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A 10-Year Prospective Trial of a Patient Management Algorithm and Screening Examination for Highly Active Individuals with ACL Injury. *Part II: Determinants of Dynamic Knee Stability*

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Abstract

Objectives—To clarify the determinants of dynamic knee stability early after anterior cruciate ligament (ACL) injury.

Materials and Methods—345 consecutive patients who were regular participants in IKDC level I/II sports before injury and had an acute isolated ACL 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 an average 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, pre-injury activity level, and anterior knee laxity on hop test performance, as well as the influence of timed hop, cross-over hop, quadriceps strength, pre-injury activity level, and anterior knee laxity on self-assessed global function.

Results—Neither anterior knee laxity nor quadriceps strength differed between potential copers and non-copers. Quadriceps strength influenced hop test performance more significantly than pre-injury 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 impacted self-assessed global function.

Conclusions—Traditional surgical decision making based on passive anterior knee laxity and pre-injury activity level is not supported by the results, as neither are good predictors of dynamic knee stability. Clinical tests that capture neuromuscular adaptations, including the timed hop test, may be useful in predicting function and guiding individualized patient management after ACL injury.

Keywords

Knee; quadriceps strength; neuromuscular control

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INTRODUCTION

Management and counseling of the nearly half a million new patients each year in the weeks after anterior cruciate ligament (ACL) injury is one of the most controversial topics in sports medicine. Evidence suggests that there is a differential response to the injury. While the majority of individuals cannot return to high level athletic activities after ACL injury because of continued episodes of knee giving way (*non-copers*) [14], a small percentage of individuals make a full, asymptomatic return to all pre-injury activities (*copers*).[11, 14] The inability to prospectively identify candidates for non-operative 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. Though 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 (e.g., 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* non-operative 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 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 23-39%.[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 pre-injury activities with non-operative management after ACL rupture is dependent 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 (e.g., detection of passive motion, joint repositioning tests), and general neuromuscular function (e.g., stabilometry). These tests are limited to static conditions. In contrast, single leg 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[11] concluded that that total pre-injury 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 non operative management and not require late (more than six months removed from the index injury) ACL or meniscus surgery. Fithian[17] used the Daniel [11] SURF (surgical risk factor) 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 [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 [17] suggested there are in fact only two 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 non-operative management.

In our institution 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 pre-injury activities without surgical intervention, and also recommended activities while on a surgical waiting list. The patient classification system devised at the University of XXXXXXXX [18] was influenced by the earlier work by Eastlack [14], who had compared highly active (level I or II) subjects with isolated ACL injury who had been identified as either copers (N=12) or symptomatically ACL deficient (non-copers) (N=33). In this study, non-copers and copers were distinguished by quadriceps strength, global rating, Knee Outcome Survey-Sports, and cross-over hop scores. Knee laxity, age, time from injury, and activity levels were similar for both groups. From these results, Eastlack [14] suggested a group of tests would be necessary to prospectively discriminate patient functional abilities. Fitzgerald [18] tested the effectiveness of the University of XXXXXXXX treatment algorithm using identical inclusion and exclusion criteria as Daniel [11] and Fithian [17] except that all subjects were classified as level I or II athletes. Therefore, this population, according to Fithian [17] and Daniel [11] was at a high and uniformly equal risk of future knee giving way episodes if they returned to all pre-morbid 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-ADL ≥ 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[18] reported 79% of those identified as potential copers were able to successfully (defined as no episodes of knee giving way) return to all pre-injury activities at the pre-injury level. Ten year outcomes substantiated the screening examination as an effective tool for discriminating between surgical and non-operative candidates, as 72% of potential copers during this period were successful (i.e., full return to pre-injury activities with no episodes of giving way) with a non-operative return to pre-injury 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 [14] reported that only non-copers demonstrated large quadriceps strength deficits. Wojtys [49] reported similar findings: patients who were categorized as the “best” ACL deficient group had no significant difference in quadriceps strength compared to 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 post-injury functional levels. [47] The prevalence and magnitude of quadriceps strength deficits among patients with poor dynamic knee stability prompted Rudolph [37, 39] to call quadriceps weakness the hallmark of the non-coper patient.

The University of XXXXXXXX and SURF algorithms have been offered as clinical tools to identify non-surgical candidates after ACL rupture. Previous reports of both classification algorithms are, however, limited in their ability to provide insight to 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 ACL reconstruction. During the development of the University of XXXXXXXX classification algorithm, Eastlack[14] and Fitzgerald[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 while 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 paper in a two part series utilizes results of prospective testing and classification of a large, homogenous sample of highly active patients from the practice of a single orthopedic surgeon to clarify the determinants of dynamic knee stability after ACL rupture.

MATERIALS AND METHODS

Subjects

Three hundred forty-five consecutive patients with acute, complete unilateral ACL rupture from the practice of a single orthopaedic surgeon (XXX) were evaluated for this study from 1996 to 2006. All ACL tears were confirmed with magnetic resonance imaging (MRI) and knee arthrometer testing. Prior to injury all subjects had been regular participants (> 50 hours/year) in IKDC level I or II activities. [11, 20] Subjects 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 subjects 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 meniscal tear, full thickness chondral lesion, ipsilateral hip or ankle abnormalities, and chronic (> 7 months) ACL injuries. [18]

Subjects were classified as either a non-coper or potential coper 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 subject being classified as a non-coper.

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

Evaluation of Anterior Knee Joint Laxity

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

Evaluation of Quadriceps Strength

Quadriceps strength was measured during a maximum voluntary isometric contraction (MVIC) 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 subjects were seated and stabilized in an electromechanical dynamometer (KinCom, Chattanooga Corporation, Chattanooga, TN) with their hips and knees flexed to 90°. After debriding the skin with rubbing alcohol, 3”× 5” self-adhesive electrodes were placed over the proximal quadriceps lateral to the midline and distal quadriceps medial to the midline in order to cover all 4 motor points of the quadriceps muscle. Subjects performed 3 practice trials, and testing was initiated after 5 minutes of rest.

For the test subjects were instructed to maximally contract their quadriceps for 5 seconds during which a supramaximal burst of electrical stimulation (amplitude 130 V, pulse duration 600μs, pulse interval 10ms, train duration 100ms) (Grass Instruments, Braintree, MA) 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, subjects 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. [32] Subjects performed two practice trials followed by two 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, cross-over 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 .92 to .96 for the unilateral[2, 3], cross-over[2, 3], and triple hop for distance[2, 3], and the 6-m timed hop[2]. All patients wore an off the shelf, de-rotational functional knee brace on the injured limb during hop testing. The two 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, their 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 0-100% the patient estimates represents their current activity level (including athletics) compared to pre-injury activities. The KOS-ADLS is a questionnaire consisting of 14 questions with 6 possible answers (each possible answer weighted from 0 to 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 non-copers. 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 pre-injury 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 cross-over hop test, quadriceps strength, pre-injury activity level, and anterior knee joint laxity. Beta coefficients calculated from the hierarchical regression were evaluated to identify the nature (positive versus negative) of the relationship between the dependent and independent variables. Bonferonni correction was used to adjust for multiple comparisons for regression analyses (adjusted alpha=0.01). Subject classification was subsequently compared to results obtained using the SURF algorithm.[11]

RESULTS

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

Predictors of Hop Test Performance

Quadriceps strength had the greatest influence on performance during all four hop tests (Table 3). Neither pre-injury 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 cross-over 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 pre-injury activity level on self-assessed global rating did significantly improve the model; the higher the pre-injury activity level, the higher the global rating (Table 3).

SURF Algorithm

Based on pre-injury activity levels and knee laxity, all but 1/345 subjects would have been categorized as high-risk surgical candidates according to Fithian's recent modification of 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 pre-injury 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 major risk-factors necessitating surgery after ACL injury. Recent reports of long term results after ACL reconstruction have illustrated surgically restoring knee stability does not ubiquitously permit a return to sports activities, or prevent future symptom complaints or degenerative knee arthritis.[16, 26, 31, 45] Yet clinicians continue to infer knee instability that 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 homogenous: all subjects 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 subjects were regular participants in IKDC level I/II sports. Consequently each subject in this study was equally at risk for future knee giving way episodes based on pre-injury activity participation. Finally, subjects were classified as rehabilitation versus early surgical candidates using a screening examination developed at the University of XXXXXXXX.[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 non-surgical candidates after ACL injury.

There was a statistically significant relationship between pre-injury activity level and global function. The nature of the relationship, however, was negative: those with the highest pre-injury activity level perceived their overall function higher during the screening examination than individuals who were less active before injury. 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 pre-injury activity level and hop test performance as well as self-assessed global function was variable. These results suggest pre-injury activity level is neither a meaningful nor reliable predictor of dynamic knee stability.

There was no difference in passive anterior knee laxity between non-copers and potential copers, nor did anterior knee joint laxity 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 multi-planar tibia displacement as the examiner attempts to evoke simultaneous anterior and rotational subluxation of the tibia-femoral 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 [25] measured anterior knee displacement in 41 subjects with an isolated ACL injury who were an average of 26.5 months removed from injury. Knee laxity was assessed with a KT-1000 during an anterior pull using 20 pounds of force. Lephart [25] found no relationship between the side-to-side difference in anterior knee displacement and performance during functional testing (e.g., carioca maneuver, semicircular co-contraction maneuver, and a shuttle run). Lephart [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, though consistent with the results from the current study, are limited by the use of sub-maximal force during arthrometer testing. Snyder-Mackler [44] also found no relationship between anterior knee laxity and knee function. A total of 20 subjects were tested, including 10 non-copers who had not been able to resume pre-injury activities (minimum time from injury = 2 months), and 10 copers (minimum time from injury = 1 year) who had asymptomatically resumed all pre-injury sporting activities. Side-to-side differences in anterior knee laxity (KT-1000 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 [44] underscored that, though 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. Non-copers implement a generalized joint stiffening strategy (including generalized muscle co-contraction 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 [7] evaluated tibial position in 20 ACL deficient subjects (potential copers N=10, non-copers N=10) and 10 uninjured subjects during a unilateral stance task. Subjects 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 subjects. Potential copers also demonstrated greater medial quadriceps muscle activity than either uninjured or non-coper subjects. In contrast, non-copers had a *posterior* tibia position relative to the femur. Non-copers also asynchronously recruited their medial and lateral hamstring muscles in response to plate movement. The posterior tibia position indicates the knee has been over-constrained with compensatory hamstring muscle activity. This suggests giving way episodes in a non-coper population results 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 impact on the development of dynamic knee stability. Although quadriceps strength did influence hop test performance significantly more than either pre-injury 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 subjects with ACL deficiency[4, 32] and who had undergone ACL reconstruction[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.

Eastlack's[14] early work suggested quadriceps strength may be a useful clinical measure to identify good candidates for non-operative care after ACL injury, however the cohort included known copers (i.e., they had already asymptomatically resumed pre-injury activity levels) and non-copers who ranged 1-175 months from injury. Our results are consistent with those reported by Fitzgerald.[18] There was no difference in quadriceps strength between potential copers and non-copers, 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 while non-copers are not, making group differences and the influence of quadriceps strength more apparent. Given the positive relationship between quadriceps strength and function reported in subjects 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 impact of improving quadriceps strength on function in both potential copers and non-copers.

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 non-copers were excluded from participating in the screening examination secondary to weakness, thus raising the quadriceps strength average for this group. We do not, however, advocate eliminating strength as a criterion to undergo screening to test this hypothesis. Allowing individuals 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 one of the less demanding of the four hop tests.[35] However, unlike the other hopping tasks that require subjects to hop for maximum distance, the timed hop requires subjects to hop a fixed distance as quickly as possible. Subjects are free to utilize 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 cross-over 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 non-copers.[18] Eastlack[14] suggested all four 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 (i.e., the last test would have the greatest predictive ability). In the screening examination the timed hop was performed after the cross-over 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 non-operative 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 pre-injury activity and acute post-injury 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 non-operative management while high risk patients are advised to undergo early ACL reconstruction. 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 post-injury 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 XXXXXXXX [18] used in this study categorizes patients as non-copers or potential copers based on giving way episodes, timed-hop, global rating of knee function, and KOS-ADL 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 one of the subjects in the current study would have been recommended to undergo early ACL reconstruction: 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 pre-injury activity levels are not predictive of functional abilities after ACL injury. Patient management after ACL injury in active individuals 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 pre-injury activity level. Clinical tests that capture neuromuscular adaptations may be useful in predicting function and guiding individualized patient management after ACL injury.

References

1. Andersson AC. Knee laxity and function after conservative treatment of anterior cruciate ligament injuries. A prospective study. Int J Sports Med 1993;14:150–153. [PubMed: 8509243]
2. Bandy WD, Rusche KR, Tekulve FY. Reliability and symmetry for five unilateral functional tests of the lower extremity. Isokinetics and Exercise Science 1994;4:108–111.
3. Bolgla LA, Keskula DR. Reliability of lower extremity functional performance tests. J Orthop Sports Phys Ther 1997;26:138–142. [PubMed: 9276854]
4. Borsa PA, Lephart SM, Irrgang JJ. Comparison of performance-based and patient-reported measures of function in anterior cruciate-deficient individuals. J Orthop Sports Phys Ther 1998;28:392–399. [PubMed: 9836170]
5. Bradley JP, Klimkiewicz JJ, Rytel MJ, Powell JW. Anterior cruciate ligament injuries in the National Football League: epidemiology and current treatment trends among team physicians. Arthroscopy 2002;18:502–509. [PubMed: 11987061]
6. Chmielewski TL, Hurd WJ, Rudolph KS, et al. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. Phys Ther 2005;85:740–749. discussion 750-744. [PubMed: 16048422]
7. Chmielewski TL, Hurd WJ, Snyder-Mackler L. Elucidation of a potentially destabilizing control strategy in ACL deficient non-copers. J Electromyogr Kinesiol 2005;15:83–92. [PubMed: 15642656]
8. Chmielewski TL, Ramsey DK, Snyder-Mackler L. Evidence for differential control of tibial position in perturbed unilateral stance after acute ACL rupture. J Orthop Res 2005;23:54–60. [PubMed: 15607875]
9. Chmielewski TL, Rudolph KS, Fitzgerald GK, et al. Biomechanical evidence supporting a differential response to acute ACL injury. Clin Biomech (Bristol, Avon) 2001;16:586–591.
10. Chmielewski TL, Stackhouse S, Axe MJ, Snyder-Mackler L. A prospective analysis of incidence and severity of quadriceps inhibition in a consecutive sample of 100 patients with complete acute anterior cruciate ligament rupture. J Orthop Res 2004;22:925–930. [PubMed: 15304261]
11. Daniel DM, Stone ML, Dobson BE, et al. Fate of the ACL-injured patient. A prospective outcome study. Am J Sports Med 1994;22:632–644. [PubMed: 7810787]
12. Delay BS, Smolinski RJ, Wind WM, Bowman DS. Current practices and opinions in ACL reconstruction and rehabilitation: results of a survey of the American Orthopaedic Society for Sports Medicine. Am J Knee Surg 2001;14:85–91. [PubMed: 11401175]
13. Donaldson WF 3rd, Warren RF, Wickiewicz T. A comparison of acute anterior cruciate ligament examinations. Initial versus examination under anesthesia. Am J Sports Med 1985;13:5–10. [PubMed: 3976980]
14. Eastlack ME, Axe MJ, Snyder-Mackler L. Laxity, instability, and functional outcome after ACL injury: copers versus noncopers. Med Sci Sports Exerc 1999;31:210–215. [PubMed: 10063808]
15. Engstrom B, Gornitzka J, Johansson C, Wredmark T. Knee function after anterior cruciate ligament ruptures treated conservatively. Int Orthop 1993;17:208–213. [PubMed: 8407034]
16. Fink C, Hoser C, Hackl W, et al. Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture--is sports activity a determining variable? Int J Sports Med 2001;22:304–309. [PubMed: 11414676]

17. Fithian DC, Paxton EW, Stone ML, et al. Prospective trial of a treatment algorithm for the management of the anterior cruciate ligament-injured knee. Am J Sports Med 2005;33:335–346. [PubMed: 15716249]

18. Fitzgerald GK, Axe MJ, Snyder-Mackler L. A decision-making scheme for returning patients to high-level activity with nonoperative treatment after anterior cruciate ligament rupture. Knee Surg Sports Traumatol Arthrosc 2000;8:76–82. [PubMed: 10795668]

19. Fitzgerald GK, Lephart SM, Hwang JH, Wainner RS. Hop tests as predictors of dynamic knee stability. J Orthop Sports Phys Ther 2001;31:588–597. [PubMed: 11665746]

20. Hefti F, Muller W, Jakob RP, Staubli HU. Evaluation of knee ligament injuries with the IKDC form. Knee Surg Sports Traumatol Arthrosc 1993;1:226–234. [PubMed: 8536037]

21. Houck JR, Duncan A, Haven KE. Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. Gait Posture. 2005

22. Hurd WJ, Axe MJ, Snyder-Mackler L. Part I. 2007 unpublished.

23. Irrgang JJ, Snyder-Mackler L, Wainner RS, et al. Development of a patient-reported measure of function of the knee. J Bone Joint Surg Am 1998;80:1132–1145. [PubMed: 9730122]

24. Kapoor B, Clement DJ, Kirkley A, Maffulli N. Current practice in the management of anterior cruciate ligament injuries in the United Kingdom. Br J Sports Med 2004;38:542–544. [PubMed: 15388535]

25. Lephart SM, Perrin DH, Fu FH. Relationship between selected physical characteristics and functional capacity in the anterior cruciate ligament-insufficient athlete. J Orthop Sports Phys Ther 1992:174–181. [PubMed: 18796757]

26. Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum 2004;50:3145–3152. [PubMed: 15476248]

27. Marx RG, Jones EC, Angel M, et al. Beliefs and attitudes of members of the American Academy of Orthopaedic Surgeons regarding the treatment of anterior cruciate ligament injury. Arthroscopy 2003;19:762–770. [PubMed: 12966385]

28. McDaniel WJ Jr, Dameron TB Jr. Untreated ruptures of the anterior cruciate ligament. A follow-up study. J Bone Joint Surg Am 1980;62:696–705. [PubMed: 7391092]

29. Millett PJ, Willis AA, Warren RF. Associated injuries in pediatric and adolescent anterior cruciate ligament tears: does a delay in treatment increase the risk of meniscal tear? Arthroscopy 2002;18:955–959. [PubMed: 12426537]

30. Mirza F, Mai DD, Kirkley A, et al. Management of injuries to the anterior cruciate ligament: results of a survey of orthopaedic surgeons in Canada. Clin J Sport Med 2000;10:85–88. [PubMed: 10798788]

31. Myklebust G, Holm I, Maehlum S, et al. Clinical, functional, and radiologic outcome in team handball players 6 to 11 years after anterior cruciate ligament injury: a follow-up study. Am J Sports Med 2003;31:981–989. [PubMed: 14623667]

32. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med 1991;19:513–518. [PubMed: 1962720]

33. Noyes FR, Mooar PA, Matthews DS, Butler DL. The symptomatic anterior cruciate-deficient knee. Part I: the long-term functional disability in athletically active individuals. J Bone Joint Surg Am 1983;65:154–162. [PubMed: 6687391]

34. Petschnig R, Baron R, Albrecht M. The relationship between isokinetic quadriceps strength test and hop tests for distance and one-legged vertical jump test following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 1998;28:23–31. [PubMed: 9653687]

35. Reid T, Birmingham TB, Stratford PW, et al. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. Phys Ther 2007;87:337–349. [PubMed: 17311886]

36. Risberg MA, Hom I, Tjomsland O, et al. Prospective study of changes in impairments and disabilities after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 1999;29:400–412. [PubMed: 10416180]

37. Rudolph KS, Axe MJ, Buchanan TS, et al. Dynamic stability in the anterior cruciate ligament deficient knee. Knee Surg Sports Traumatol Arthrosc 2001;9:62–71. [PubMed: 11354855]

38. Rudolph KS, Axe MJ, Snyder-Mackler L. Dynamic stability after ACL injury: who can hop? Knee Surg Sports Traumatol Arthrosc 2000;8:262–269. [PubMed: 11061293]
39. Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L. 1998 Basmajian Student Award Paper: Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. J Electromyogr Kinesiol 1998;8:349–362. [PubMed: 9840891]
40. Rudolph KS, Snyder-Mackler L. Effect of dynamic stability on a step task in ACL deficient individuals. J Electromyogr Kinesiol 2004;14:565–575. [PubMed: 15301775]
41. Sernert N, Kartus J, Kohler K, et al. Analysis of subjective, objective and functional examination tests after anterior cruciate ligament reconstruction. A follow-up of 527 patients. Knee Surg Sports Traumatol Arthrosc 1999;7:160–165. [PubMed: 10401652]
42. Shelton WR, Barrett GR, Dukes A. Early season anterior cruciate ligament tears. A treatment dilemma. Am J Sports Med 1997;25:656–658. [PubMed: 9302471]
43. Snyder-Mackler L, De Luca PF, Williams PR, et al. Reflex inhibition of the quadriceps femoris muscle after injury or reconstruction of the anterior cruciate ligament. J Bone Joint Surg Am 1994;76:555–560. [PubMed: 8150823]
44. Snyder-Mackler L, Fitzgerald GK, Bartolozzi AR 3rd, Ciccotti MG. The relationship between passive joint laxity and functional outcome after anterior cruciate ligament injury. Am J Sports Med 1997;25:191–195. [PubMed: 9079172]
45. von Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. Ann Rheum Dis 2004;63:269–273. [PubMed: 14962961]
46. Wilk KE, Romaniello WT, Soscia SM, et al. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. J Orthop Sports Phys Ther 1994;20:60–73. [PubMed: 7920603]
47. Williams GN, Buchanan TS, Barrance PJ, et al. Quadriceps weakness, atrophy, and activation failure in predicted noncopers after anterior cruciate ligament injury. Am J Sports Med 2005;33:402–407. [PubMed: 15716256]
48. Williams GN, Chmielewski T, Rudolph K, et al. Dynamic knee stability: current theory and implications for clinicians and scientists. J Orthop Sports Phys Ther 2001;31:546–566. [PubMed: 11665743]
49. Wojtys EM, Huston LJ. Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities. Am J Sports Med 1994;22:89–104. [PubMed: 8129117]

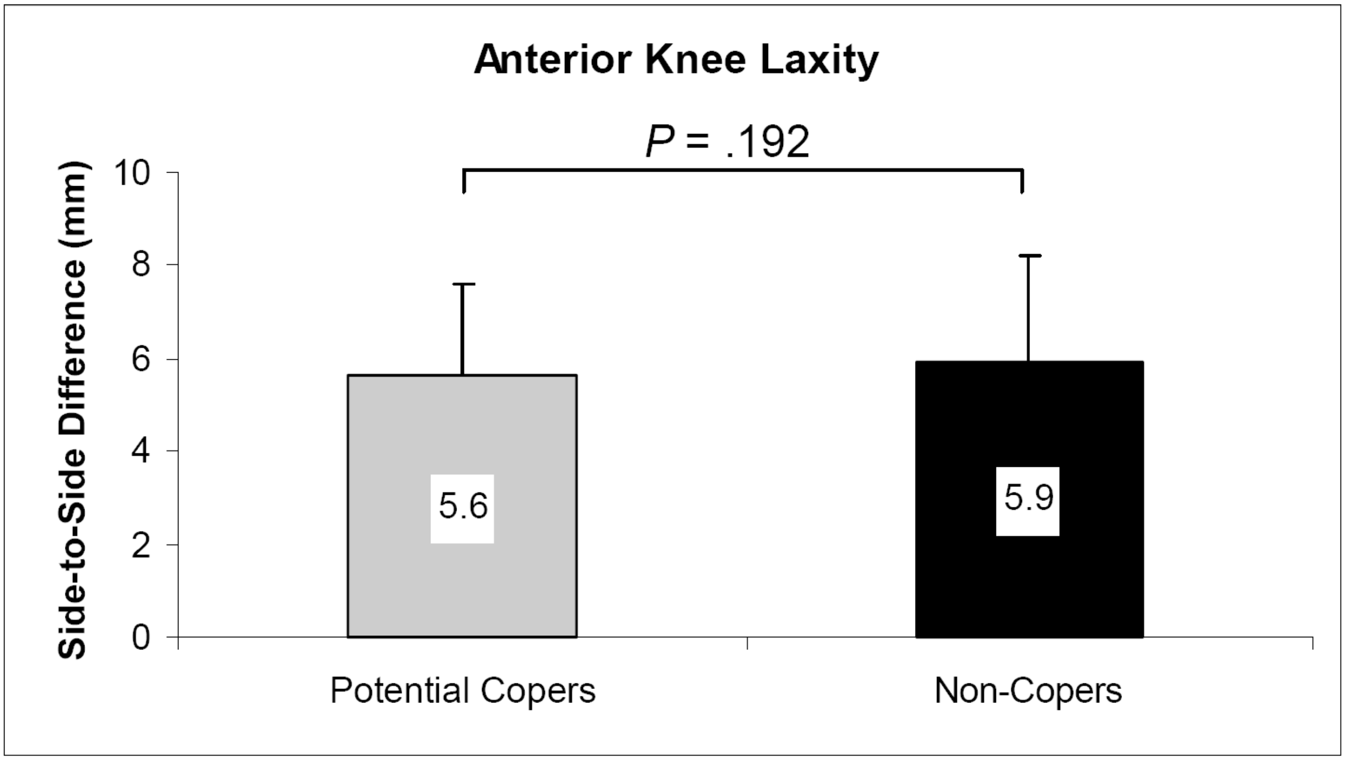

Figure 1. Anterior Knee Laxity in Potential Copers and Non-Copers

Side-to-side difference in anterior knee laxity using a manual maximum pull during KT-1000 arthrometer testing.

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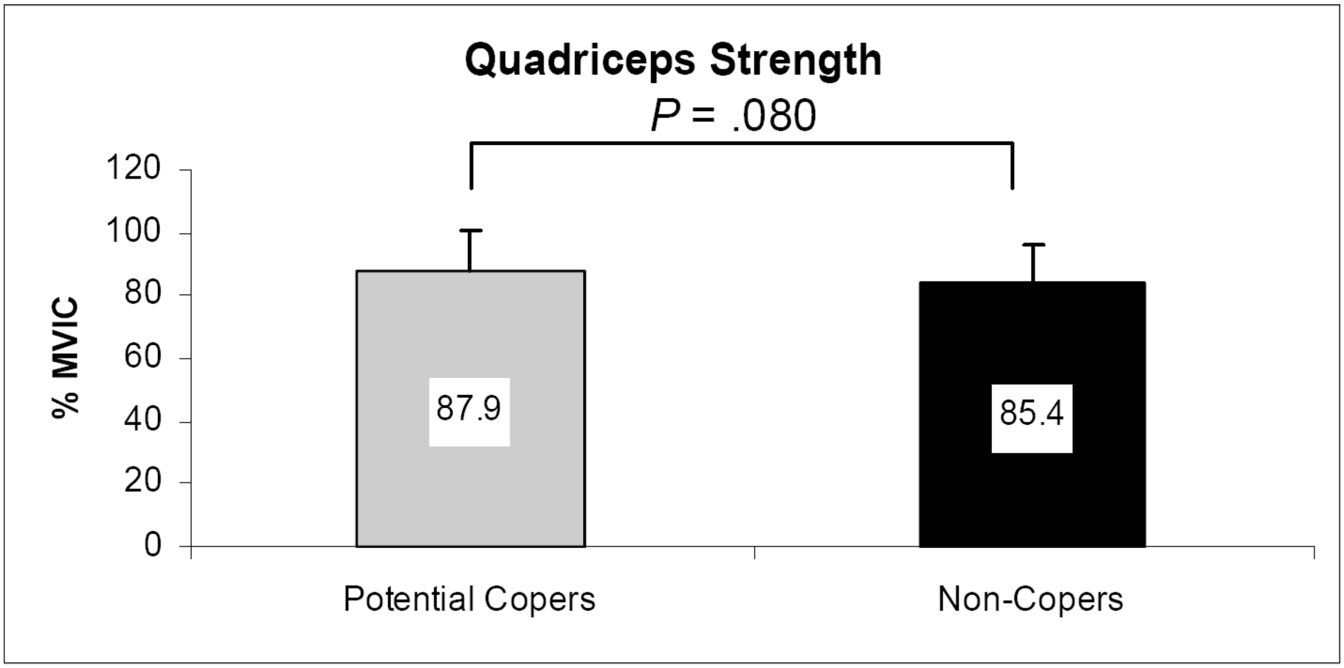

Figure 2. Quadriceps Strength in Potential Copers and Non-Copers

Table 1

Group demographics. Data presented as Mean (SD).

	***Potential Copers* (N=146)**	***Non-Copers* (N=199)**
Age (years)	25.9 (10.6)	28.0 (9.9)
Height (m)	1.7 (.1)	1.7 (.1)
Weight (kg)	79.8 (17.5)	77.9 (16.2)
Time from Injury (weeks)	5.5 (4)	6.5 (5)

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Table 2

Influence of quadriceps strength, anterior knee laxity, and pre-injury activity level on hop test performance.

		R^2	R^2 Change	Beta Coefficient[a]	F Change	Sig. F Change
Single Hop						
	Quadriceps Strength[b]	.069	.069	+	22.884	<.001*
	Activity Level[c]	.074	.005	-	1.570	.211
	Laxity[d]	.076	.002	-	.658	.418
Triple Hop						
	Quadriceps Strength	.043	.043	+	13.891	<.001*
	Activity Level	.044	.001	+	.094	.760
	Laxity	.047	.003	-	1.211	.272
Cross-Over Hop						
	Quadriceps Strength	.075	.075	+	24.969	<.001*
	Activity Level	.076	.001	+	.102	.749
	Laxity	.077	.001	-	.523	.470
Timed Hop						
	Quadriceps Strength	.038	.038	+	12.146	.001*
	Activity Level	.038	.000	-	.009	.923
	Laxity	.046	.008	-	2.605	.108

[a] Relationship between dependent and independent variables

[b] % MVIC

[c] Pre-injury IKDC classification

[d] Side-to-side difference in anterior knee laxity using manual, maximum pull with KT-2000 arthrometer

* Statistically significant (P<.01)

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Table 3

Predictors of global function.

		R^2	R^2 Change	Beta Coefficient[a]	F Change	Sig. F Change
Global Rating						
	Timed Hop	.157	.157	+	57.113	<.001*
	Cross-Over Hop	.168	.010	+	3.748	.054
	Quadriceps Strength[b]	.172	.004	+	1.603	.206
	Activity Level[c]	.192	.020	-	7.437	.007*
	Laxity[d]	.192	.000	+	.183	.669

[a] Relationship between dependent and independent variables

[b] % MVIC

[c] Pre-injury IKDC classification

[d] Side-to-side difference in anterior knee laxity using manual, maximum pull with KT-2000 arthrometer

* Statistically significant (P<.01)

Table 4

Anterior knee laxity distribution for groups

Knee Laxity*	Potential Copers	Non-Copers
<5	38%	32%
5-7	41%	41%
>7	21%	26%

*Side-to-side difference (mm) during manual maximum KT-2000 arthrometer testing