

Neuromuscular Evaluation With Single-Leg Squat Test at 6 Months After Anterior Cruciate Ligament Reconstruction

Michael P. Hall,* MD, Ronald S. Paik,^{†||} MD, Anthony J. Ware,[‡] DPT, Karen J. Mohr,[§] PT, and Orr Limpisvasti,[§] MD

Investigation performed at Kerlan-Jobe Orthopaedic Clinic, Los Angeles, California, USA

Background: Criteria for return to unrestricted activity after anterior cruciate ligament (ACL) reconstruction varies, with some using time after surgery as the sole criterion—most often at 6 months. Patients may have residual neuromuscular deficits, which may increase the risk of ACL injury. A single-leg squat test (SLST) can dynamically assess for many of these deficits prior to return to unrestricted activity.

Hypothesis: A significant number of patients will continue to exhibit neuromuscular deficits with SLST at 6 months after ACL reconstruction.

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

Methods: Patients using a standardized accelerated rehabilitation protocol at their 6-month follow-up after primary ACL reconstruction were enrolled. Evaluation included bilateral SLST, single-leg hop distance, hip abduction strength, and the subjective International Knee Documentation Committee (IKDC) score.

Results: Thirty-three patients were enrolled. Poor performance of the operative leg SLST was found in 15 of 33 patients (45%). Of those 15 patients, 7 (45%) had concomitant poor performance of the nonoperative leg compared with 2 of 18 patients (11%) in those who demonstrated good performance in the operative leg. The poor performers were significantly older (33.6 years) than the good performers (24.2 years) ($P = .007$). Those with poor performance demonstrated decreased hip abduction strength (17.6 kg operative leg vs 20.5 kg nonoperative leg) ($P = .024$), decreased single-leg hop distance (83.3 cm operative leg vs 112.3 cm nonoperative leg) ($P = .036$), and lower IKDC scores (67.9 vs 82.3) ($P = .001$).

Conclusion: Nearly half of patients demonstrated persistent neuromuscular deficits on SLST at 6 months, which is when many patients return to unrestricted activity. Those with poor performance were of a significantly older age, decreased hip abduction strength, decreased single-leg hop distance, and lower IKDC subjective scores.

Clinical Relevance: The SLST can be used to identify neuromuscular risk factors for ACL rupture. Many patients at 6 months have persistent neuromuscular deficits on SLST. Caution should be used when using time alone to determine when patients can return to unrestricted activity.

Keywords: anterior cruciate ligament; return to unrestricted activity; single-leg squat test; neuromuscular evaluation

^{||}Address correspondence to Ronald S. Paik, MD, Nirschl Orthopaedic Center, 1715 N. George Mason Drive, Suite 504, Arlington, VA 22205, USA (email: ronaldpaikmd@gmail.com).

*Kaiser Permanente Los Angeles Medical Center, Los Angeles, California, USA.

[†]Nirschl Orthopaedic Center, Arlington, Virginia, USA.

[‡]Select Physical Therapy, Los Angeles, California, USA.

[§]Kerlan-Jobe Orthopaedic Clinic, Los Angeles, California, USA.

The authors declared that they have no conflicts of interest in the authorship and publication of this contribution.

The Orthopaedic Journal of Sports Medicine, 3(3), 2325967115575900

DOI: 10.1177/2325967115575900

© The Author(s) 2015

Substantial research has supported neuromuscular deficits to be risk factors for anterior cruciate ligament (ACL) rupture.^{24-26,48,54,59} Increased valgus loading of the knee and deficits in trunk stability have both been shown to predict ACL injury with high sensitivity and specificity in female athletes.^{8,25,26,39,54,58,59} Recent kinematic research has now supported a link between increased knee abduction forces and lateral trunk displacement during noncontact ACL injuries.^{2,6,26,27} This association has provided a strong rationale for the development of trunk- and core-based strengthening programs, which have demonstrated a decreased risk of ACL injury.^{17,18,20,23,26,37,56}

In addition to preventing ACL injury, preventing reinjury after ACL reconstruction is a concern for orthopaedic surgeons. The risk of ACL rerupture is substantially higher than it is prior to the initial ACL injury,^{22,44,47,50,52} and traumatic rerupture after ACL reconstruction is the most common mechanism of failure in the first 2 years postoperatively.⁵⁷ Increasing emphasis is being placed on postoperative rehabilitation, as increased rerupture rates have been observed when deficits in postural stability and hip dynamics are not addressed.^{22,45}

Currently, there is little evidence-based guidance on appropriate criteria, including in-office screening, for determining readiness for return to play after ACL reconstruction. A single-leg squat test (SLST) is used as an indicator of residual deficits in hip abduction strength and pelvic stability and has been used in baseball players returning from shoulder injury.^{12,34} There is a correlation between performance on SLST and hip abductor function.^{5,12,31,35} Hip abductor weakness increases the risk of ACL injury by leading to increased trunk displacement, pelvic droop, hip adduction, and valgus knee loads.^{2,7,15,23,29,53} Abnormal transverse plane hip kinetics and deficits in postural stability are predictive of secondary injury after ACL reconstruction.⁴⁵ The SLST has been shown to have excellent inter- and intrarater agreement.¹²

A systematic review of 264 ACL reconstruction studies found that 32% of the studies listed time as the only criteria considered for return to sport.⁴ Of the 158 studies that described the amount of time postoperatively prior to return to sport, 84 (53%) listed 6 months or greater as the time period for return to sport. Nineteen of 158 (12%) studies had return to sport earlier than 6 months. The 6-month time period is when many surgeons consider releasing patients to sport and unrestricted activities.^{4,46,50}

The purpose of this study was to evaluate patients for neuromuscular deficits using the SLST at 6 months after ACL reconstruction. Single-leg hop distance and hip abduction strength are measured to further provide validity and comparison of clinical screening examinations for return to sport and unrestricted activity. The null hypothesis of this study is that no patient will exhibit neuromuscular deficits with SLST at 6 months after ACL reconstruction. The experimental hypothesis is a significant number of patients will continue to exhibit neuromuscular deficits with SLST at 6 months after ACL reconstruction.

METHODS

After institutional review board approval, patients presenting for follow-up between 22 and 30 weeks after primary ACL reconstruction were identified through medical records. Inclusion criteria consisted of patients aged 15 to 50 years who had undergone primary ACL reconstruction with 1 of 5 surgeons at a single institution. All surgeons utilized a similar surgical technique (anteromedial portal drilling, tibial and femoral screw fixation), graft type (bone–patellar tendon–bone [BTB] autograft or Achilles tendon allograft), and standardized postoperative accelerated rehabilitation protocol under the same physical therapy department. Exclusion

criteria included: prior ipsilateral knee or hip surgery, concomitant meniscal repair or recognized grade 4 chondral defect at the time of surgery, and any postoperative infection or arthrofibrosis requiring surgical treatment. Enrollment and informed consent for the study was obtained at the time of the postsurgical follow-up visit. Demographic information, surgical details, and time to follow-up were recorded. Patients were also given an International Knee Documentation Committee (IKDC) subjective form to complete. After completion, patients were taken to the physical therapy gym for evaluation of bilateral SLST, hip abduction strength testing, and a single-leg hop test under the guidance of one of the study investigators.

Thirty-three patients were enrolled in the study over a time period of 6 months. There were 19 male and 14 female patients, with a mean age of 28.5 years (range, 15–48 years). Mean evaluation was at 25.6 weeks postoperatively (range, 22.3–30.1 weeks). Nineteen patients had an ACL reconstruction performed with BTB autograft, and 14 had a reconstruction with Achilles tendon allograft. Nine patients had a concomitant partial meniscectomy (4 medial, 5 lateral).

Rehabilitation Protocol

All patients underwent physical therapy at the same facility. For the first 2 weeks postoperatively, the focus was on range of motion. Continuous passive motion was used for approximately 6 hours per day with the goal of obtaining full extension and greater than 120° of flexion. At week 1, the patients started hip adduction and hamstring strengthening as well as isometric quadriceps strengthening. Hip abduction strengthening and use of a stationary bicycle began at week 2. At 4 weeks, patients began using a Stairmaster. Progressive running on a flat treadmill began at 3 months. At 4 months, patients started agility drills, and at 5 months, patients began sports-specific drills, gradually progressing to full participation. This timeline was a general guideline. Clearance to advance to each stage was under the discretion of the therapist.

Single-Leg Squat Test

Performance of the SLST was similar to that described by Crossley et al.¹² Briefly, the patients were asked to stand on a 20-cm box with their arms held out in front of them. The SLST was demonstrated by one of the study investigators. Patients were advised not to lean forward and were told to place their free leg behind them to make it easier to assess pelvic tilt and hip adduction. Patients were asked to squat to 60° of knee flexion in a slow, controlled manner at a rate of approximately 1 squat per 2 seconds. The patients were allowed 3 practice attempts with each limb prior to the actual trial. Three trials were performed for each limb. The trials were captured on digital video, with the video camera placed approximately 3 m in front of the participant on a tripod at the height of the patient's pelvis. A single orthopaedic surgeon reviewed the videos to grade the tests.

TABLE 1
Single-Leg Squat Grading Criteria^a

1. Ipsilateral trunk lean
2. Pelvic tilt
3. Hip adduction or internal rotation
4. Dynamic knee valgus
5. Loss of balance

^aA good rating requires the absence of all 5 criteria in 2 of 3 trials. Otherwise, it was considered a poor result.



Figure 1. Illustration demonstrating good (right) and poor (left) performance of a single-leg squat test. Poor performance is identified by the presence of a trunk lean, contralateral pelvic droop, hip adduction, and knee valgus, while good performance has an absence of all pathologic criteria. (Image reproduced with permission from Limpisvasti O, ElAttrache NS, Jobe FW. Understanding shoulder and elbow injuries in baseball. *J Am Acad Orthop Surg.* 2007;15:139-147.)

Grading of the performances (Table 1) was based on the presence of ipsilateral trunk lean, pelvic tilt (Figure 1) or rotation, hip adduction or internal rotation, dynamic knee valgus, or overall loss of balance, as described by Crossley et al.¹² A good performance required the absence of all 5 pathologic criteria in 2 of 3 trials. Poor performance was characterized by the presence of any of the 5 pathologic criteria in 2 of 3 trials (see the Appendix for Crossley grading).

Hip Abduction Strength

Hip abduction strength was measured similar to other studies using a handheld dynamometer, which has good inter- and intrarater reliability.^{11,12,16,49} Participants were placed

in the lateral decubitus position with their surgical leg up with slight hip flexion and 30° of knee flexion. A handheld dynamometer was placed 10 cm above the lateral knee joint line, and patients were asked to abduct their hip with maximal force. After 2 warm-up trials, the peak force from 3 trials was recorded. The procedure was repeated for the control limb.

Single-Leg Hop Test

Patients were asked to perform a single-leg forward hop for maximum distance, similar to the description in previous studies.^{3,13,19,30,43} The patients were instructed to hop as far as possible with their hands at their sides. The patients were allowed up to 3 practice attempts prior to their actual trials. They completed 3 trials each with the surgical and control limbs. The distance was measured in centimeters from the location of the distal aspect of their toes from start to landing. A mean of the 3 trials was recorded.

Statistical Analysis

The patients were placed into either good or poor performance groups depending on their evaluation with SLST of the operative leg and were analyzed based on these groups. The paired Student *t* test was used to evaluate the operative versus nonoperative sides with regard to hip abduction strength and single-leg hop test. Single-leg hop distance and hip abduction strength were normalized to the nonoperative side and to height and weight. The Student *t* test was used to compare data between the good and poor performance groups. Analysis of variance was used to compare the 2 subgroups (nonoperative leg good and poor performance subgroups) in the operative leg poor performance group to the bilateral leg good performance subgroup. The Fisher exact test was used to compare the graft types and sex disposition between the good and poor performance groups. The *P* value for significance of all tests was set at <.05.

RESULTS

Single-Leg Squat Test Performance

Poor performance on SLST of the operative leg was demonstrated in 15 of 33 patients (45%). Of those 15 patients, 7 demonstrated poor performance concomitantly in the nonoperative leg (47%) compared with only 2 of 18 (12%) patients in the operative leg good performance group.

There was a statistically significant difference in age between the good and poor performance groups (Table 2). Those with good performance had a mean age of 24.2 years (range, 17-48 years) compared with 33.6 years (range, 15-42 years) ($P = .007$) for those with poor performance. Time to testing postoperatively was similar at 24.8 vs 25.7 weeks ($P = .297$) in the good and poor performance groups, respectively. Sex make-up was comparable, with 10 males and 8 females in the good performance group and 9 males and 6 females in the poor performance group ($P > .999$). Regarding graft type, there were 13 patients with BTB

TABLE 2
Demographics of Good and Poor Operative Side Single-Leg Squat Test Performance Groups^a

	Poor Performance (n = 15)	Good Performance (n = 18)	P Value
Mean age, y (range)	33.6 (15-42)	24.2 (17-48)	.007
Mean time to testing, wk (range)	24.8 (22.1-29.2)	25.7 (23.1-30.0)	.297
Sex	9 male, 6 female	9 male, 8 female	>.999
Body mass index, kg/m ² (range)	26.6 (21.4-40.7)	24.2 (19.5-34.4)	.151
Graft type	6 BTB, 9 Achilles allograft	13 BTB, 5 Achilles allograft	.085

^aBTB, bone–patellar tendon–bone autograft.

TABLE 3
Comparison of Normalized Group Data According to the Operative Side Single-Leg Squat Test^a

	Poor Performance (n = 15)	Good Performance (n = 18)	P Value ^b
IKDC score (range)	67.9 (52 to 88)	82.3 (54 to 100)	.001
Single-leg hop distance operative/nonoperative, % (range)	79.4 (36.2 to 118.8) ^c	93.6 (63.1 to 118.5)	.085
Hip abduction strength operative/nonoperative, % (range)	85.4 (57.6 to 113.7)	103.3 (75.1 to 128.5)	.001
Operative single-leg hop distance/height, % (range)	46.5 (26.9 to 65.7) ^c	76.2 (44.4 to 111.4)	.004
Nonoperative single-leg hop distance/height, % (range)	62.7 (39.3 to 96.0) ^c	80.9 (44.9 to 115.7)	.080
Single-leg hop distance difference/height, % (range)	16.2 (–9.7 to 30.3) ^c	5.3 (–13.5 to 21.4)	.059
Operative hip abduction strength/weight, % (range)	22.1 (11.9 to 34.8)	28.3 (19.7 to 35.3)	.002
Nonoperative hip abduction strength/weight, % (range)	25.7 (18.7 to 35.4)	27.6 (20.8 to 35.6)	.236
Hip abduction strength difference/weight, % (range)	3.6 (–3.9 to 10.4)	–0.7 (–7.8 to 6.8)	.002

^aIKDC, International Knee Documentation Committee.

^bThe Student *t* test was used to compare the groups. Significance set at $P < .05$.

^cn = 9. Six patients refused to perform the single-leg hop test.

autograft and 5 with Achilles tendon allograft in the good performance group compared with 6 BTB autografts and 9 Achilles tendon allografts in those with poor performance ($P = .085$). Four patients had a concomitant partial meniscectomy in the poor performance group compared with 5 patients with good performance. The body mass index (BMI) was similar between the good performance group (26.6 kg/m²) and poor performance group (24.2 kg/m²) ($P = .151$).

Functional Testing and Clinical Scores

Patients with poor performance on SLST of the operative leg had significantly lower hip abduction strength in the surgical leg (17.6 kg) compared with the nonoperative leg (20.5 kg) ($P = .024$). Those with good performance had similar hip abduction strength in both legs, with a mean of 20.5 kg in the surgical leg versus a mean of 20.1 kg in the nonoperative leg ($P = .50$). On single-leg hop testing, patients with poor performance of the operative leg had a significantly lower hop distance in the surgical leg compared with the nonoperative leg (mean, 83.3 vs 112.3 cm) ($P = .036$). Seven of 15 patients in the poor performance group declined to perform the single-leg hop test for fear of injury to the surgical limb. Patients with good performance also had similar hop distances between the surgical (mean, 132.6 cm) and nonoperative legs (mean, 141.7 cm; $P = .46$). Patients with poor performance on SLST of the operative leg demonstrated lower mean IKDC subjective scores (mean, 67.9) compared with those with good performance (mean, 82.3) ($P = .001$).

The data for the groups were normalized using the nonoperative leg and body morphometric data such as height and weight (Table 3). The groups were further divided into subgroups based on the nonoperative leg. The normalized data evaluating the 2 subgroups within the operative leg poor performance group and the bilateral leg good performance subgroup are presented in Table 4.

DISCUSSION

The single-leg squat test has received increasing attention as a tool for trainers, physicians, and physical therapists in the evaluation of trunk and pelvic stability, functional balance, and hip abduction strength.^{6,12,42,51,55} Poor neuromuscular control in these areas can lead to an increased valgus moment at the knee, increasing risk of injury and reinjury to the ACL.^{25,26,45,48,58,59} Paterno et al⁴⁵ found that abnormal transverse plane hip kinetics and deficits in postural stability were 2 factors predictive of secondary injury after ACL reconstruction. The SLST can be performed in an office setting and can help determine a patient's readiness for safe return to unrestricted activity and possibly aid in preventing ACL reinjury.

Neuromuscular testing is often used in determining clearance for return to unrestricted activities. However, a recent systematic review of ACL reconstruction studies⁴ found that 32% of the studies listed time as the only criteria considered for return to sport. Six months was the most commonly cited time point for release to unrestricted activity.^{4,46,50}

TABLE 4
Comparison of Normalized Data of Operative Side Single-Leg Squat Test (SLST) Subgroups^a

	Poor Performance			Good Performance ^c (n = 16)	P Value ^d
	Good (Control) (n = 8)	Poor (Control) (n = 7)	P Value ^b		
IKDC score	65.0 (52 to 88)	71.3 (59 to 81)	.002	83.4 (54 to 100)	.002
Single-leg hop distance operative/nonoperative, % (range)	70.0 (36.2 to 95.1) ^e	94.9 (60.8 to 118.8) ^f	.157	93.3 (63.1 to 118.5)	.031
Hip abduction strength operative/nonoperative, % (range)	83.2 (57.6 to 112.5)	87.9 (77.6 to 113.7)	.586	103.4 (75.1 to 128.5)	.009
Operative single-leg hop distance/height, % (range)	43.7 (26.9 to 65.7) ^e	50.1 (45.8 to 57.4) ^f	.423	75.2 (44.4 to 111.4)	.003
Nonoperative single-leg hop distance/height, % (range)	67.6 (45.3 to 96.0) ^e	56.7 (39.3 to 75.4) ^f	.392	81.5 (44.9 to 115.7)	.062
Single-leg hop distance difference/height, % (range)	23.9 (2.2 to 30.3) ^d	6.6 (-9.7 to 29.6) ^e	.194	5.7 (-13.5 to 21.4)	.040
Operative hip abduction strength/weight, % (range)	20.6 (11.9 to 34.8)	23.8 (15.5 to 32.6)	.353	28.5 (19.7 to 35.3)	.006
Nonoperative hip abduction strength/weight, % (range)	24.6 (20.7 to 34.8)	27.0 (18.7 to 35.4)	.340	27.8 (20.8 to 35.6)	.267
Hip abduction strength difference/weight, % (range)	3.9 (-2.8 to 10.4)	3.2 (-3.9 to 6.2)	.735	-0.6 (-7.8 to 6.8)	.017

^aIKDC, International Knee Documentation Committee.

^bThe Student *t* test was used to compare subgroups within the operative side poor performance SLST group. Significance set at $P < .05$.

^cGroup consists of patients demonstrating good performance in SLST of both the operative and nonoperative legs.

^dAnalysis of variance was used to compare the 2 poor performance groups and the good performance group. Significance set at $P < .05$.

^e $n = 5$. Three patients refused to perform the single-leg hop test.

^f $n = 4$. Three patients refused to perform the single-leg hop test.

In this study, 15 of 33 (45%) patients demonstrated continued neuromuscular deficits on SLST of the operative leg at 6 months after ACL reconstruction. Should these patients have been released to unrestricted activity if time alone was used as the sole criterion, they would be at increased risk of rerupture. Furthermore, these data support the lack of a direct association between time after ACL reconstruction and neuromuscular control as well as the importance of neuromuscular evaluation prior to return to unrestricted activity.⁴⁰

Patients with poor performance on SLST were on average significantly older than those with good performance. This correlates with previous data that show a decrease in neuromuscular control and a decreased effect of neuromuscular training with age.^{36,41} This may be counter to the data that show that younger patients have a higher incidence of secondary injury after ACL reconstruction, but the higher incidence in younger patients may also be a result of their higher level of activity, which independently leads to a higher incidence of secondary injury.⁵⁰ There were no significant differences between male and female performance, in contrast to increasing evidence that females are at higher risk of poor neuromuscular control and ACL reinjury.^{26,33,50,54,59}

Patients with poor performance on SLST had a significant decrease in hip abduction strength compared with their nonoperative leg ($P = .024$). When the patients were divided into the subgroups, the significant differences remained with regard to the normalized data comparing the operative leg with the nonoperative leg ($P = .009$) and weight ($P = .017$). The importance of hip abduction strength to coronal and overall knee motion has been demonstrated in a study that examined single-leg squat performance and gluteus medius electromyographic activity in patients with and without anterior knee pain.¹² They found a significantly earlier onset of timing of gluteus medius activity and an increase in hip abduction torque in good

performers compared with poor performers of the SLST. Claiborne et al¹⁰ also demonstrated a high correlation of decreased hip abduction torque with greater dynamic knee valgus during single-leg squat.

Patients with poor performance on SLST had a significantly lower single-leg hop distance in the operative leg compared with the nonoperative leg ($P = .036$). This significant difference remained when the subgroups were evaluated and the operative leg was normalized to the nonoperative leg ($P = .031$) and height ($P = .040$). Nearly half of patients in the poor performance group declined to perform the single-leg hop examination for fear of injury, which may have resulted in the lack of significance. The large amount of patients refusing the single-leg hop examination highlights an advantage of using the SLST as a functional test in comparison with the single-leg hop test since it can safely be performed in all patients at this time period after ACL reconstruction.

Further advantages of the SLST are that it does not require comparison with the nonpathologic side, which may also demonstrate neuromuscular deficits. For example, the single-leg hop test is commonly compared with the other side, with most studies considering 80% to 90% of the nonoperative side normal.^{3,13,19,30,43} This may give an inaccurate result, highlighted by the group of 7 patients who demonstrated poor performance on SLST of both legs. These patients would have been cleared using the single-leg hop test since they were able to hop a distance of 94.9% compared with their nonoperative leg (see Table 4). The data for this group skewed the results appearing in Table 3, which assumes the nonoperative leg is normally functioning.

When the groups are subdivided based on the SLST performance of the nonoperative leg (see Table 4), a significant difference is found when it previously was not with regard to normalized single-leg hop distance of the operative side compared with the nonoperative side ($P = .031$) and the difference in single-leg hop distance between the operative and nonoperative legs normalized for height ($P = .040$). If

the patients in this group returned to unrestricted activity based on their almost equivalent results of the operative leg compared with the nonoperative leg, they would be at increased risk of injury due to their continued neuromuscular deficits of both legs. Other advantages of the SLST are that it requires no additional equipment and is normalized to the patient's own biometrics.

Patients with poor performance on SLST had significantly decreased IKDC subjective scores, which suggests that poor neuromuscular control is correlated with the patients' own subjective outcomes. This suggests that SLST performance should be tracked until performance and, ultimately, clinical outcome improves. The question of whether performance will ever improve is a valid one. Almost 50% of patients with poor performance with their surgical leg also had poor performance with their control limb. However, it is not fully known if the poor performance in the control limb demonstrates the baseline preoperative function or is the result of a bilateral neuromuscular response to the injured side. Studies have shown neuromuscular deficits can develop in both the injured and contralateral normal leg as a result of an ACL-deficient knee and after ACL reconstruction.^{14,21,22}

The clinical implications of the SLST should be consistent with other neuromuscular tests that are used to evaluate patients for return to unrestricted activity. If a patient continues to demonstrate deficiency then they would benefit from continued therapy, particularly of the area of deficit. This does lead to the question of what to do for those patients who may never improve. After 1 year of dedicated rehabilitation, it would be difficult to expect a great deal of improvement. In those patients, our recommendation is to caution patients about the increased risk and allow them to come to their own decision.

This study is not without limitations. First, inclusion of more patients could have allowed a significant difference to be detected with regard to sex and graft type. More patients may have allowed further evaluation of the subgroup consisting of patients who demonstrate good performance on SLST of their operative leg but poor performance on their nonoperative leg. This group was not included in the analysis of variance calculation due to only 2 patients being in the group. However, this subgroup may provide limited value in terms of comparison since the group of patients who demonstrated good performance on SLST of both legs is essentially the standard. Second, only a single investigator graded the single-leg squat performance. Although good inter- and intrarater reliability has been demonstrated,^{1,10} further examination of this with multiple judges of performance could be valuable. Third, a standardized accelerated postoperative physical therapy protocol was given to all patients, but there may have been slight variations as a result of the patients seeing different therapists within the same department. Fourth, this study included both BTB autograft and Achilles allograft reconstructions. However, multiple systematic reviews and meta-analyses have found no differences in short-term clinical outcomes between autografts and allografts.^{9,28,32,38} Last, preoperative activity levels were not analyzed, and baseline IKDC scores were not obtained. The preoperative activity levels could have

affected the subjective IKDC scores, and preoperative IKDC scores could provide more information on whether good performance on SLST correlated with an improvement in the IKDC score.

CONCLUSION

Nearly half of the patients demonstrated poor performance on SLST of the operative leg at 6 months after ACL reconstruction. Those with poor performance had a significantly older age, decreased hip abduction strength, decreased single-leg hop distance, and lower IKDC subjective scores. The SLST is a good test to use that will not be biased as a result of neuromuscular deficits in the nonoperative leg. Many patients at 6 months after ACL reconstruction continue to have persistent neuromuscular deficits, which should caution surgeons who release patients to unrestricted activity using this often cited time point as the sole criterion.

REFERENCES

- Ageberg E, Bennell KL, Hunt MA, Simic M, Roos EM, Creaby MW. Validity and inter-rater reliability of medio-lateral knee motion observed during a single-limb mini squat. *BMC Musculoskelet Disord*. 2010;11:265.
- Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*. 2009;17:705-729.
- Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clin Orthop Relat Res*. 1990; (255):204-214.
- Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. *Arthroscopy*. 2011;27:1697-1705.
- Boren K, Conrey C, Le Coguic J, Paprocki L, Voight M, Robinson TK. Electromyographic analysis of gluteus medius and gluteus maximus during rehabilitation exercises. *Int J Sports Phys Ther*. 2011;6:206-223.
- Boudreau SN, Dwyer MK, Mattacola CG, Lattermann C, Uhl TL, McKeon JM. Hip-muscle activation during the lunge, single-leg squat, and step-up-and-over exercises. *J Sport Rehabil*. 2009;18:91-103.
- Brent JL, Myer GD, Ford KR, Paterno MV, Hewett TE. The effect of sex and age on isokinetic hip-abduction torques. *J Sport Rehabil*. 2013; 22:41-46.
- Brophy RH, Chiaia TA, Maschi R, et al. The core and hip in soccer athletes compared by gender. *Int J Sports Med*. 2009;30:663-667.
- Carey JL, Dunn WR, Dahm DL, Zeger SL, Spindler KP. A systematic review of anterior cruciate ligament reconstruction with autograft compared with allograft. *J Bone Joint Surg Am*. 2009;91:2242-2250.
- Claiborne TL, Armstrong CW, Gandhi V, Pincivero DM. Relationship between hip and knee strength and knee valgus during a single leg squat. *J Appl Biomech*. 2006;22:41-50.
- Click Fenter P, Bellew JW, Pitts TA, Kay RE. Reliability of stabilised commercial dynamometers for measuring hip abduction strength: a pilot study. *Br J Sports Med*. 2003;37:331-334.
- Crossley KM, Zhang WJ, Schache AG, Bryant A, Cowan SM. Performance on the single-leg squat task indicates hip abductor muscle function. *Am J Sports Med*. 2011;39:866-873.
- Engelen-van Melick N, van Cingel RE, Tijssen MP, Nijhuis-van der Sanden MW. Assessment of functional performance after anterior cruciate ligament reconstruction: a systematic review of measurement procedures. *Knee Surg Sports Traumatol Arthrosc*. 2013;21:869-879.

14. Ferber R, Osternig LR, Woollacott MH, Wasielewski NJ, Lee JH. Bilateral accommodations to anterior cruciate ligament deficiency and surgery. *Clin Biomech (Bristol, Avon)*. 2004;19:136-144.
15. Frank B, Bell DR, Norcross MF, Blackburn JT, Goerger BM, Padua DA. Trunk and hip biomechanics influence anterior cruciate loading mechanisms in physically active participants. *Am J Sports Med*. 2013;41:2676-2683.
16. Fulcher ML, Hanna CM, Raina Elley C. Reliability of handheld dynamometry in assessment of hip strength in adult male football players. *J Sci Med Sport*. 2010;13:80-84.
17. Gagnier JJ, Morgenstern H, Chess L. Interventions designed to prevent anterior cruciate ligament injuries in adolescents and adults: a systematic review and meta-analysis. *Am J Sports Med*. 2013;41:1952-1962.
18. Gilchrist J, Mandelbaum BR, Melancon H, et al. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *Am J Sports Med*. 2008;36:1476-1483.
19. Gustavsson A, Neeter C, Thomee P, et al. A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2006;14:778-788.
20. Hagglund M, Atroschi I, Wagner P, Walden M. Superior compliance with a neuromuscular training programme is associated with fewer ACL injuries and fewer acute knee injuries in female adolescent football players: secondary analysis of an RCT. *Br J Sports Med*. 2013;47:974-979.
21. Hart JM, Ko JW, Konold T, Pietrosimone B. Sagittal plane knee joint moments following anterior cruciate ligament injury and reconstruction: a systematic review. *Clin Biomech (Bristol, Avon)*. 2010;25:277-283.
22. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2013;41:216-224.
23. Hewett TE, Myer GD. The mechanistic connection between the trunk, hip, knee, and anterior cruciate ligament injury. *Exerc Sport Sci Rev*. 2011;39:161-166.
24. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: part 1, mechanisms and risk factors. *Am J Sports Med*. 2006;34:299-311.
25. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33:492-501.
26. Hewett TE, Myer GD, Ford KR, Paterno MV, Quatman CE. The 2012 ABJS Nicolas Andry Award: the sequence of prevention: a systematic approach to prevent anterior cruciate ligament injury. *Clin Orthop Relat Res*. 2012;470:2930-2940.
27. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med*. 2009;43:417-422.
28. Hu J, Qu J, Xu D, Zhou J, Lu H. Allograft versus autograft for anterior cruciate ligament reconstruction: an up-to-date meta-analysis of prospective studies. *Int Orthop*. 2013;37:311-320.
29. Jacobs CA, Uhl TL, Mattacola CG, Shapiro R, Rayens WS. Hip abductor function and lower extremity landing kinematics: sex differences. *J Athl Train*. 2007;42:76-83.
30. Juris PM, Phillips EM, Dalpe C, Edwards C, Gotlin RS, Kane DJ. A dynamic test of lower extremity function following anterior cruciate ligament reconstruction and rehabilitation. *J Orthop Sports Phys Ther*. 1997;26:184-191.
31. Kivlan BR, Martin RL. Functional performance testing of the hip in athletes: a systematic review for reliability and validity. *Int J Sports Phys Ther*. 2012;7:402-412.
32. Lamblin CJ, Waterman BR, Lubowitz JH. Anterior cruciate ligament reconstruction with autografts compared with non-irradiated, non-chemically treated allografts. *Arthroscopy*. 2013;29:1113-1122.
33. Leys T, Salmon L, Waller A, Linklater J, Pinczewski L. Clinical results and risk factors for reinjury 15 years after anterior cruciate ligament reconstruction: a prospective study of hamstring and patellar tendon grafts. *Am J Sports Med*. 2012;40:595-605.
34. Limpisvasti O, ElAttrache NS, Jobe FW. Understanding shoulder and elbow injuries in baseball. *J Am Acad Orthop Surg*. 2007;15:139-147.
35. Lubahn AJ, Kernozek TW, Tyson TL, Merkitich KW, Reutemann P, Chestnut JM. Hip muscle activation and knee frontal plane motion during weight bearing therapeutic exercises. *Int J Sports Phys Ther*. 2011;6:92-103.
36. Madhavan S, Burkart S, Baggett G, et al. Influence of age on neuromuscular control during a dynamic weight-bearing task. *J Aging Phys Act*. 2009;17:327-343.
37. Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med*. 2005;33:1003-1010.
38. Mariscalco MW, Magnussen RA, Mehta D, Hewett TE, Flanigan DC, Kaeding CC. Autograft versus nonirradiated allograft tissue for anterior cruciate ligament reconstruction: a systematic review. *Am J Sports Med*. 2014;42:492-499.
39. Myer GD, Chu DA, Brent JL, Hewett TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clin Sports Med*. 2008;27:425-448, ix.
40. Myer GD, Martin L Jr, Ford KR, et al. No association of time from surgery with functional deficits in athletes after anterior cruciate ligament reconstruction: evidence for objective return-to-sport criteria. *Am J Sports Med*. 2012;40:2256-2263.
41. Myer GD, Sugimoto D, Thomas S, Hewett TE. The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. *Am J Sports Med*. 2013;41:203-215.
42. Nakagawa TH, Moriya ET, Maciel CD, Serrao FV. Trunk, pelvis, hip, and knee kinematics, hip strength, and gluteal muscle activation during a single-leg squat in males and females with and without patellofemoral pain syndrome. *J Orthop Sports Phys Ther*. 2012;42:491-501.
43. 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.
44. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med*. 2012;22:116-121.
45. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38:1968-1978.
46. Petersen W, Zantop T. Return to play following ACL reconstruction: survey among experienced arthroscopic surgeons (AGA instructors). *Arch Orthop Trauma Surg*. 2013;133:969-977.
47. Pinczewski LA, Lyman J, Salmon LJ, Russell VJ, Roe J, Linklater J. A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: a controlled, prospective trial. *Am J Sports Med*. 2007;35:564-574.
48. Sadoghi P, von Keudell A, Vavken P. Effectiveness of anterior cruciate ligament injury prevention training programs. *J Bone Joint Surg Am*. 2012;94:769-776.
49. Scott DA, Bond EQ, Sisto SA, Nadler SF. The intra- and interrater reliability of hip muscle strength assessments using a handheld versus a portable dynamometer anchoring station. *Arch Phys Med Rehabil*. 2004;85:598-603.
50. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. *Am J Sports Med*. 2009;37:246-251.
51. Shirey M, Hurlbutt M, Johansen N, King GW, Wilkinson SG, Hoover DL. The influence of core musculature engagement on hip and knee kinematics in women during a single leg squat. *Int J Sports Phys Ther*. 2012;7:1-12.
52. Smith HC, Vacek P, Johnson RJ, et al. Risk factors for anterior cruciate ligament injury: a review of the literature—part 2: hormonal,

- genetic, cognitive function, previous injury, and extrinsic risk factors. *Sports Health*. 2012;4:155-161.
53. Stearns KM, Powers CM. Improvements in hip muscle performance result in increased use of the hip extensors and abductors during a landing task. *Am J Sports Med*. 2014;42:602-609.
54. Sutton KM, Bullock JM. Anterior cruciate ligament rupture: differences between males and females. *J Am Acad Orthop Surg*. 2013; 21:41-50.
55. Willy RW, Davis IS. The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. *J Orthop Sports Phys Ther*. 2011;41:625-632.
56. Wingfield K. Neuromuscular training to prevent knee injuries in adolescent female soccer players. *Clin J Sport Med*. 2013;23: 407-408.
57. Wright RW, Huston LJ, Spindler KP, et al. Descriptive epidemiology of the Multicenter ACL Revision Study (MARS) cohort. *Am J Sports Med*. 2010;38:1979-1986.
58. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med*. 2007;35:1123-1130.

59. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med*. 2007;35: 368-373.

APPENDIX

Crossley Grading^a

Nonoperative Leg	Operative Leg		
	Poor	Fair	Good
Poor	3	1	0
Fair	2	1	2
Good	5	3	16

^aThe grading represents the lower of the 2 highest ratings on the 3 trials.