Poor Performance on Single-Legged Hop Tests Associated With Development of Posttraumatic Knee Osteoarthritis After Anterior Cruciate Ligament Injury

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Background: The risk for knee osteoarthritis (OA) is substantially increased after anterior cruciate ligament (ACL) injury. Tools are needed to identify characteristics of patients after ACL injury who are most at risk for posttraumatic OA.

Purpose: To determine whether clinical measures of knee function after ACL injury are associated with the development of radiographic knee OA 5 years after injury.

Study Design: Cohort study; Level of evidence, 2.

Methods: A total of 76 athletes (mean age, 28.7 ± 11.3 years; 35.5% female) with ACL injury were included. Clinical measures of knee function (quadriceps strength, single-legged hop tests, patient-reported outcomes) were assessed after initial impairment resolution (baseline), after 10 additional preoperative or nonoperative rehabilitation sessions (posttraining), and 6 months after ACL reconstruction or nonoperative rehabilitation. Posterior-anterior bent-knee radiographs were completed at 5 years and graded in the medial compartment by use of the Kellgren-Lawrence system. Logistic regression models were used at each of the 3 time points to determine the ability of clinical measures to predict knee OA at 5 years.

Results: Of the 76 patients, 9 (11.8%) had knee OA at 5 years. After adjustment for ACL reconstruction compared with nonoperative management, ipsilateral second ACL injuries, and the presence of contralateral knee OA, clinical measures of knee function at posttraining (6-m timed hop, Knee Outcomes Survey–Activities of Daily Living Scale) explained the most variance in posttraumatic OA development at 5 years ($P = .006$; ΔR^2, 27.5%). The 6-m hop test was the only significant posttraining predictor of OA at 5 years ($P = .023$; patients without OA, 96.6% ± 5.4%; patients with OA, 84.9% ± 14.1%). Similar significant group differences in hop scores and subjective knee function were present at baseline. No significant group differences in clinical measures existed at 6 months after ACL reconstruction or nonoperative rehabilitation.

Conclusion: Poor performance in single-legged hop tests early after ACL injury but not after reconstruction or nonoperative rehabilitation is associated with the development of radiographic posttraumatic knee OA 5 years after injury. Clinical measures of knee function were most predictive of subsequent OA development following an extended period of rehabilitation early after ACL injury.

Keywords: anterior cruciate ligament; osteoarthritis; hop tests; subjective function; rehabilitation

Anterior cruciate ligament (ACL) injury is a musculoskeletal abnormality that results in negative sequelae beyond the short-term limitations in function and physical activity, including a predisposition for the development of knee osteoarthritis (OA). Although the precise mechanisms causing long-term joint degeneration are unknown, more than half of patients will demonstrate radiographic and symptomatic knee OA within 10 to 20 years of ACL injury.[6,35,44,45,53] Initial phases of articular cartilage degradation likely occur early after ACL injury. Tibial cartilage thinning is evident on magnetic resonance imaging (MRI) as early as 4 months after isolated ACL injury,[56] and these undesirable changes persist despite ACL reconstruction.[30] The identification of individuals with developing posttraumatic knee OA is difficult without routine imaging because typical osteoarthritic symptoms such as pain, stiffness, and decreased function are often absent when initial signs of joint damage are detectable.[28,48,57] Establishment of clinically measurable patient characteristics and outcomes is needed to allow prospective identification of patients at greatest risk for early development of knee OA after ACL injury.

Factors that increase the risk for development of knee OA after ACL injury include age, body mass index, manual labor occupation, and concomitant meniscal and chondral injury.[6,40] Although these factors provide information regarding patient risk for development of posttraumatic

knee OA, correlates such as age and concomitant injury are unmodifiable through rehabilitative interventions. One modifiable risk factor of OA after ACL injury is knee joint mechanics. For example, neuromuscular training prior to ACL reconstruction reduces movement asymmetries present after ACL reconstruction.[25] Altered knee joint moments and contact forces demonstrated during walking early after injury and reconstruction have been linked to the development of radiographic knee OA within 5 years of ACL injury.[58] Unfortunately, biomechanical gait asymmetries can exist despite the absence of observational gait impairments.[16,21,22,25,32,49] The current inability of clinicians to prospectively screen patients for risk of posttraumatic knee OA after ACL injury necessitates further evaluation of clinical measures early after injury with comparison to subsequent radiographic evidence of articular cartilage destruction.

Posttraumatic OA accounts for approximately \$3 billion of health care costs spent within the United States annually.[10] The negative consequences that ensue following its development include pain, impaired knee function, reduced physical activity, and poor quality of life.[44] To minimize the socioeconomic impact and considerable health concerns imparted by posttraumatic OA after ACL injury, the development of targeted rehabilitation programs to decrease the risk of OA is needed. However, effective testing of such rehabilitation strategies requires identification of patients with ACL injury who are most likely to develop posttraumatic OA and benefit from such interventions. No clinical tools currently exist to identify patients early after ACL injury who are at greatest risk for subsequent posttraumatic OA. Therefore, the primary purpose of this study was to determine whether clinical measures of knee function after ACL injury are associated with the development of radiographic knee OA 5 years after ACL injury. We hypothesized that patients who developed posttraumatic knee OA would demonstrate poorer knee function early after ACL injury compared with those who did not develop OA. A secondary purpose was to determine whether prediction models would be different before and after rehabilitation.

METHODS

Patients

This prospective cohort study included 142 athletes with an acute, unilateral ACL injury (confirmed by a positive Lachman test and ≥3-mm difference in anterior tibial excursion with instrumented arthrometry)[13] (KT-1000 arthrometer; MEDmetric) who participated in level 1 (eg, soccer, basketball) or level 2 (eg, tennis, downhill skiing) cutting and pivoting activities[13,27] prior to injury. Patients were enrolled in this study following physical therapy treatment to resolve initial impairments (ie, pain, effusion, knee range of motion, obvious gait impairments, and quadriceps strength deficits [70% of uninvolved limb required]) using a protocol previously described.[31] Exclusion criteria included a repairable meniscus (identified by an orthopaedic surgeon (M.J.A.) using preoperative MRI), symptomatic grade 3 injury to other knee ligaments, or articular cartilage lesions larger than 1 cm^2 at the time of study enrollment. This study was approved by the institutional review board at the University of Delaware, and all participants provided written informed consent prior to initiation of the study. Of the 142 patients who were enrolled from July 2005 to April 2011, a total of 84 patients (mean ± SD baseline age, 29.3 ± 11.7 years; 38.1% female) returned for 5-year testing and completed radiographs (Figure 1).

After study enrollment, all patients completed an additional 10 physical therapy sessions to further restore lower extremity strength and neuromuscular deficits.[26] Patients self-selected operative or nonoperative treatment with counsel from the orthopaedic physician (M.J.A.) and physical therapy team. Patients managed nonoperatively were discharged to a home exercise program to maintain strength and neuromuscular control after the additional 10 physical therapy sessions. Patients managed operatively underwent reconstruction by a single, board-certified orthopaedic surgeon (M.J.A.) using either a 4-bundle semitendinosus-gracilis autograft or soft tissue allograft. After ACL reconstruction, patients completed criterion-based postoperative rehabilitation early after surgery.[1] Clinical testing was completed by patients managed operatively and nonoperatively at 3 time points: at study enrollment after initial impairment resolution (baseline), immediately following the 10 additional physical therapy sessions (posttraining), and 6 months after completion of nonoperative rehabilitation or ACL reconstruction.

Baseline Concomitant and Second ACL Injuries

Medial meniscal injuries and acute and chronic damage to the articular cartilage in the medial tibiofemoral compartment were recorded from the initial MRI after ACL injury prior to study enrollment. Second ACL injuries were tracked throughout the prospective trial and confirmed at 5-year follow-up testing.

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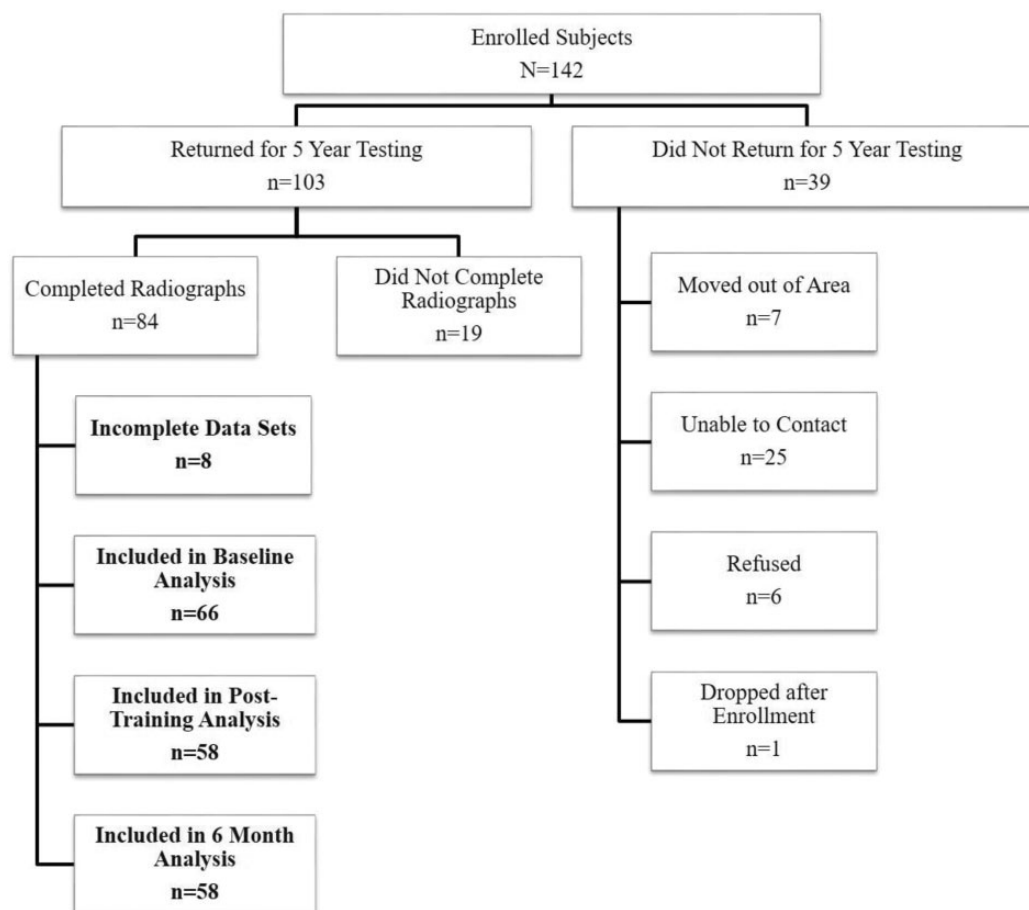
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Figure 1. Flow diagram of study cohort.

Clinical Measures of Knee Function

Clinical testing consisted of quadriceps strength testing, single-legged hop testing, and completion of patient-reported outcomes at each time point (baseline, posttraining, 6 months). Patient-reported outcomes included the Knee Outcome Survey–Activities of Daily Living Scale (KOS-ADLS), Global Rating of Perceived Function Scale (GRS), and International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form.

Quadriceps strength was tested by use of the burst superimposition technique during maximal voluntary isometric contraction (MVIC) with an electromechanical dynamometer (Kin-Com; DJO Global); patients were seated in 90° of hip and knee flexion.[54] Stabilization straps secured the pelvis and thighs, with the force transducer placed just proximal to the talocrural joint. Two 3 × 5–inch self-adhesive electrodes were placed proximally over the vastus lateralis and distally over the vastus medialis. Submaximal (50%, 75% of perceived maximum) and maximal (100% of perceived maximum) isometric knee extension contractions were completed to provide familiarization with the task and to ensure absence of knee pain. Patients then completed an MVIC with an imposed supramaximal 10-pulse (600 μs, 135 V), 100-pulse-per-second train of

electrical stimulation. Quadriceps activation was calculated as the MVIC divided by the maximal force output during the superimposed electrical stimulation multiplied by 100. Up to 3 trials were completed on each limb (uninvolved first, followed by involved) until 95% quadriceps activation was achieved, activation levels plateaued, or the patient fatigued. Quadriceps index was the strength variable of interest in this study, calculated as the quotient of the involved limb MVIC to the uninvolved limb MVIC multiplied by 100.

Two single-legged hop tests (single hop, 6-m timed hop) were completed on each limb; hop tests were conducted with a 6 m–long, 15 cm–wide strip.[5,12,46] The uninvolved limb was tested first, followed by the involved limb for each hop test. Two practice trials provided familiarization with the task, and the next 2 usable trials on each limb were recorded (controlled landing on unilateral limb required). The average of 2 trials for each limb was used to calculate limb symmetry indexes for the single hop (involved limb divided by uninvolved limb multiplied by 100) and 6-m timed hop (uninvolved limb divided by involved limb multiplied by 100). Single-legged hop tests were not completed if the quadriceps index was less than 70% in patients after nonoperative rehabilitation or awaiting ACL

reconstruction, if pain was present while the patient was hopping in place on the involved limb, if large effusion was present, or if repeated giving way of the knee had occurred since ACL injury. Single-legged hop tests were not completed after ACL reconstruction if the quadriceps index was less than 80%.

The KOS-ADLS is a valid and reliable measure of impairment and functional limitation experienced during activities of daily living secondary to knee abnormality.[34] Fourteen items are scored on a 6-point ordinal scale; a total score out of a possible 70 points is represented as a percentage. A score of 100% represents the absence of knee impairment and functional limitation during activities of daily living.

The GRS consists of a single, reliable question asking patients to rate their current perceived level of knee function compared with their perceived knee function prior to injury, on a scale from 0 to 100.[29,43] Zero represents the inability to perform any activity, and 100 indicates the level of activity prior to injury.

The IKDC Subjective Knee Evaluation Form is a measure of knee-specific symptoms, function, and sports activities that is valid and reliable for a variety of knee conditions including ACL injury.[3,33] It is calculated from 18 items and scored on a scale from 0 to 100, with higher scores indicating higher self-reported levels of knee function.

Radiographs

Patients completed weightbearing posterior-anterior bent-knee (30°) radiographs 5 years after ACL reconstruction or completion of nonoperative rehabilitation. Baseline radiographs early after ACL injury were not available for analysis. SigmaView software (Agfa HealthCare) was used to view radiographs. OA in the medial and lateral tibiofemoral compartment of each limb was graded by use of the Kellgren-Lawrence (KL) system.[36] Excellent between-day, intrarater reliability for KL grading was previously demonstrated in 20 radiographs of patients 5 years after ACL injury (graded by E.W.) (Cohen kappa = 0.904, $P < .001$; all KL grades verified by a board-certified orthopaedic surgeon [M.J.A.]). The presence of OA was defined as a KL grade of 2 or higher.

Statistical Analysis

Statistical analyses were completed through use of PASSW 25.0 software (SPSS Inc). Independent t tests and Fisher exact tests were used to test differences in baseline characteristics, concomitant injuries, second ACL injuries, and the presence of OA in the uninvolved medial and lateral compartment between those patients with medial compartment OA (OA group) at 5 years and those without (non-OA group). Independent t tests and Fisher exact tests were also used to test group differences (OA group vs non-OA group) in clinical measures at each of the 3 time points (baseline, posttraining, 6 months). A logistic regression was used at each of the 3 time points (baseline, posttraining, 6 months) to determine the ability of clinical measures to predict the later development of medial

compartment knee OA at 5 years. Baseline variables, concomitant baseline meniscal injury, second ACL injury, and uninjured tibiofemoral OA with between-group differences (OA group vs non-OA group) of $P < .25$ were entered into the first block of the regression model. Clinical variables (quadriceps index, single hop, 6-m timed hop, KOS-ADLS, GRS, IKDC) with between-group differences of $P < .25$ at each time point were added to the second block of each regression model. To decrease the effects of collinearity within the regression models, only 1 hop test and 1 patient-reported outcome (KOS-ADLS, GRS, IKDC) was used within each regression model, chosen a priori by using the variable with the greatest effect size (ES). A priori statistical significance for independent t tests, Fisher exact tests, and logistic regressions was set at $\alpha \le .05$.

RESULTS

Of the 84 patients who returned for radiographic testing 5 years after ACL reconstruction or completion of nonoperative management, 8 did not have a complete clinical data set at a minimum of 1 time point (baseline, posttraining, or 6 months) and were thus excluded, leaving 76 patients in the current analysis. Not all 76 patients included in this study had complete data sets at each time point, leaving 66 patients in the baseline analysis (8 patients did not complete hop testing secondary to pain, effusion, or previous episodes of giving way; 2 patients did not complete IKDC form), 58 patients in the posttraining analysis (2 patients did not complete posttraining testing; 10 patients did not complete hop testing secondary to pain, effusion, or previous episodes of giving way; 6 patients did not complete IKDC form), and 58 patients in the 6-month post-ACL reconstruction or nonoperative rehabilitation analysis (10 patients did not complete 6-month testing; 2 patients did not complete hop testing secondary to quadriceps index <80% after ACL reconstruction or patient refusal; 6 patients did not complete IKDC form) (Figure 1).

Of the 76 study patients, 59 underwent ACL reconstruction and 17 completed nonoperative management. Nine of the 76 (11.8%) patients had medial compartment OA at 5 years (8 patients with KL grade 2, 1 patient with KL grade 3), and 67 (88.2%) did not. No statistically significant differences ($P < .05$) were found in baseline characteristics between patients with and without OA at 5 years (Table 1). Completion of ACL reconstruction compared with nonoperative management, ipsilateral second ACL injuries, and the presence of OA in the uninvolved tibiofemoral joint demonstrated P values of less than .25 and these 3 variables were entered into the first block of the logistic regression models for each time point (Table 1).

At baseline, patients with OA at 5 years performed significantly worse on single-legged hop tests (single hop, $P = .001$; non-OA, 88.9% ± 12.9%; OA, 70.3% ± 22.3%; ES, 1.33; 6-m timed hop, $P = .003$; non-OA, 94.9% ± 9.4%; OA, 81.9% ± 19.3%; ES, 1.21) and reported lower knee function on the IKDC form ($P = .200$; non-OA, 71.8 ± 13.0; OA, 65.0 ± 14.4; ES, 0.52) compared with

TABLE 1
Overall Baseline Group Characteristics: Baseline,
Concomitant, and Additional Knee Injury Characteristics
Between Those With and Without Radiographic Medial
Compartment Knee OA 5 Years After ACL Reconstruction
or Completion of Nonoperative Rehabilitation[a]

Characteristic	Non-OA (n = 67)	OA (n = 9)	P
Age at baseline, y, mean (SD)	28.8 (11.3)	28.3 (11.5)	.900
Body mass index, kg/m^2, mean (SD)	25.3 (3.6)	25.5 (4.8)	.881
Time from injury to initial evaluation, wk, mean (SD)	5.4 (6.2)	6.4 (5.4)	.649
Time from injury to baseline, wk, mean (SD)	7.6 (6.7)	10.1 (5.3)	.271
Sex, male/female, n	43/24	6/3	≤.999
Preinjury activity level (1/2), n[b]	46/21	6/3	≤.999
ACL reconstruction/nonoperative rehabilitation, n	50/17	9/0	.195
Concomitant meniscal tear (medial compartment) (yes/no), n	19/48	4/5	.441
Concomitant articular cartilage injury (medial compartment) (yes/no), n	0/67	0/9	≤.999
Chronic articular cartilage damage (medial compartment) (yes/no), n	0/67	0/9	≤.999
Second ACL injury after initial ACL injury (yes/no), n	8/59	2/7	.337
Ipsilateral second ACL injury after initial ACL injury (yes/no), n	5/62	2/7	.191
Uninvolved medial/lateral compartment OA at 5 years (yes/no), n	3/64	2/7	.104

[a]ACL, anterior cruciate ligament; OA, osteoarthritis.
[b]Classified according to Daniel et al[13] and Heft et al.[27]

those patients without OA (Table 2). The single hop and IKDC results were entered into the second block of the baseline logistic regression model. The single hop and IKDC results explained an additional 19.8% of the variability in the development of medial OA at 5 years (Table 3). The only significant predictor of 5-year OA was the single hop (P = .033, β = .937).

At the posttraining assessment, patients with OA at 5 years again performed significantly worse on the single-legged hop tests (single hop, P = .001; non-OA, 95.6% ± 9.7%; OA, 80.0% ± 20.9%; ES, 1.36; 6-m timed hop, P < .001; non-OA, 96.6% ± 5.4%; OA, 84.9% ± 14.1%; ES, 1.70) and also reported lower knee function on the KOS-ADLS (P = .031; non-OA, 94.8% ± 6.3%; OA, 89.0% ± 7.6%; ES, 0.89) and the IKDC form (P = .087; non-OA, 80.9 ± 12.7; OA, 71.6 ± 17.4; ES, 0.70) compared with those patients without OA (Table 2). The 6-m timed hop and KOS-ADLS were entered into the second block of the posttraining logistic regression model. The 6-m time hop and KOS-ADLS explained an additional 27.5% of the variability in the development of medial OA at 5 years (Table 3). The only significant predictor of 5-year OA was the 6-m timed hop (P = .023, β = .824).

Six months after ACL reconstruction or completion of nonoperative management, no differences (P < .25) were seen in any clinical measures between the group with OA and the group without OA at 5 years (Table 2). Therefore, a logistic regression analysis was not completed.

DISCUSSION

The purpose of this study was to determine whether clinical measures of knee function after ACL injury were associated with the later development of radiographic knee OA 5 years after ACL injury. Our findings support our hypothesis that poorer knee function after ACL injury would be associated with the development of posttraumatic knee OA. Patients with radiographic medial compartment OA at 5 years demonstrated poorer performance on single-legged hop tests and reported lower subjective knee function early after injury compared with those who did not develop OA by 5 years. The capability to assess the future risk of posttraumatic knee OA development after ACL injury is critical. The findings of this study provide potential clinical components in the prospective identification of patients who are at greatest risk for early development of knee OA after ACL injury and who therefore may require specific rehabilitation strategies.

Hop performance and subjective report of knee function are predictive of objective outcomes after ACL reconstruction. Single-legged hop tests have previously demonstrated the ability to predict normal and below-normal knee function 1 year after nonoperative rehabilitation or ACL reconstruction.[23,41] A more positive subjective assessment of knee function after ACL reconstruction increases the likelihood of returning to preinjury levels of sport.[4] Further, the incorporation of subjective knee function into an objective test battery can successfully identify patients who can return to cutting and pivoting activities without undergoing ACL reconstruction and can also identify patients with persistent abnormal movement patterns after reconstruction.[15,19,20] In the current study, patients with medial compartment knee OA by 5 years demonstrated worse scores on both hop tests (single hop, 6-m timed) and lower KOS-ADLS scores at time points before and after an extended bout of rehabilitation early after injury. The link between self-reported knee function and subsequent knee degeneration emphasizes the importance of implementing patient-reported outcomes in clinical practice, considering that a patient's self-assessment does not always match clinical measures of function.[50] The minimal need for special equipment to assess single-legged hop performance and subjective knee function provides the possibility for these measures to be powerful and impactful screening tools for posttraumatic OA risk after ACL injury.

Quadriceps strength after ACL injury was not found to be a predictor for the development of posttraumatic knee OA. However, the importance of quadriceps strength after ACL injury is clear. Greater levels of quadriceps strength early after injury have resulted in improved outcomes after reconstruction, including higher levels of subjective knee function and the ability to return to sport.[11,14,17,39,42,51,59]

TABLE 2
Clinical Group Comparisons: Clinical Measures Between Those With and Without Radiographic Medial Compartment
Knee OA 5 Years After ACL Reconstruction or Completion of Nonoperative Rehabilitation[a]

Measurement and Group	Baseline[b]			Posttraining[c]			6 Months[d]		
	Mean (SD)	95% CI	P	Mean (SD)	95% CI	P	Mean (SD)	95% CI	P
Quadriceps index, %									
Non-OA	89.1 (13.7)	85.6-92.7	.844	96.3 (13.9)	92.4-100.2	.810	102.0 (12.3)	98.5-105.5	.937
OA	88.1 (11.5)	77.5-98.7		97.7 (18.1)	81.0-114.4		101.6 (9.2)	93.9-109.3	
Single hop, %									
Non-OA	88.9 (12.9)	85.5-92.2	**.001**	95.6 (9.7)	92.8-98.3	**.001**	95.0 (6.8)	93.1-97.0	.970
OA	70.3 (22.3)	49.6-90.9		80.0 (20.9)	60.7-99.3		94.9 (3.8)	91.7-98.1	
6-m timed hop, %									
Non-OA	94.9 (9.4)	92.5-97.4	**.003**	96.6 (5.4)	95.1-98.1	**<.001**	98.3 (8.1)	96.0-100.6	.432
OA	81.9 (19.3)	64.1-99.7		84.9 (14.1)	71.9-97.9		96.0 (4.8)	92.0-100.0	
KOS-ADLS									
Non-OA	87.3 (10.0)	84.7-89.9	.369	94.8 (6.3)	93.0-96.5	**.031**	97.7 (2.7)	97.0-98.5	.371
OA	83.7 (9.5)	74.9-92.5		89.0 (7.6)	81.9-96.0		96.8 (2.3)	94.9-98.8	
GRS									
Non-OA	77.5 (15.7)	73.4-81.6	.526	84.8 (13.7)	80.9-88.6	.535	93.2 (5.2)	91.7-94.7	.921
OA	73.6 (12.8)	61.7-85.4		81.4 (10.3)	71.9-90.9		93.4 (4.9)	89.3-97.4	
IKDC									
Non-OA	71.8 (13.0)	68.4-75.2	.200	80.9 (12.7)	77.3-84.5	.087	90.2 (7.9)	87.9-92.4	.658
OA	65.0 (14.4)	51.7-78.3		71.6 (17.4)	55.5-87.7		88.8 (9.9)	80.5-97.0	

[a]Boldface numbers indicate statistically significant group differences. ACL, anterior cruciate ligament; GRS, Global Rating of Perceived Function Scale; IKDC, International Knee Documentation Committee Subjective Knee Evaluation Form; KOS-ADLS, Knee Outcome Survey Activities of Daily Living Scale; OA, osteoarthritis.
[b]Non-OA, n = 59; OA, n = 7.
[c]Non-OA, n = 51; OA, n = 7
[d]Non-OA, n = 50; OA, n = 8.

TABLE 3
Clinical Predictors of OA: Logistic Regression Analyses Identifying Baseline and Posttraining
Clinical Predictors of Development of Medial Compartment Knee OA 5 Years After ACL Reconstruction
or Completion of Nonoperative Rehabilitation[a]

Clinical Predictor	P (Model)	Nagelkerke R^2	P	β[b]
Baseline (Non-OA, n = 59; OA, n = 7)				
Block 1	.161	0.153		
ACL reconstruction/nonoperative management			.998	<.001
Ipsilateral second ACL injury			.613	.541
Uninvolved tibiofemoral OA at 5 years			.319	.270
Block 2	**.026**	0.351		
ACL reconstruction/nonoperative management			.998	<.001
Ipsilateral second ACL injury			.373	.311
Uninvolved tibiofemoral OA at 5 years			.761	.553
Single hop			**.033**	.937
IKDC			.698	.986
Posttraining (Non-OA, n = 51; OA, n = 7)				
Block 1	.108	0.191		
ACL reconstruction/nonoperative management			.998	<.001
Ipsilateral second ACL injury			.390	.323
Uninvolved tibiofemoral OA at 5 years			.390	.323
Block 2	**.006**	0.469		
ACL reconstruction/nonoperative management			.998	<.001
Ipsilateral second ACL injury			.387	.261
Uninvolved tibiofemoral OA at 5 years			.581	3.848
6-m timed hop			**.023**	.824
KOS-ADLS			.941	.994

[a]Boldface numbers indicate statistical significance ($P < .05$). ACL, anterior cruciate ligament; IKDC, International Knee Documentation Committee Subjective Knee Evaluation Form; KOS-ADLS, Knee Outcome Survey Activities of Daily Living Scale; OA, osteoarthritis.
[b]Standardized β values.

The role of quadriceps strength in the development of both nontraumatic (primary) and posttraumatic knee OA is not clear. The presence of quadriceps weakness with concurrent evidence of radiographic primary knee OA has been well established, but its link to the development and progression of the disease is conflicting.[2,7,8,52] Our finding that quadriceps strength was not associated with OA at 5 years suggests that the relationship between quadriceps strength and radiographic OA after ACL injury may be similar to primary OA development. The potential that this study was underpowered may also explain the lack of statistically significant relationships between quadriceps strength and the development of radiographic knee OA. Further study is needed to determine whether quadriceps weakness leads to or results from the development of posttraumatic OA.

Clinical measures of knee function measured early after ACL injury (baseline, posttraining) were effective predictors of posttraumatic knee OA development by 5 years after reconstruction or nonoperative rehabilitation. It is unclear why clinical measures of knee function were not effective predictors 6 months after ACL reconstruction or nonoperative rehabilitation. The prediction of OA was not a primary aim of this cohort when patients were enrolled in this study. Although quadriceps strength, single-legged hop test scores, and patient-reported outcome scores at 6 months were nearly identical between those with and without knee OA at 5 years, this study may have been underpowered to detect group differences. Only 7 patients included in the 6-month analysis had OA at 5 years. Further, 18 of the 76 participants in this study were not included in the 6-month analysis because of incomplete data sets.

Previous studies have shown that within months of ACL injury, a cascade of changes in biochemical and structural biomarkers indicating negative joint alterations occurs.[9,24,37] Perhaps the period between ACL injury and reconstruction is critical for whether early-onset OA will develop after joint injury. In addition, although not statistically significant, patients with OA at 5 years required an additional 2.5 weeks to achieve resolution of initial knee pain, range of motion, gait impairments, joint effusion, and strength impairments after ACL injury compared with those who did not develop radiographic OA (10.1 vs 7.6 weeks, respectively). These 2.5 additional weeks required by the group with OA at 5 years could be due to a delayed initiation of rehabilitation or difficulty for these patients in resolving initial impairments after ACL injury. Early resolution of these impairments may critically factor into the risk for later OA development. For example, knee joint loading and inflammatory pathways may be avenues for initial articular cartilage destruction.[44,55] Failure to quickly resolve impairments such as range of motion, joint effusion, and abnormal gait patterns may therefore create early risk for cartilage degeneration. In contrast, early and effective rehabilitation after ACL injury may curb the increased risk for posttraumatic OA development in this population.

Single-legged hop tests were the only significant predictors of subsequent posttraumatic knee OA in our multivariate analyses. Although hop performance likely does not directly result in OA, it may represent a global change in movement to decrease loading to the injured limb. Abnormal joint loading has previously been linked to morphologic changes in articular cartilage and radiographic knee OA after ACL injury.[38,47,58] Thus, correction of abnormal loading patterns such as those identified by single-legged hop tests might reduce risk of subsequent OA development. The ability of hop tests to effectively predict early development of OA points to its likely multifactorial evolution and advocates for the increased use of criterion-based rehabilitation interventions that implement objective measures of patient function. An extended bout of early, criterion-based rehabilitation after ACL injury is known to result in clinically relevant improvements in knee function.[18] The benefits of extended rehabilitation prior to ACL reconstruction or as part of a nonoperative management strategy are further demonstrated by the results of this study.

The ability of clinical measures of knee function to predict subsequent OA development was greater at the posttraining assessment compared with baseline testing, accounting for 27.5% compared with 19.8% of the variance in medial compartment OA at 5 years, respectively. Using objective measures of knee function to screen for posttraumatic OA risk may be most effective following early, extended rehabilitation. However, it is unknown whether additional intervention to avoid the initiation of articular cartilage breakdown will be effective at this time point or whether irreversible processes have already begun.

This study had several limitations. Baseline radiographs early after ACL injury were not available to determine whether radiographic knee OA was present in patients prior to ACL injury. However, none of the 76 patients had acute or chronic findings of articular cartilage damage in the medial tibiofemoral compartment as reported on postinjury MRI. Thus, the potential for baseline chondral damage to explain the presence of radiographic OA at 5 years in this sample of patients is small. Next, only 9 of the 76 patients had radiographic knee OA at 5 years, resulting in a potentially underpowered study. The comprehensive battery of clinical measures, missing data, and long course of follow-up used within this study limited the number of patients who completed the full testing protocol; there were 19 patients who did not complete radiographic testing at 5 years as well as incomplete clinical data sets at earlier time points (10 incomplete data sets at baseline, 18 at posttraining, 18 at 6 months). Therefore, analyses to determine whether longitudinal changes in clinical measures of knee function influence early OA development could not be made. Missing 5-year radiographs were largely attributable to patients who moved out of the region and mailed back patient-reported outcomes but did not complete functional or radiographic testing.

In addition, it is likely that more patients will develop signs of radiographic OA beyond 5 years after injury. Therefore, these findings may only apply to the rapid development of radiographic knee OA within 5 years of ACL injury. Last, patients included in this study were active in sports activities prior to ACL injury and did not have diagnosed repairable menisci or large articular cartilage lesions at the time of injury. It is unknown whether patients with

nonathletic backgrounds or with more extensive concomitant injuries will demonstrate similar relationships between clinical measures of knee function and early OA development as presented in this study.

CONCLUSION

Poor performance in single-legged hop tests early after ACL injury but not after reconstruction is associated with the development of radiographic posttraumatic knee OA 5 years after injury. Clinical measures of knee function were most predictive of subsequent development of OA following an extended period of rehabilitation early after ACL injury. Individuals identified to be at high risk for posttraumatic OA may benefit from additional secondary prevention strategies early after ACL injury.

ACKNOWLEDGMENT

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