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A 10-Year Prospective Trial of a Patient Management Algorithm and Screening Examination for Highly Active Individuals With Anterior Cruciate Ligament Injury

Part 2, Determinants of Dynamic Knee Stability

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Objective: To clarify the determinants of dynamic knee stability early after anterior cruciate ligament injury.

Study Design: Cohort study (diagnosis); Level of evidence, 1.

Methods: Three hundred forty-five consecutive patients who were regular participants in International Knee Documentation Committee level I/II sports before injury and had an acute isolated anterior cruciate ligament injury from the practice of a single orthopaedic surgeon underwent a screening examination including clinical measures, knee laxity, quadriceps strength, hop testing, and patient self-reported knee function a mean of 6 weeks after injury when impairments were resolved. Independent *t* tests were performed to evaluate differences in quadriceps strength and anterior knee laxity between potential copers and noncopers. Hierarchical regression was performed to determine the influence of quadriceps strength, preinjury activity level, and anterior knee laxity on hop test performance, as well as the influence of timed hop, crossover hop, quadriceps strength, preinjury activity level, and anterior knee laxity on self-assessed global function.

Results: Neither anterior knee laxity nor quadriceps strength differed between potential copers and noncopers. Quadriceps strength influenced hop test performance more significantly than did preinjury activity level or anterior knee laxity, but the variance accounted for by quadriceps strength was low (range, 4%-8%). Timed hop performance was the only variable that affected self-assessed global function.

Conclusion: Traditional surgical decision making based on passive anterior knee laxity and preinjury activity level is not supported by the results, as neither is a good predictor of dynamic knee stability. A battery of clinical tests that capture neuromuscular adaptations, including the timed hop test, may be useful in predicting function and guiding individualized patient management after anterior cruciate ligament injury.

Keywords: knee; quadriceps strength; neuromuscular control

Management and counseling of the nearly half-million new patients each year in the weeks after ACL injury is one of the most controversial topics in sports medicine. Evidence suggests that there is a differential response to the injury. Although the majority of patients cannot return to high-level athletic activities after ACL injury because of continued episodes of knee giving way (noncopers),[14] a small percentage make a full, asymptomatic return to all preinjury activities (copers).[11,14] The inability to prospectively identify candidates for nonoperative management has strongly influenced practice patterns in the United States: For physically active patients who wish to return to high-level athletic activities, the treatment of choice is early ACL reconstruction (ACLR).[5,12,27]

There is a global need for a treatment algorithm that guides patient management in the weeks after ACL injury.

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Although most highly active patients in the United States are advised to undergo early ACLR, there are specific circumstances that would make delayed surgery advantageous for the patient (eg, the senior in high school competing for a collegiate athletic scholarship). In the skeletally immature athlete, delay is common.[29] Practice patterns in Europe and Canada are often quite different.[24,30] In some countries, patients are counseled to undergo surgery only if nonoperative care has failed. For patients who are advised to have ACLR, resources may be limited, and the patient can be placed on a lengthy waiting list before surgery can be performed and counseled to refrain from participation in International Knee Documentation Committee (IKDC) level I and II sports (activities that involve jumping, cutting, pivoting, and lateral movements). Generally, active patients on the waiting list who wish to return to demanding athletics on a regular basis are thought to be at high risk for future episodes of knee giving way, potentially leading to irreparable meniscal and chondral damage. Success of patients attempting to return to high-level activities without experiencing giving way has been poor, with success rates ranging from 23% to 39%.[1,15,42] The ability to accurately identify patients with the potential to succeed with nonoperative management would help clinicians appropriately counsel their patients with acute ACL rupture.

Successful return to preinjury activities with nonoperative management after ACL rupture depends on the development of dynamic knee stability. Operationally defined as the ability of a joint to remain stable when subjected to rapidly changing loads during activity,[48] dynamic stability is accomplished via neuromuscular adaptations in the absence of ligamentous support. Many tests are available to measure the neurosensory system (eg, detection of passive motion, joint repositioning tests) and general neuromuscular function (eg, stabilimetry). These tests are limited to static conditions. In contrast, single-legged hop tests are dynamic tasks that clinicians use to challenge patients' knee joint stability and measure functional performance capacity.[19] Hop tests have also been used in studies as a clinical measure of progress in response to surgical or rehabilitation interventions.[19] There is not, however, a strong relationship between hop test performance and strength,[4,33,34,36,46] passive anterior knee joint laxity,[14,36,41] or self-assessed function[4,33,41,46] after either ACL rupture or ACLR. This suggests multiple clinical measures may be needed to completely describe a patient's functional abilities after ACL injury.[19]

Daniel et al[11] concluded that total preinjury hours of participation in level I and II sports was "the most important single variable" and that side-to-side arthrometer differences also added to the prediction of who would succeed with nonoperative management and not require late (more than 6 months removed from the index injury) ACL or meniscus surgery. Fithian et al[17] used the Daniel et al[11] surgical risk factor (SURF) algorithm to prospectively classify 209 patients with acute, isolated ACL injury by surgical risk according to activity level and side-to-side laxity values. Fithian et al[17] reported low-risk patients (those with small side-to-side laxity differences and low activity levels) were not significantly at risk for later surgery but that they were unable to distinguish between moderate- (intermediate laxity differences and activity levels) and high-risk (large side-to-side laxity difference and high activity levels) groups with respect to risk of late surgery. Fithian et al suggested there are in fact only 2 risk levels for late meniscus or ligament surgery: low risk and high risk, which is largely based on activity level. These results suggest the SURF algorithm[17] has limited usefulness for counseling a highly active population regarding their potential to succeed with nonoperative management.

A screening examination was developed[18] to classify highly active patients with and without good dynamic knee stability early after ACL rupture. This classification algorithm has been used for 10 years to counsel patients about short-term return to preinjury activities without surgical intervention and to recommend activities while on a surgical waiting list. The patient classification system devised at the University of Delaware[18] was influenced by the earlier work by Eastlack et al,[14] who had compared highly active (level I or II) persons with isolated ACL injury who had been identified as either copers (n = 12) or symptomatically ACL deficient (noncopers, n = 33). In this study, noncopers and copers were distinguished by quadriceps strength, global rating, Knee Outcome Survey–Sports, and crossover hop scores. Knee laxity, age, time from injury, and activity levels were similar for both groups. From these results, Eastlack et al[14] suggested a group of tests would be necessary to prospectively discriminate patient functional abilities. Fitzgerald et al[18] tested the effectiveness of the University of Delaware treatment algorithm using identical inclusion and exclusion criteria as those of Daniel et al[11] and Fithian et al[17] except that all patients were classified as level I or II athletes. Therefore, this population, according to Fithian et al[17] and Daniel et al,[11] was at a high and uniformly equal risk of future knee giving-way episodes if they returned to all premorbid activities. Analysis indicated the global rating scale, Knee Outcome Survey–Activities of Daily Living Scale (KOS-ADLS),[23] timed hop, and giving-way episodes were predictive of patient functional abilities. Criteria for classification as a rehabilitation candidate (potential coper) included timed hop ≥80%, KOS-ADLS ≥80%, global rating ≥60%, and ≤1 giving-way episodes after the incident injury. Passive anterior knee joint laxity did not play a role in predicting patient function. Fitzgerald et al[18] reported that 79% of those identified as potential copers were able to successfully (defined as no episodes of knee giving way) return to all preinjury activities at the preinjury level. Ten-year outcomes substantiated the screening examination as an effective tool for discriminating between surgical and nonoperative candidates, as 72% of potential copers during this period were successful (ie, full return to preinjury activities with no episodes of giving way) with a nonoperative return to preinjury activities.[22]

Other investigators have also reported a poor relationship between the magnitude of anterior knee joint laxity and functional abilities among patients with ACL deficiency.[14,15,25,44] Their findings underscore the distinction between the clinical finding of increased joint laxity and functional instability (the inability to control the available joint motion during activities), challenging the use of anterior knee joint laxity in predicting patient function after ACL rupture.

The importance of quadriceps muscle strength has been reported among patients with varying levels of dynamic knee stability. Eastlack et al[14] reported that only noncopers demonstrated large quadriceps strength deficits. Wojtys and Huston[49] reported similar findings: Patients who were categorized as the "best" ACL-deficient group had no significant difference in quadriceps strength compared with a control group. Conversely, the ACL-deficient patients who were in the "worst" group had appreciable quadriceps strength deficits. Other investigators have also reported quadriceps weakness among ACL-deficient patients with low postinjury functional levels.[47] The prevalence and magnitude of quadriceps strength deficits among patients with poor dynamic knee stability prompted Rudolph et al[37,39] to call quadriceps weakness the hallmark of the noncoper patient.

The University of Delaware and SURF algorithms have been offered as clinical tools to identify nonsurgical candidates after ACL rupture. Previous reports of both classification algorithms are, however, limited in their ability to provide insight into factors contributing to successful dynamic knee stability in the ACL-deficient knee. The SURF categorization appears to work well for relatively sedentary patients. Unfortunately, it does not distinguish among the compensation strategies of those who regularly participate in high-level activities and therefore is not helpful in counseling of the majority of candidates for ACLR. During the development of the University of Delaware classification algorithm, Eastlack et al[14] and Fitzgerald et al[18] identified different predictive factors that could be used to discriminate between functional abilities. Both studies, however, were limited to relatively small sample sizes. And although a series of studies have suggested that laxity does not distinguish between those who have the potential to compensate well for the injury and those who do not, these investigations included small, diverse populations. This second article in a 2-part series uses results of prospective testing and classification of a large, homogeneous sample of highly active patients from the practice of a single orthopaedic surgeon to clarify the determinants of dynamic knee stability after ACL rupture.

MATERIALS AND METHODS

Patients

Three hundred forty-five consecutive patients with acute, complete unilateral ACL rupture from the practice of a single orthopaedic surgeon (M.J.A.) were evaluated for this study from 1996 to 2006. All ACL tears were confirmed with MRI and knee arthrometer testing. Before injury, all patients had been regular participants (>50 h/y) in IKDC level I or II activities.[11,20] Patients were not tested until they had full knee range of motion, minimal knee effusion, normal gait pattern, and the ability to hop on the injured limb without pain.[18] If they did not meet all prerequisites for testing, they were enrolled in a rehabilitation program to address their impairments. Study exclusion criteria included bilateral knee involvement, concomitant ligamentous laxity, repairable meniscus tear, full-thickness chondral lesion, ipsilateral hip or ankle abnormalities, and chronic (>7 months) ACL injuries.[18]

Patients were classified as either noncopers or potential copers using an established screening examination.[18] The screening examination, which consists of hop testing, self-assessment questionnaires, and the number of giving-way episodes during activities of daily living since the index injury, has been shown to differentiate between patients who may be able to cope with ACL injury and those who will not with a high degree of accuracy.[18] Failure to meet any of the criteria for classification as a potential coper resulted in the person being classified as a noncoper.

This study was approved by the Human Subjects Committee at the University of Delaware; all participants provided informed consent before study participation.

Evaluation of Anterior Knee Joint Laxity

Passive anterior tibiofemoral knee joint laxity was measured using a knee ligament arthrometer (KT-1000 arthrometer, MedMetrics, San Diego, Calif). The arthrometer was affixed to the test limb according to manufacturer specifications with the knee flexed between 20° and 30°.[11] Anterior tibia translation was measured on each limb during 2 consecutive trials using maximum manual force. The side-to-side difference was recorded in millimeters, and the 2 trials were averaged.

Evaluation of Quadriceps Strength

Quadriceps strength was measured during a maximum voluntary isometric contraction using a burst superimposition technique.[43] This strength testing technique is an established method to evaluate quadriceps strength in patients with ACL deficiency[10,43] and after ACLR.[43] During testing, patients were seated and stabilized in an electromechanical dynamometer (KinCom, Chattanooga Corp, Chattanooga, Tenn) with their hips and knees flexed to 90°. After the skin was debrided with rubbing alcohol, 3 × 5-in self-adhesive electrodes were placed over the proximal quadriceps lateral to the midline and distal quadriceps medial to the midline to cover all 4 motor points of the quadriceps muscle. Patients performed 3 practice trials, and testing was initiated after 5 minutes of rest.

For the test, patients were instructed to maximally contract their quadriceps for 5 seconds during which a supramaximal burst of electrical stimulation (amplitude, 130 V; pulse duration, 600 microseconds; pulse interval, 10 milliseconds; train duration, 100 milliseconds; Grass Instruments, Braintree, Mass) was applied to the quadriceps to ensure complete muscle activation. If the force produced by the subject was <95% of the electrically elicited force, the test was repeated, with a maximum of 3 trials per limb. To avoid the influence of fatigue, patients were given 5 minutes of rest between trials. If full activation was not achieved (voluntary torque <95% of the electrically elicited force) during any of the trials, the highest voluntary force output from the 3 trials was used for analysis. Custom software (LabView, National Instruments, Austin, Tex) was used to identify the maximum voluntary force produced by both the uninjured and injured limbs during testing. A quadriceps index was calculated as a strength test score after testing was completed.

Evaluation of Knee Function

Knee function was evaluated using the hop testing protocol as described by Noyes et al.[32] Patients performed 2 practice trials followed by 2 test trials on both the uninjured and injured limbs. All hop tests were performed on a single leg and included, in order, the single hop for distance, crossover hop for distance in which the subjects had to cross over a 15-cm-wide tape with each hop, triple hop for distance, and a 6-m timed hop. Measurement reliability of unilateral hop test performance has been reported to be good, with intraclass correlation coefficients ranging from 0.92 to 0.96 for the unilateral,[2,3] crossover,[2,3] and triple hop for distance[2,3] and the 6-m timed hop.[2] All patients wore an off-the-shelf derotational functional knee brace on the injured limb during hop testing. The 2 test trials were averaged and results reported as a percentage of the injured limb relative to the uninjured limb. If patients were unable to complete the testing protocol, the score for the hop tests not performed was 0.

Evaluation of Self-reported Knee Function

After completion of the hop tests, patient self-assessment of knee function and performance was measured using a global rating of knee function and the KOS-ADLS.[23] Global rating of knee function is a single value on a scale of 0% to 100% the patient estimates represents his or her current activity level (including athletics) compared with preinjury activities. The KOS-ADLS is a questionnaire consisting of 14 questions with 6 possible answers (each possible answer weighted from 0-5 points). The KOS-ADLS is computed by dividing the number of points scored by the total number of points (70) and multiplying by 100%. The KOS-ADLS has been established as a valid and reliable tool for evaluating changes in knee function over time.[23] A higher value represents a higher level of function for both self-assessment tools.

DATA ANALYSIS

Descriptive statistics were used to describe the patient sample, and independent t tests ($P = .05$) were performed to identify differences in quadriceps strength and anterior knee laxity between potential copers and noncopers. Hierarchical regression analysis was performed to assess the influence of relevant variables on dynamic knee stability. The model order for determining influence on unilateral hop tests was quadriceps strength, followed by preinjury activity level and anterior knee joint laxity. The model order for determining influence on self-assessed global function was the timed hop test, followed by the crossover hop test, quadriceps strength, preinjury activity level, and anterior knee joint laxity. Beta coefficients calculated from the hierarchical regression were evaluated to identify the nature (positive vs negative) of the relationship between the dependent and independent variables. Bonferroni correction was used to adjust for multiple comparisons for regression analyses (adjusted $\alpha = .01$). Participant classification was subsequently compared with results obtained using the SURF algorithm.[11]

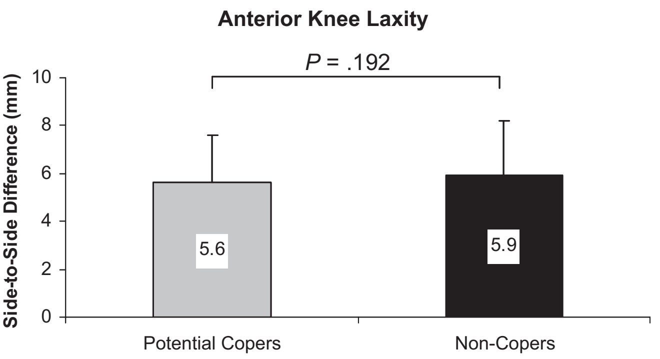

Figure 1. Anterior knee laxity in potential copers and noncopers. Side-to-side difference in anterior knee laxity using a manual maximum pull during KT-1000 arthrometer testing.

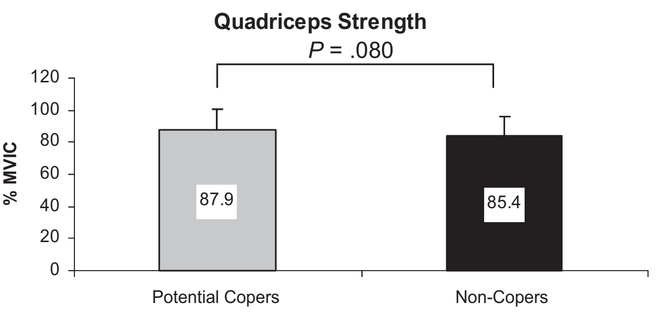

Figure 2. Quadriceps strength in potential copers and noncopers. MVIC, maximum voluntary isometric contraction.

TABLE 1
Group Demographics[a]

	Potential Copers (n = 146)	Noncopers (n = 199)
Age, y	25.9 ± 10.6	28.0 ± 9.9
Height, m	1.7 ± 0.1	1.7 ± 0.1
Weight, kg	79.8 ± 17.5	77.9 ± 16.2
Time from injury, wk	5.5 ± 4	6.5 ± 5

[a] Data presented as mean ± SD.

RESULTS

The 345 patients (129 females, 216 males) who completed the screening examination were, on average, 27 ± 10.3 years old and 6 ± 5 weeks from the index injury at the time of testing. More participants were classified as noncopers than as potential copers (noncopers, n = 199, 58%; potential copers, n = 146, 42%). Potential coper and noncoper patients were similar in age, height, weight, and time from index injury (Table 1). There was no significant difference in anterior knee joint laxity (Figure 1) or quadriceps strength (Figure 2) between the potential copers and noncopers.

TABLE 2
Influence of Quadriceps Strength, Anterior Knee Laxity, and Preinjury Activity Level on Hop Test Performance

	R^2	R^2 Change	β Coefficient[a]	F Change	Significant F Change
Single hop					
Quadriceps strength[b]	0.069	0.069	+	22.884	<.001[c]
Activity level[d]	0.074	0.005	–	1.570	.211
Laxity[e]	0.076	0.002	–	0.658	.418
Triple hop					
Quadriceps strength	0.043	0.043	+	13.891	<.001[c]
Activity level	0.044	0.001	+	0.094	.760
Laxity	0.047	0.003	–	1.211	.272
Crossover hop					
Quadriceps strength	0.075	0.075	+	24.969	<.001[c]
Activity level	0.076	0.001	+	0.102	.749
Laxity	0.077	0.001	–	0.523	.470
Timed hop					
Quadriceps strength	0.038	0.038	+	12.146	.001[c]
Activity level	0.038	0.000	–	0.009	.923
Laxity	0.046	0.008	–	2.605	.108

[a]Relationship between dependent and independent variables.
[b]Percentage maximum voluntary isometric contraction.
[c]Statistically significant ($P \leq .01$).
[d]Preinjury International Knee Documentation Committee classification.
[e]Side-to-side difference in anterior knee laxity using manual maximum pull with KT-1000 arthrometer.

TABLE 3
Predictors of Global Function

Global Rating	R^2	R^2 Change	β Coefficient[a]	F Change	Significant F Change
Timed hop	0.157	0.157	+	57.113	<.001[b]
Crossover hop	0.168	0.011	+	3.748	.054
Quadriceps strength[c]	0.172	0.004	+	1.603	.206
Activity level[d]	0.192	0.020	–	7.437	.007[b]
Laxity[e]	0.192	0.000	+	0.183	.669

[a]Relationship between dependent and independent variables.
[b]Statistically significant ($P \leq .01$).
[c]Percentage maximum voluntary isometric contraction.
[d]Preinjury International Knee Documentation Committee classification.
[e]Side-to-side difference in anterior knee laxity using manual maximum pull with KT-1000 arthrometer.

Predictors of Hop Test Performance

Quadriceps strength had the greatest influence on performance during all 4 hop tests (Table 2). Neither preinjury activity level nor anterior knee laxity significantly influenced performance during hop testing when added to the model (Table 2).

Predictors of Self-assessed Global Function

Timed hop test performance had the greatest influence on self-assessed global function (Table 3). The addition of crossover hop, quadriceps strength, and anterior knee laxity variables did not significantly influence global rating scores when added to the model (Table 3). The influence of preinjury activity level on self-assessed global rating did significantly improve the model; the higher the preinjury activity level, the higher the global rating (Table 3).

The SURF Algorithm

On the basis of preinjury activity levels and knee laxity, all but 1 of the 345 patients would have been categorized as high-risk surgical candidates according to the recent modification of Fithian et al to the SURF criteria.[17] In contrast to the SURF algorithm,[11] the magnitude of passive anterior knee laxity had no effect on dynamic knee stability (Table 4).

DISCUSSION

Neither preinjury activity level nor the amount of passive anterior knee joint laxity contributed meaningfully to knee functional performance or self-rating of knee function soon after ACL injury, when surgical decisions are typically made. Earlier investigations have reported patient age, sports activity, and the degree of knee joint laxity as the

TABLE 4
Anterior Knee Laxity Distribution for Groups

Knee Laxity,[a] mm	Potential Copers, %	Noncopers, %
<5	38	32
5-7	41	41
>7	21	26

[a]Side-to-side difference during manual maximum KT-1000 arthrometer testing.

major risk factors necessitating surgery after ACL injury. Recent reports of long-term results after ACLR have illustrated surgically restoring knee stability does not always permit a return to sports activities or prevent future symptom complaints or degenerative knee arthritis.[16,26,31,45] Yet clinicians continue to infer that knee instability necessitates surgical management based on patient age, laxity, and physical activity level.[5,12,27] The results of this study challenge such traditional decision-making schemes.

This study implemented rigorous criteria in a large sample of patients. The study sample consisted of a consecutive group of 345 patients from the practice of a single orthopaedic surgeon. The study sample was also homogeneous. All patients were tested within 7 months of the index injury; had sustained a complete, isolated ACL rupture; and had minimal swelling and full range of motion at the time of testing. This minimized the influence of confounding variables on the measures of interest (knee function). All patients were regular participants in IKDC level I/II sports. Consequently, each person in this study was equally at risk for future knee giving-way episodes based on preinjury activity participation. Finally, patients were classified as rehabilitation versus early surgical candidates using a screening examination developed at the University of Delaware.[18] This decision-making scheme has been established as an effective mechanism for classifying patients with different levels of dynamic knee stability in clinical[18,22] and laboratory[7-9] studies. The study design and results provide overwhelming evidence that clinical testing that captures dynamic knee stability is a highly effective strategy for discriminating between surgical and nonsurgical candidates after ACL injury.

There was a statistically significant relationship between preinjury activity level and global function. Those with the highest preinjury activity levels perceived their overall function as higher during the screening examination than did patients who were less active before injury (the β coefficient describing the nature of the relationship was negative because a high activity level is indicated by a low-numbered activity category). These results contradict the SURF algorithm classification scheme,[11,17] which describes a higher activity level before ACL injury as a significant indicator of who will need late surgery. Furthermore, the nature of the relationship (positive vs negative influence) between preinjury activity level and hop test performance as well as self-assessed global function was variable. These results suggest preinjury activity level is neither a meaningful nor a reliable predictor of dynamic knee stability.

There was no difference in passive anterior knee laxity between noncopers and potential copers, and anterior knee joint laxity did not have a meaningful influence on perceived function or functional measures. We used a knee arthrometer to measure anterior tibia displacement during a Lachman test, a technique that is effective in identifying ACL deficiency.[11] Unlike the Lachman test, the pivot-shift test assesses multiplanar tibia displacement as the examiner attempts to evoke simultaneous anterior and rotational subluxation of the tibiofemoral joint. Limitations of the pivot-shift test include a large percentage of false-negative results[13] and the absence of readily available tools that quantify the magnitude of tibia translation. The subjective nature of this test made it a poor tool to evaluate the relationship between function and the increase in tibia translation that occurs after ACL rupture. Furthermore, the Lachman and pivot-shift tests are both assessments of passive tibia motion, not dynamic knee stability. The distinction between laxity and instability is a critical one. Joint laxity is a clinical measure of available joint motion; joint instability is a symptom reflecting the inability to control the available motion whether it is congenital or acquired. When clinical decisions are made after an ACL injury, interventions are frequently based on laxity measures and not the presence or absence of instability.

Other investigators have also reported no relationship between anterior knee laxity and function after ACL injury. Lephart et al[25] measured anterior knee displacement in 41 subjects with an isolated ACL injury who were a mean of 26.5 months removed from injury. Knee laxity was assessed with a KT-1000 arthrometer during an anterior pull using 20 lb of force. They found no relationship between the side-to-side difference in anterior knee displacement and performance during functional testing (eg, carioca maneuver, semicircular cocontraction maneuver, and a shuttle run). Lephart et al[25] went on to conclude that the ability to dynamically compensate for ACL deficiency is not necessarily related to the amount of static laxity present in the knee. These findings, although consistent with the results from the current study, are limited by the use of submaximal force during arthrometer testing. Snyder-Mackler et al[44] also found no relationship between anterior knee laxity and knee function. A total of 20 persons were tested, including 10 noncopers who had not been able to resume preinjury activities (minimum time from injury, 2 months) and 10 copers (minimum time from injury, 1 year) who had asymptomatically resumed all preinjury sporting activities. Side-to-side differences in anterior knee laxity (KT-1000 arthrometer with a manual maximum pull) did not correlate with knee function scores, including global rating, KOS-ADLS, and Knee Outcome Survey–Sports scores. Snyder-Mackler et al[44] underscored that although passive joint laxity measurements may be useful in diagnosing the presence of an ACL injury, their poor relationship to functional ability disallowed their usefulness as a predictor of functional outcome.

Differences in compensation patterns may explain why knee laxity is not related to function after ACL injury. Noncopers implement a generalized joint stiffening strategy (including generalized muscle cocontraction of the muscles that cross the knee and reduced knee motion) as a crude compensation tactic after injury.[37-40] In contrast, potential copers compensate for the absence of ligamentous stability with rapid, coordinated muscle recruitment in the presence of more normal joint excursions and moments.[6,9,21] Alterations in neuromuscular control strategies influence tibia position. Chmielewski et al[7] evaluated tibia position in 20 ACL-deficient persons (potential copers, n = 10; noncopers, n = 10) and 10 uninjured persons during a unilateral stance task. All were instructed to maintain their balance while a platform embedded in the floor moved horizontally in an anterior direction. Potential copers maintained an anterior tibia position relative to the femur that was similar to the tibia position of uninjured persons. Potential copers also demonstrated greater medial quadriceps muscle activity than that of either the uninjured or noncoper persons. In contrast, noncopers had a posterior tibia position relative to the femur. Noncopers also asynchronously recruited their medial and lateral hamstring muscles in response to plate movement. The posterior tibia position indicates the knee has been overconstrained with compensatory hamstring muscle activity. This suggests giving-way episodes in a noncoper population result from the muscles' inability to control the available joint motion after ACL injury rather than excessive anterior positioning or subluxation secondary to an increase in joint laxity.

Quadriceps strength did not have a significant effect on the development of dynamic knee stability. Although quadriceps strength did influence hop test performance significantly more than did either preinjury activity level or anterior knee laxity, the variance in hop test performance accounted for by quadriceps strength was quite small (range, 4%-8%). Previous studies of patients with ACL deficiency[4,32] and who had undergone ACLR[36,46] have also reported low to moderate relationships between lower extremity muscle strength and performance on hop tests. This would suggest there are other factors influencing performance on hop tests in addition to an individual's level of strength.

The early work of Eastlack et al[14] suggested quadriceps strength may be a useful clinical measure to identify good candidates for nonoperative care after ACL injury; however, the cohort included known copers (ie, they had already asymptomatically resumed preinjury activity levels) and noncopers who were 1 to 175 months from injury. Our results are consistent with those reported by Fitzgerald et al.[18] There was no difference in quadriceps strength between potential copers and noncopers, and quadriceps strength was not an effective predictor of functional abilities when testing patients early after ACL rupture. Perhaps over time potential copers are able to normalize quadriceps strength whereas noncopers are not, making group differences and the influence of quadriceps strength more apparent. Given the positive relationship between quadriceps strength and function reported in patients far removed from ACL injury,[14,28,49] we advocate an emphasis on quadriceps strengthening when rehabilitating the patient with ACL deficiency. Further studies are necessary to evaluate the effect of improving quadriceps strength on function in both potential copers and noncopers.

Implementing a strength criterion may have masked the influence of quadriceps strength on the development of dynamic knee stability. Because of the demands placed on the knee during hop testing, we established a minimum quadriceps strength level (70%) as a requirement for screening examination eligibility. It is possible many noncopers were excluded from participating in the screening examination secondary to weakness, thus raising the quadriceps strength mean for this group. We do not, however, advocate eliminating strength as a criterion to undergo screening to test this hypothesis. Allowing patients to perform the unilateral hop test protocol in the presence of marked quadriceps weakness may contribute to an increased risk of giving way during testing.

Among the variables entered into the regression analysis, the timed hop test was the single best predictor of self-rated function after ACL injury. The timed hop was influenced the least by quadriceps muscle strength and has been described as 1 of the less demanding of the 4 hop tests.[35] However, unlike the other hopping tasks that require persons to hop for maximum distance, the timed hop requires persons to hop a fixed distance as quickly as possible. Persons are free to use their preferred hopping strategy over 6 m. We believe the task demands—selecting and repeatedly performing a dynamic movement strategy—effectively challenge the neuromuscular control of patients early after ACL injury. It is possible the unique demands of the timed hop are the reason this task has the greatest influence on self-perceived function. These results illustrate dynamic knee stability is not a consequence of forceful muscle contractions but rather coordinated muscle contractions.

Although initial grouping criteria identified the crossover hop test as an effective predictor of function,[14] subsequent refinement of the screening examination indicated the timed hop was more effective in distinguishing between potential copers and noncopers.[18] Eastlack et al[14] suggested all 4 hop tests needed to be performed as part of the screening examination as the order of testing may have affected which hop task was predictive of group assignment (ie, the last test would have the greatest predictive ability). In the screening examination, the timed hop was performed after the crossover hop, yet the results of the hierarchical regression indicated there was no additive influence of both tests on self-rated global function. These results suggest the timed hop may be used alone in the screening examination to effectively predict group assignment. Future studies will be necessary to determine if the screening examination may be refined to further improve the success rates of nonoperative management after ACL injury.

The SURF algorithm[11] has been proposed as a decision-making scheme to assist with patient management after ACL injury.[17] This classification system uses preinjury activity and acute postinjury knee laxity to group patients as being either a low- or high-risk candidate for late-phase meniscus or ACL surgery. Low-risk patients are advised to pursue nonoperative management, whereas high-risk patients are advised to undergo early ACLR. Activity levels and knee laxity were chosen as predictive variables from a group that also included patient age, sex, injury activity, hyperextension of the contralateral knee, pivot-shift tests under anesthesia, and associated collateral ligament injuries during a discriminate analysis.[11] None of the variables in the discriminate analysis assessed muscle performance or evaluated postinjury function. Neuromuscular adaptations after ACL injury that contribute to dynamic knee stability are therefore not a component of the SURF algorithm.

The classification algorithm developed at the University of Delaware[18] used in this study categorizes patients as noncopers or potential copers based on giving-way episodes, timed hop, global rating of knee function, and KOS-ADLS scores. This classification algorithm uses a group of variables that collectively capture neuromuscular function and predict patient outcomes. Based on the SURF algorithm, all but 1 of the patients in the current study would have been recommended to undergo early ACLR; all were highly active before injury, and there was no difference in knee laxity between groups after injury.

CONCLUSION

Passive anterior knee joint laxity and preinjury activity levels are not predictive of functional abilities after ACL injury. Patient management after ACL injury in active persons may be improved by evaluating function as a consequence of dynamic knee stability using simple hop tests and validated knee outcome surveys, rather than the magnitude of knee laxity and preinjury activity level. Clinical tests that capture neuromuscular adaptations may be useful in predicting function and guiding individualized patient management after ACL injury.

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