ACL. These postoperative protocols/guidelines all indicate that based on quantitative measures such as those previously mentioned, the athlete will be ready to initiate sport-specific training by 6 months postsurgery.^{1,10,58} In a systematic review of factors used to determine readiness to return to unrestricted activity after ACLR,⁴ time from surgery was used as an RTP criterion in 60% of the 264 studies, 40% failed to report any criteria, and only 13% included any measurable objective criteria that an athlete had to achieve before clearance to RTP. In a survey of 271 experienced surgeons,⁴⁶ RTP criteria included a variety of clinical measures (81% Lachman test, 60% pivot-shift test, 45% anterior drawer test, 78% knee range of motion, 15% instrumented anterior laxity measurement, 3% magnetic resonance imaging) and quantitative measures such as SL hop tests and measures of strength and proprioception. The importance of adding quality of movement to the RTP decision-making process has only recently surfaced,^{16,37,57} and recent systematic reviews and consensus statements advocate the inclusion of measures of strength, hop tests, and video analysis of quality of movement.^{16,17,55}

Although the exact mechanism of noncontact ACL injury is not well-understood, it appears to be the result of a combined loading pattern of reduced hip and knee flexion angles,²⁶ increased knee valgus²⁶ and internal rotation of the femur on the tibia, and high quadriceps activity unbalanced by the hamstrings.^{6,27,29,31,35,59} Paterno and colleagues⁴⁵ identified specific movement patterns that were highly predictive risk factors for incurring a second ACL injury in athletes returning to full activity. In their study, they found that the risk of second injury was increased 2-fold in athletes who demonstrated deficits in postural stability on the involved limb, 3-fold in those who demonstrated a side-to-side difference in sagittal plane knee moment at initial contact or greater frontal plane knee motion during landing, and 8-fold in those demonstrating decreased hip external rotator moment during the initial 10% of landing.⁴⁵ These movement patterns are consistent with those known to predict primary ACL injury, yet are rarely used to inform the RTP decision-making process.

Considering the documented high risk of sustaining a second injury when returning to play after ACLR, we developed a quality of movement assessment (QMA) to identify the presence of such risky movement patterns in athletes after ACLR and demonstrated the reliability of the QMA. The purpose of this study was to identify the presence of movement patterns in both the involved and the uninvolved limbs associated with ACL injury in athletes 6 months after ACLR using the QMA.

METHODS

Participants

A clinical database was searched to identify patients who had a QMA at the outpatient sports rehabilitation center of our institution between January 2013 and September 2014 using a retrospective cross-sectional study design. Patients who had a QMA performed 5 to 7 months after ACLR were included in the study. Only the first eligible QMA was included in the analysis for patients with multiple assessments during this time frame (Figure 1). All patients had undergone ACLR at our institution, a hospital specializing in the treatment of orthopaedic and rheumatological conditions, and were referred for a QMA by the patient's surgeon. The patients came to our institution for surgery from a wide geographical area and received rehabilitation from a local provider. There were 235 patients who had a primary ACLR, without revision or

*Address correspondence to Polly deMille, RN, MA, ACSM-CEP, CSCS, Hospital for Special Surgery, 535 East 70th Street, New York, NY 10021, USA (email: pollydemille@gmail.com).

[†]Hospital for Special Surgery, New York, New York, USA.

[‡]Physical Therapy, Rehabilitation Sciences and Medicine, Boston University, Boston, Massachusetts, USA.

[§]Rehabilitation and Movement Sciences, Rutgers University, Brunswick, New Jersey, USA.

Final revision submitted September 23, 2024; accepted November 25, 2024.

One or more of the authors has declared the following potential conflict of interest or source of funding: With grant support provided to his institution, Mr. Nguyen was supported in part by funds from the Clinical Translational Science Center (CTSC), National Center for Advancing Translational Sciences (NCATS) grant #UL1-RR024996. The content is solely the responsibility of the authors and does not necessarily represent the official views of the funding source NCATS based in Rockville, MD. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approved granted by Hospital for Special Surgery (2015-287 and 14029).

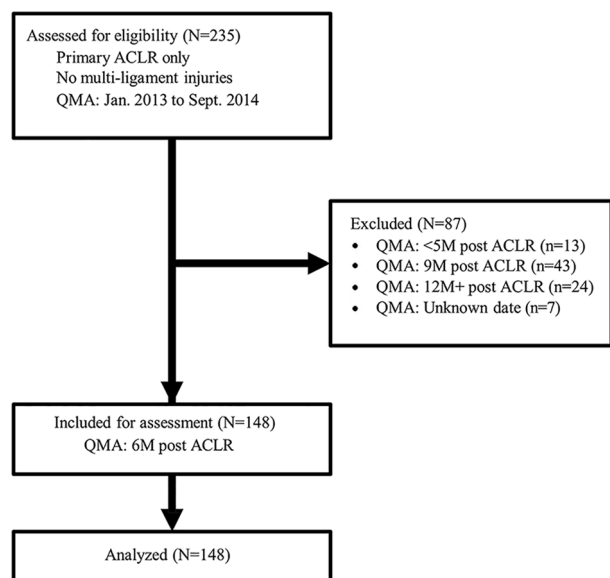


Figure 1. Flow diagram for study population. ACLR, anterior cruciate ligament reconstruction; DOS, date of service; M, months; QMA, quality of movement assessment.

multiligament injury. Of those, 80 patients were excluded because their first QMA was performed outside the inclusion time frame (mean \pm SD, 6 ± 1 months from surgery), and 7 were excluded because the timing of their QMA was unknown. A total of 148 participants were eligible for inclusion into our study. Approval from our institutional review board was obtained before study commencement.

Procedures

The QMA included up to 10 tasks, which progressed from double- to single-limb, static to dynamic, and vertical to horizontal tasks. Not all patients performed all 10 tasks; the examiners were allowed to end the assessment at any point if the patient was unable to perform a given task or the examiner felt it was not safe to perform the task.

Tasks ranged from double-leg movements such as squats and jumps to similar movements on a single leg. Both a physical therapist and a certified strength and conditioning specialist guided the patient through the task sequence and observed each task in the frontal and sagittal planes. The assessment evaluated movement strategy, depth, alignment, symmetry, and control. The presence or absence of pain was noted for all movements (Table 1).

Performance was recorded as optimal or faulty on a checklist for each task and each limb. Faulty movement strategy referred to the athlete's initiating the movement with the knees first and/or continuing to drive the movement with the knee, or where the knees flexed beyond the toes (Figure 2). Depth of movement was rated as faulty if the athlete demonstrated limited knee and hip flexion angles during tasks as indicated by not achieving thighs

parallel to floor for the double-leg squat or 60° of knee flexion for jumping and SL tasks. Alignment was rated as faulty if the patient was not able to maintain the trunk, hip, knee, and foot in a single line and level hips in the frontal plane and/or if the trunk and shins were not parallel in the sagittal plane during the task. Asymmetry, described as a shift biased toward either lower extremity, was assessed during double-limb movements. Control was defined as the athlete's ability to maintain one's center of mass within the base of support without being wobbly at any joint during SL tasks and was first assessed during the SL stance. Thus, lack of control referred to the individual's inability to control the rate or direction of movement. The inability to demonstrate smooth, coordinated kinetic linking in a task or to sustain a static position in good alignment for the requisite period of time also indicated lack of control.

Athletes were asked about pain when performing each movement, as pain would influence their movement patterns. If the athlete reported pain or if the examiner determined that an athlete should not perform a movement due to exhibiting faulty movements on a previously less demanding task, then the assessment was abbreviated. The examiner then rated each task as "faulty" or "optimal" based on the evaluation of movement characteristics as described above and patient-reported pain with the task. Several examples of faulty movement are depicted in Table 2.

Statistical Analysis

Study data were collected via paper forms and later transferred to the Research Electronic Data Capture (REDCap) electronic data capture tool.^{24,25} Descriptive statistics of the study population included reporting of means and standard deviations for continuous variables and frequencies and percentages for discrete variables. Chi-square tests were used to evaluate any potential differences in performance of each exercise between involved and uninvolved legs (Chi-square tests were used to assess differences in exercise performance between involved and uninvolved limbs; Fisher's exact test was used when assumptions for the chi-square test were not met). Additional analyses included comparison of faulty movement between patient sex, meniscal injury status, and age within the involved and uninvolved leg. To examine the differences in age, patients were divided into age groups based on their age at the time of surgery (<14, 14-18, 19-25, 26-34, and ≥ 35 years). All analyses were performed using SAS Version 9.3 (SAS Inc) with statistical significance defined as $P < .05$.

RESULTS

From January 2013 to September 2014, a total of 148 patients who had undergone primary ACLR were evaluated using the QMA. All patients had their ACLR between May 2012 and March 2014 and were 5 to 7 months postsurgery. The mean \pm SD age of the study population was 19.3 ± 8.3 years (range, 9.5-53.1 years). Females comprised

TABLE 1
Quality of Movement Assessment Tasks

Quality of Movement Assessment				
Task	Instructions	Repetitions/Time	Criteria	
Squat	Squat down as far as you can	20 repetitions	Sagittal view: movement strategy, alignment, depth Frontal: symmetry, alignment	
Single-leg stance	Stand on 1 leg with knee soft or bent slightly	30-second hold	Frontal: alignment, control	
8-inch forward stepdown	Stand with hands on hips and front edge of sneaker flush with front of platform; slowly step down off step, landing on your heel; finish with both feet on the ground (return to step not assessed)	6 repetitions	Frontal: alignment, control Sagittal: preload strategy	(L) Forward Step Down 
Single-leg squat	Stand on uninvolved leg with uninvolved side facing examiner; with involved knee bent, hip in neutral (thigh vertical), squat as far as you can; repeat on involved side	9 repetitions	Sagittal view: movement strategy, alignment, depth Frontal: control, alignment	

(continued)

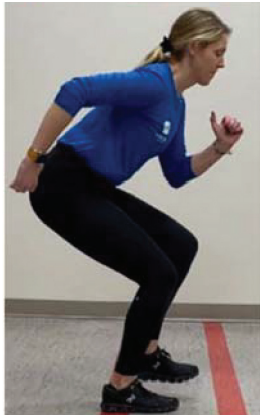

TABLE 1
(continued)

Quality of Movement Assessment				
Task	Instructions	Repetitions/Time	Criteria	
Single-leg bridge	Lie on your back with your knees bent and head facing the examiner; tighten your buttocks and stomach; lift your buttocks off the mat; now extend your involved knee with your thighs even and hold; repeat and extend your uninvolved knee	30-second hold	Time, alignment	
In-place jump (vertical)	Jump in place; perform the jump consecutively	10 repetitions	Sagittal view: movement strategy, alignment, depth Frontal: symmetry, alignment	
Side-to-side jump	Facing the examiner, stand on 1 leg and perform a lateral jump, landing on contralateral leg; jump back and forth repeatedly	10 repetitions	Frontal: alignment, control Sagittal: strategy, depth, alignment	
Broad jump	Stand on 2 legs; jump forward, landing on 2 legs	5 repetitions	Frontal: alignment, symmetry Sagittal: strategy, depth, alignment	

(continued)

TABLE 1
(continued)

Quality of Movement Assessment			
Task	Instructions	Repetitions/Time	Criteria
Hop to opposite	Stand on 1 leg (involved first) and jump forward landing on the other leg (uninvolved); hold for 2 seconds; repeat on opposite side (initiating on uninvolved side and landing on involved side)	5 repetitions	Frontal: alignment, control Sagittal: strategy, alignment, control
Single-leg hop	Stand on 1 leg (uninvolved first) and jump forward, landing on the same leg; hold for 2 seconds; repeat on involved leg	5 repetitions	Frontal: alignment, control Sagittal: strategy, alignment, control



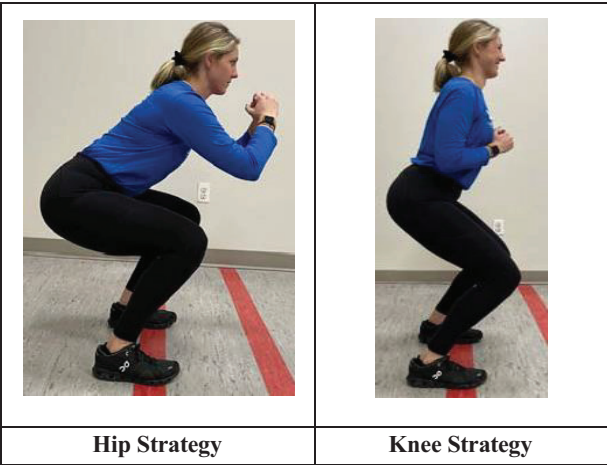





Figure 2. Hip versus knee strategy for performing a squat.

55% of the study population, while injury side was evenly distributed between left (50%) and right (50%) sides. Concomitant meniscal injury was found in 59 patients (42%). All participants completed ≥ 5 of the QMA tasks. As tasks were not completed if the patient was unable to perform the task or the examiner felt it was not safe for the patient to perform the task, only 29% of patients completed all 10 tasks. Full description of patient characteristics and task completion rates can be found in Table 3.

Overall Performance Between Involved and Uninvolved Leg

Patient performance on the QMA was different between the involved and uninvolved leg depending on the task (Figure 3). The proportion of patients demonstrating faulty movement patterns for a task on the involved leg (among the tasks completed) ranged from 52% to 95%, with

TABLE 2
Examples of Faulty Movement

Description of Faulty Movement	
	8-inch forward stepdown Right forward stepdown with (left) contralateral hip drop
	Left single-leg squat Sagittal view: knee strategy with shin angle > trunk angle (upright trunk) Patient initiated the movement knee first
	Left single-leg squat Frontal view: knee strategy with increased femoral internal rotation

(continued)

TABLE 2
(continued)



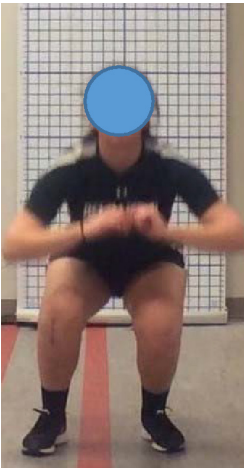
Description of Faulty Movement	
	Side-to-side jump Frontal view: left-side trunk lean evident
	In-place jump- Take off Asymmetrical: both right and left demonstrate valgus alignment
	In-place jump- Landing Asymmetrical to left: left demonstrates valgus alignment

TABLE 3
Demographic and Clinical Characteristics
of Study Population (N = 148)^a

Variable	Total	Mean \pm SD or N (%)
Time from ACLR to QMA, months	148	6.4 \pm 0.7
Age at surgery, years	146	19.3 \pm 8.3
<14 years	146	22 (15%)
14-18 years	146	84 (58%)
19-25 years	146	18 (12%)
26-34 years	146	10 (7%)
35+ years	146	12 (8%)
Patient sex		
Male	148	66 (45%)
Female	148	82 (55%)
Involved side		
Right	148	74 (50%)
Left	148	74 (50%)
Graft type		
Autograft	141	139 (99%)
BPTB	141	71 (51%)
Hamstring	141	67 (48%)
Iliotibial Band	141	1 (<1%)
Allograft	141	2 (1%)
Concomitant isolated meniscal injury		
No	141	82 (58%)
Yes	141	59 (42%)
Meniscal injury treatment		
No Treatment	59	10 (17%)
Meniscal Repair	59	39 (66%)
Meniscectomy	59	10 (17%)
Concomitant cartilage and meniscal injury		
No	141	140 (99%)
Yes	141	1 (1%)
Task completion rates		
First 5 tasks	148	148 (100%)
≥ 6 tasks	148	131 (89%)
≥ 7 tasks	148	127 (86%)
≥ 8 tasks	148	106 (72%)
≥ 9 tasks	148	75 (51%)
All 10 tasks	148	43 (29%)

^aData are shown as Mean \pm SD or N (%). ACLR, anterior cruciate ligament reconstruction; BPTB, bone-patellar tendon-bone; N, number; QMA, quality of movement assessment; SD, standard deviation.

a mean of 83% among tasks. The proportion of patients with faulty movement patterns on the uninvolved side ranged from 45% to 92%, with an overall mean of 76%. A significantly higher proportion of faulty tasks was observed in forward stepdown ($P < .001$), SL squat ($P = .03$), side-to-side jump ($P = .03$), and hop to opposite ($P = .04$) on the involved as compared with the uninvolved legs.

Faulty Movement Between Sex, Meniscal Injury, and Age Group

No statistical differences in performance were found between male and female patients on either the involved

or the uninvolved leg (Figure 4). Similarly, no performance differences were found between patients with and without meniscal injury on either leg (Figure 5). No differences were found among age groups on either side for most tasks (Table 4). However, in the involved leg, there was a significant difference overall in SL stance among age groups ($P = .05$). Post hoc comparisons found that percentage of faulty movements in patients aged 19 to 25 years (22%) was lowest among all age groups and significantly lower compared with patients aged 14 to 18 years (55%; $P = .02$), 26-34 (60%; $P = .046$), and ≥ 35 years (75%; $P = .008$) for the SL stance on the involved leg. On the uninvolved leg, there was a significant difference overall in SL bridge ($P = .02$). During the SL bridge, patients ≥ 35 years (50%) had significantly lower faulty movements compared with all other age groups (<14: 91%, $P = .01$; 14-18: 80%, $P = .02$; and 26-34: 100%, $P = .02$).

DISCUSSION

Our results, after reviewing the QMA in athletes after ACLR, indicate that deficits in quality of movement are present 6 months postoperatively, a time when many athletes are progressing to sport-specific training and planning their RTP. Depending on the task, 52% to 95% of patients demonstrated faulty movement on the involved side; patients were only slightly better on the uninvolved side with 45% to 92% demonstrating faulty movement. As many of the faulty movement patterns identified during QMA testing are the same movement patterns known to put the athlete at risk for both primary and second ACL tears,^{26,27,45} the high prevalence of faulty movement on both sides suggests high risk for reinjury for the involved side and future injury on the uninvolved side. It is possible that these deficits might not be identified on conventional quantitative measures used in standard RTP decision making.

Time from surgery, restoration of joint range of motion, and a negative Lachman test are the most commonly cited criteria by surgeons when determining readiness to RTP.^{4,46} Other commonly cited criteria are quantitative measures such as isokinetic testing or hop tests for distance. While these quantitative measures are valuable tools in the RTP decision-making process, their purpose is not to identify movement patterns that have been associated with increased risk of both primary and second ACL injury. In the systematic review of measurement procedures after ACLR, Engelen-van Melick and colleagues¹⁶ concluded that qualitative measures, in addition to the assortment of quantitative measures available, would complete the picture when determining readiness for unrestricted activity after ACLR. This conclusion has been supported by others,^{14,17,22,23,53,55,57} encouraging clinicians to implement functional testing before allowing athletes to RTP.

The evidence suggests that it takes longer than 6 months to restore neuromuscular control and correct faulty movement patterns after ACLR. Sensory and motor deficits in ACL-reconstructed knees have been reported to

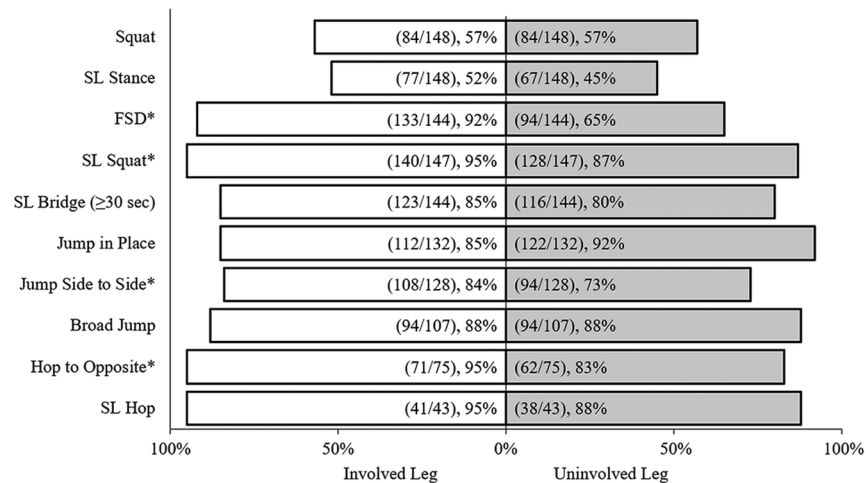


Figure 3. Percentage of faulty movement in all completed tasks, involved versus uninvolved leg. *Indicates statistically significant difference between involved and uninvolved leg ($P \leq .05$). FSD, forward stepdown; SL, single leg.

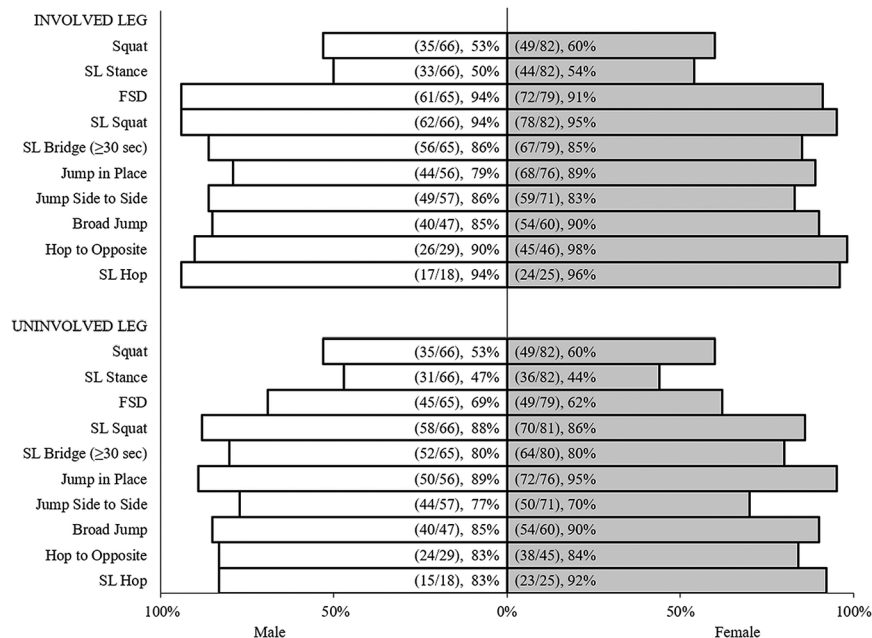


Figure 4. Percentage of faulty movement by sex in the involved and uninvolved leg. FSD, forward stepdown; SL, single leg.

persist for 12 to 30 months postoperatively while altered joint kinematics have been documented to persist for 12 months.^{8,13,18,42,52} These deficits may contribute to movement patterns that have been associated with an increased risk of ACL injury. It is also possible that these deficits may amplify preexisting faulty movement patterns that contributed to the primary ACL injury. Since our cohort represented athletes who had already been injured, the prevalence of faulty movement patterns is not surprising. While the greatest percentage of faulty movements were noted in single-limb movements, faulty movement patterns were also highly prevalent in double-limb movements.

Nagelli and Hewett⁴¹ have called for young athletes to delay their return to competitive sport until 2 years after ACLR. This recommendation was based on findings from their review that the risk of reinjury is highest within the first 2 years and that knee health recovers to baseline levels only after that time. There is a growing consensus that a more robust battery of measures combined with a more gradual RTP is warranted in light of the high rate of reinjury and relatively low rate of successful RTP.^{3,15,20,23,53,55}

The equal presence of faulty movement patterns in the involved and uninvolved limb supports the possibility

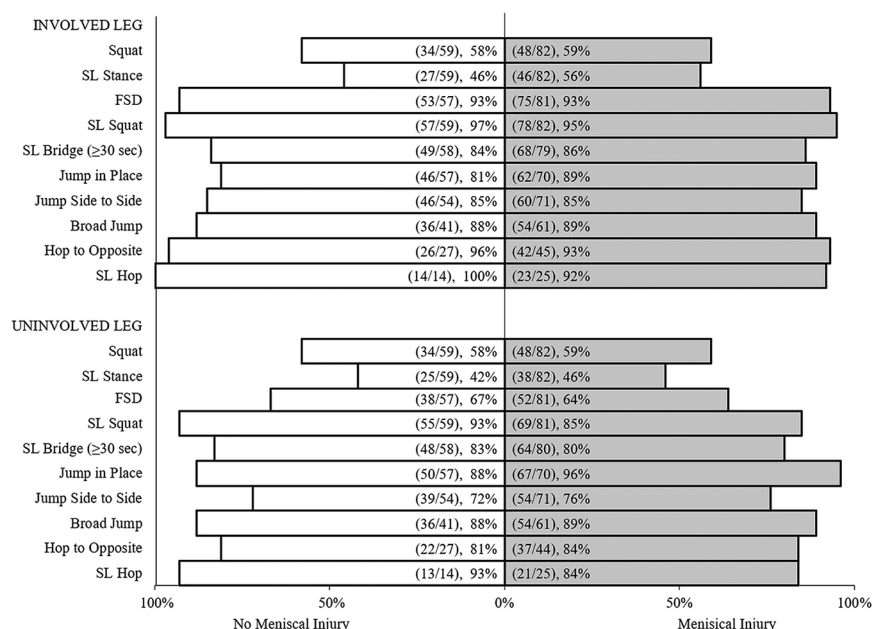


Figure 5. Percentage of faulty movement by meniscal pathology in the involved and uninvolved leg. FSD, forward stepdown; SL, single leg.

that these movement patterns contribute to the initial injury and remain a risk factor for subsequent injury. The only movement patterns in which the involved limb demonstrated significantly more at-risk movement patterns were the forward stepdown, the SL squat, the side-to-side jump, and hop to opposite. The forward stepdown requires specific eccentric quadriceps control, and the disparity between involved and uninvolved may reflect the relative deficit in quadriceps strength that persists at 6 months postsurgery. The forward stepdown and SL squat require the ability to decelerate over a planted leg. The side-to-side jump begins to assess deceleration in a more dynamic, yet controlled environment. Hop to opposite progresses this challenge to control deceleration and shear forces upon landing. Since ACL injuries are predominantly noncontact in origin and occur during deceleration (landing from a jump or cutting),^{7,12,32} the inability to maintain optimal alignment during relatively simple deceleration tasks is a significant concern when considering readiness to RTP. The similarity in faulty movement patterns seen in the involved versus uninvolved limbs should also bring into question the use of the LSI in RTP decision making. Using the uninvolved limb as the standard for comparison may not be appropriate if this limb is demonstrating movement patterns associated with risk of ACL injury,^{34,56} and the presence of faulty movement patterns in the uninvolved limb speaks to the high rate of contralateral ACL injury after returning to sport. Asymmetry is the most common deficit noted during double-legged tasks, whereby loss of alignment is the most common during SL tasks. When asymmetrical, the athlete shifts more weight onto the uninvolved limb yet displays faulty movement patterns on that limb as well. Webster and Hewett⁵⁴ have also cited this pattern as a possible explanation for the increased risk

in contralateral injury. These findings were present whether or not patients had meniscal pathology and across a range of age groups.

Strengths and Limitations

A strength of this study was the wide variety of surgeons, surgical protocols, and rehabilitation protocols received from a wide geographical area. Despite the heterogeneous sample, the results were uniform in the striking prevalence of faulty movement patterns displayed in common sport-specific movements regardless of sex, age, or concomitant injury. Our previously published study²¹ utilizing the QMA in skeletally immature athletes (10-15 years of age) also showed that faulty movement patterns existed in a younger population. In particular, no skeletally immature athlete could perform a 2-legged squat without some degree of compensation at 6 months.³⁸

A limitation of the study is the lack of inclusion of an uninjured group and validation of observed deficits against the gold standard of 3-dimensional motion capture. However, the criteria by which movements were deemed faulty have been validated in another study.¹¹ These movement patterns are commonly used to identify “at risk” athletes in primary ACL injury prevention programs. While this is a retrospective analysis of previously collected data from 2013 to 2014, these data form the basis of a larger ongoing study. Clinically, we continue to see a higher proportion of faulty movement patterns in athletes after ACLR. In addition, the QMA was conducted based on a referral from the patient’s surgeon; this may limit the potential generalizability to all patients after ACLR. Future research will focus on establishing the internal

TABLE 4
Frequency of Faulty Movement in Involved and Uninvolved Leg by Age Group^a

	Age Group					P
	<14 y	14-18 y	19-25 y	26-34 y	≥35 y	
Involved leg						
Squat	(13/22) 59	(52/84) 62	(5/18) 28	(5/10) 50	(7/12) 58	.12
Single-leg stance	(11/22) 50	(46/84) 55	(4/18) 22	(6/10) 60	(9/12) 75	.05
Forward stepdown	(20/21) 95	(76/82) 93	(15/18) 83	(9/10) 90	(11/11) 100	.51
Single-leg squat	(21/22) 95	(79/84) 94	(16/18) 89	(10/10) 100	(12/12) 100	.65
Single-leg bridge, ≥30 sec	(20/22) 91	(68/81) 84	(14/17) 82	(8/10) 80	(11/12) 92	.85
In-place jump	(17/18) 94	(66/80) 83	(11/13) 85	(9/9) 100	(9/11) 82	.49
Side-to-side jump	(15/17) 88	(64/75) 85	(13/15) 87	(6/8) 75	(8/11) 73	.75
Broad jump	(16/16) 100	(51/62) 82	(11/13) 85	(6/6) 100	(9/9) 100	.19
Hop to opposite	(8/9) 89	(46/48) 96	(9/9) 100	(3/4) 75	(4/4) 100	.35
Single-leg hop	(2/3) 67	(28/29) 97	(6/6) 100	(2/2) 100	(3/3) 100	.19
Uninvolved leg						
Squat	(13/22) 59	(52/84) 62	(5/18) 28	(5/10) 50	(7/12) 58	.12
Single-leg stance	(12/22) 55	(37/84) 44	(7/18) 39	(4/10) 40	(7/12) 58	.73
Forward stepdown	(15/21) 71	(51/83) 61	(13/18) 72	(6/9) 67	(7/11) 64	.87
Single-leg squat	(19/22) 86	(73/84) 87	(13/17) 76	(10/10) 100	(11/12) 92	.50
Single-leg bridge, ≥30 sec	(20/22) 91	(66/82) 80	(12/17) 71	(10/10) 100	(6/12) 50	.02
In-place jump	(18/18) 100	(71/80) 89	(13/13) 100	(9/9) 100	(10/11) 91	.31
Side-to-side jump	(16/17) 94	(54/75) 72	(8/15) 53	(6/8) 75	(8/11) 73	.14
Broad jump	(16/16) 100	(51/62) 82	(11/13) 85	(6/6) 100	(9/9) 100	.19
Hop to opposite	(7/9) 78	(39/47) 83	(8/9) 89	(3/4) 75	(4/4) 100	.84
Single-leg hop	(2/3) 67	(26/29) 90	(6/6) 100	(1/2) 50	(3/3) 100	.24

^aData are presented as (n/N) %, where n is the number of patients exhibiting a faulty movement pattern, N is the number of patients in that age group that performed the movement, and % represents the corresponding percentage.

and external validity of the QMA, determining whether qualitative measures are predictive of an athlete's successful return to preinjury levels of play, and ascertaining whether correlations exist between quantitative and qualitative measures.

Another limitation is the lack of control of the rehabilitation protocol these patients received at clinics close to their homes. As patients came to our institution from a wide geographical area, we did not provide all the rehabilitation at our institution. That said, the high prevalence of faulty movement patterns regardless of rehabilitation

protocol is notable. Future studies would be useful to identify which, if any, rehabilitation protocols lead to better movement quality.

CONCLUSION


The results of this study demonstrated that bilateral faulty movement patterns exist in ACLR athletes 5 to 7 months after surgery. A shift in the mindset of the orthopaedic community is warranted to modify rehabilitation

guidelines toward the incorporation of a QMA, correction of potentially risky movement patterns, and modification of suggested timing of full RTP to provide athletes, parents, and coaches with realistic expectations of readiness for RTP.

ACKNOWLEDGMENT

The authors thank Liz Selvaggio for her help with data entry, Huong Do for her assistance with data analysis, and Gwen Weinstock-Zlotnick for her patience, guidance, and support in this project.

ORCID iD

Joseph T. Nguyen  <https://orcid.org/0000-0003-1686-3911>

REFERENCES

- Adams D, Logerstedt D, 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(7):601-614.
- Arder CL. Anterior cruciate ligament reconstruction—not exactly a one-way ticket back to the preinjury level: a review of contextual factors affecting return to sport after surgery. *Sports Health*. 2015;7(3):224-230.
- Arder CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med*. 2011;39(3):538-543.
- Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. *Arthroscopy*. 2011;27(12):1697-1705.
- Barber-Westin SD, Noyes FR. Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. *Phys Sportsmed*. 2011;39(3):100-110.
- Boden BP, Dean GS, Feagin JA, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573-578.
- Boden BP, Sheehan FT, Torg JS, Hewett TE. Non-contact ACL injuries: mechanisms and risk factors. *J Am Acad Orthop Surg*. 2010;18(9):520-527.
- Bonfim TR, Jansen Paccola CA, Barela JA. Proprioceptive and behavior impairments in individuals with anterior cruciate ligament reconstructed knees. *Arch Phys Med Rehabil*. 2003;84(8):1217-1223.
- Brophy RH, Schmitz L, Wright RW, et al. Return to play and future ACL injury risk after ACL reconstruction in soccer athletes from the Multicenter Orthopaedic Outcomes Network (MOON) group. *Am J Sports Med*. 2012;40(11):2517-2522.
- Cavanaugh J. Anterior cruciate ligament reconstruction. In: Cavanaugh J, Wolff AL, Corradi-Scalise D, Rudnick HB, eds. *Postsurgical Rehabilitation Guidelines for the Orthopedic Clinician*. Mosby Elsevier; 2006:425-439.
- Crossley KM, Zhang WJ, Schache AG, Bryant A, Cowan SM. Performance on the single-leg squat task indicates hip abductor muscle function. *Am J Sports Med*. 2011;39(4):866-873.
- DeMorat G, Weinhold P, Blackburn T, Chudik S, Garrett W. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med*. 2004;32(2):477-483.
- Deneweth JM, Bey MJ, McLean SG, Lock TR, Kolowich PA, Tashman S. Tibiofemoral joint kinematics of the anterior cruciate ligament-reconstructed knee during a single-legged hop landing. *Am J Sports Med*. 2010;38(9):1820-1828.
- Dingenen B, Gokeler A. Optimization of the return-to-sport paradigm after anterior cruciate ligament reconstruction: a critical step back to move forward. *Sports Med*. 2017;47(8):1487-1500.
- Dingenen B, Malfait B, Vanrenterghem J, Verschueren SMP, Staes FF. The reliability and validity of the measurement of lateral trunk motion in two-dimensional video analysis during unipodal functional screening tests in elite female athletes. *Phys Ther Sport*. 2014;15(2):117-123.
- Engelen-van Melick N, van Cingel REH, Tijssen MPW, Nijhuis-van der Sanden, MWG. Assessment of functional performance after anterior cruciate ligament reconstruction: a systematic review of measurement procedures. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(4):869-879.
- Flagg KY, Karavatas SG, Thompson S, Bennett C. Current criteria for return to play after anterior cruciate ligament reconstruction: an evidence-based literature review. *Ann Transl Med*. 2019;7(suppl 7):S252.
- Gokeler A, Hof AL, Arnold MP, Dijkstra PU, Postema K, Otten E. Abnormal landing strategies after ACL reconstruction. *Scand J Med Sci Sports*. 2010;20(1):e12-e19.
- Gokeler A, Welling W, Benjaminse A, Lemmink K, Seil R, Zaffagnini S. A critical analysis of limb symmetry indices of hop tests in athletes after anterior cruciate ligament reconstruction: a case control study. *Orthop Traumatol Surg Res*. 2017;103(6):947-951.
- Grassi A, Vascellari A, Combi A, Tomaello L, Canata GL, Zaffagnini S; SIGASCOT Sports Committee. Return to sport after ACL reconstruction: a survey between the Italian Society of Knee, Arthroscopy, Sport, Cartilage and Orthopaedic Technologies (SIGASCOT) members. *Eur J Orthop Surg Traumatol*. 2016;26(5):509-516.
- Graziano J, Chiaia T, de Mille P, Nawabi DH, Green DW, Cordasco FA. Return to sport for skeletally immature athletes after ACL reconstruction: preventing a second injury using a quality of movement assessment and quantitative measures to address modifiable risk factors. *Orthop J Sports Med*. 2017;5(4):2325967117700599.
- Grindem H, Engebretsen L, Axe M, Snyder-Mackler L, Risberg MA. Activity and functional readiness, not age, are the critical factors for second anterior cruciate ligament injury—the Delaware-Oslo ACL cohort study. *Br J Sports Med*. 2020;54(18):1099-1102.
- Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med*. 2016;50(13):804-808.
- Harris PA, Taylor R, Minor BL, et al; REDCap Consortium. The REDCap consortium: building an international community of software platform partners. *J Biomed Inform*. 2019;95:103208.
- Harris PA, Taylor R, Thielke R, Payne J, Gonzalez N, Conde JG. Research electronic data capture (REDCap)—a metadata-driven methodology and workflow process for providing translational research informatics support. *J Biomed Inform*. 2009;42(2):377-381.
- Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492-501.
- Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med*. 2009;43(6):417-422.
- Hui C, Salmon LJ, Kok A, Maeno S, Linklater J, Pinczewski LA. Fifteen-year outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft for “isolated” anterior cruciate ligament tear. *Am J Sports Med*. 2011;39(1):89-98.
- Ireland ML. The female ACL: why is it more prone to injury? *Orthop Clin North Am*. 2002;33(4):637-651.
- Kocher MS, Saxon HS, Hovis WD, Hawkins RJ. Management and complications of anterior cruciate ligament injuries in skeletally

- immature patients: survey of the Herodicus Society and The ACL Study Group. *J Pediatr Orthop*. 2002;22(4):452-457.
31. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med*. 2010;38(11):2218-2225.
 32. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35(3):359-367.
 33. Laboute E, Savalli L, Puig P, et al. Analysis of return to competition and repeat rupture for 298 anterior cruciate ligament reconstructions with patellar or hamstring tendon autograft in sportspeople. *Ann Phys Rehabil Med*. 2010;53(10):598-614.
 34. Larsen JB, Farup J, Lind M, Dalgas U. Muscle strength and functional performance is markedly impaired at the recommended time point for sport return after anterior cruciate ligament reconstruction in recreational athletes. *Hum Mov Sci*. 2015;39:73-87.
 35. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon)*. 2001;16(5):438-445.
 36. Marx RG, Jones EC, Angel M, Wickiewicz TL, Warren RF. Beliefs and attitudes of members of the American Academy of Orthopaedic Surgeons regarding the treatment of anterior cruciate ligament injury. *Arthroscopy*. 2003;19(7):762-770.
 37. Mayer SW, Queen RM, Taylor D, et al. Functional testing differences in anterior cruciate ligament reconstruction patients released versus not released to return to sport. *Am J Sports Med*. 2015;43(7):1648-1655.
 38. McCullough KA, Phelps KD, Spindler KP, et al; MOON Group. Return to high school- and college-level football after anterior cruciate ligament reconstruction: a Multicenter Orthopaedic Outcomes Network (MOON) cohort study. *Am J Sports Med*. 2012;40(11):2523-2529.
 39. McRae SM, Chahal J, Leiter JR, Marx RG, Macdonald PB. Survey study of members of the Canadian Orthopaedic Association on the natural history and treatment of anterior cruciate ligament injury. *Clin J Sport Med*. 2011;21(3):249-258.
 40. 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(5):435-440.
 41. Nagelli CV, Hewett TE. Should return to sport be delayed until 2 years after anterior cruciate ligament reconstruction? Biological and functional considerations. *Sports Med*. 2017;47(2):221-232.
 42. Papannagari R, Gill TJ, Defrate LE, Moses JM, Petruska AJ, Li G. In vivo kinematics of the knee after anterior cruciate ligament reconstruction: a clinical and functional evaluation. *Am J Sports Med*. 2006;34(12):2006-2012.
 43. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med*. 2012;22(2):116-121.
 44. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *Am J Sports Med*. 2014;42(7):1567-1573.
 45. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38(10):1968-1978.
 46. Petersen W, Zantop T. Return to play following ACL reconstruction: survey among experienced arthroscopic surgeons (AGA instructors). *Arch Orthop Trauma Surg*. 2013;133(7):969-977.
 47. Prodromos CC, Han Y, Rogowski J, Joyce B, Shi K. A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. *Arthroscopy*. 2007;23(12):1320-1325.e6.
 48. Renström PA. Eight clinical conundrums relating to anterior cruciate ligament (ACL) injury in sport: recent evidence and a personal reflection. *Br J Sports Med*. 2013;47(6):367-372.
 49. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. *Arthroscopy*. 2005;21(8):948-957.
 50. Sanders TL, Maradit Kremers H, Bryan AJ, et al. Incidence of anterior cruciate ligament tears and reconstruction: a 21-year population-based study. *Am J Sports Med*. 2016;44(6):1502-1507.
 51. 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(9):750-759.
 52. Tashman S, Kolowich P, Collon D, Anderson K, Anderst W. Dynamic function of the ACL-reconstructed knee during running. *Clin Orthop Relat Res*. 2007;454:66-73.
 53. 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(24):1506-1515.
 54. Webster KE, Hewett TE. Meta-analysis of meta-analyses of anterior cruciate ligament injury reduction training programs. *J Orthop Res*. 2018;36(10):2696-2708.
 55. Webster KE, Hewett TE. What is the evidence for and validity of return-to-sport testing after anterior cruciate ligament reconstruction surgery? A systematic review and meta-analysis. *Sports Med*. 2019;49(6):917-929.
 56. 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(5):334-338.
 57. Wilk KE. Anterior cruciate ligament injury prevention and rehabilitation: let's get it right. *J Orthop Sports Phys Ther*. 2015;45(10):729-730.
 58. Wilk KE, Macrina LC, Cain EL, Dugas JR, Andrews JR. Recent advances in the rehabilitation of anterior cruciate ligament injuries. *J Orthop Sports Phys Ther*. 2012;42(3):153-171.
 59. Withrow TJ, Huston LJ, Wojtyś EM, Ashton-Miller JA. The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. *Am J Sports Med*. 2006;34(2):269-274.
 60. Zore MR, Kregar Velikonja N, Hussein M. Pre-and post-operative limb symmetry indexes and estimated preinjury capacity index of muscle strength as predictive factors for the risk of ACL reinjury: a retrospective cohort study of athletes after ACLR. *Appl Sci*. 2021;11(8):3498.