Following surgical anterior cruciate ligament (ACL) reconstruction, deficits of proprioception and strength have been widely reported.1-6 These deficits have been recorded from 6 weeks to 9 years postoperatively, placing increasing importance on the development of progressive functional rehabilitation programs.7,8 Exercise protocols commonly combine both uniplanar, nonweight bearing, open kinetic chain exercises and more functional, multiplanar, closed kinetic chain exercises.9-11 Coinciding with the more frequent use of closed kinetic chain exercises, there has been a large push to develop clinically relevant performance tests. This study evaluated the performance of an ACL reconstruction group and a control group during two functional tests.

**MATERIALS AND METHODS**

Two study groups were recruited for this investigation: an ACL reconstruction group and a control group. The study was approved by an institutional review board, and all individuals signed an informed consent form prior to participation.

The ACL reconstruction group consisted of 18 patients (13 men and 5 women) who underwent bone-patellar tendon-bone ipsilateral graft or quadruple semitendinosus/gracilis tendon graft and were at least 6 months postoperative (mean=58±19 weeks). Average patient age was 22.8±5.8 years, average weight 77.7±21.5 kg, and average height 176.3±10.1 cm. All patients had a KT-1000 (MEDmetric Corp, San Diego, Calif) side-to-side difference of ≤3 mm. Patients had no history of hip, knee, or ankle injuries within the past 6 months or any predisposing cardiovascular or cardiorespiratory conditions. All ACL reconstruction patients were cleared by a physician (D.L.J.) prior to participation in this study.

The control group consisted of 18 recreationally active individuals (10 men and 8 women) with no history of knee or lower extremity pathologies or any cardiovascular or cardiorespiratory conditions. Average age was 22.5±4.1 years, average weight 71.2±13 kg, and average height 172.5±8.4 cm. No significant differences existed between the groups for age or height; however, the ACL reconstruction group was heavier than the control group.

A repeated measures post-test only
control group design was used. The independent variables and respective levels were group (ACL reconstruction and control) and extremity (involved and uninjured). All testing was performed in the University of Kentucky Biodynamics Laboratory. Following a 5-minute treadmill warm-up, all individuals performed a step-up-and-over test and a forward lunge on the long force plate of the Neurocom SMART Balance Master (Neurocom Inc, Clackamas, Ore). The test order (step-up-and-over and forward lunge) and leg to be tested (left and right) were counterbalanced to prevent a learning effect.
To perform the step-up-and-over test, each individual started by standing with both feet stationary on the force plate. They then stepped with one leg (lead leg) up onto a box 12-in tall, which was also on the force plate. The lagging leg was carried up and over the box, landing on the surface opposite from the original starting position (Figures 1 and 2).

Three aspects of this test were analyzed: the lift-up index, movement time, and impact index. The lift-up index quantifies the maximum lifting (concentric) force exerted by the leading leg and is expressed as a percentage of the individual’s body weight. A higher lift-up index indicates a greater ability to produce force during a concentric quadriceps contraction. Movement time quantifies the number of seconds required to complete the maneuver, beginning with the initial weight shift to the non-stepping (lagging) leg and ending with the impact of the lagging leg onto the surface. Lastly, the impact index quantifies the maximum vertical impact force as the lagging leg lands on the surface.

Similar to the lift-up index, the impact index is expressed as a percentage of the individual’s body weight. The impact index measures the eccentric performance of the leg that is on the box. If an individual has a weak lead leg, a high impact index would be expected, because the individual would not be able to control the lowering of the lagging leg back onto the force plate. Conversely, an individual with a strong lead leg would be able to control the lowering motion more effectively, thus decreasing the force with which the lagging leg impacts the surface.

The forward lunge test was used to measure the movement characteristics as the individual started in a standing position, lunged forward with one leg, and then returned to the original standing position (Figures 3 and 4). The following dependent variables were measured with the forward lunge test: distance, contact time, impact index, and force impulse. Distance is the lunge length expressed as a percentage of the individual’s height. The larger the distance measurement, it is assumed the better the lunge leg is at controlling the weight of the individual. Also, a larger distance would indicate greater initial force production. Contact time (sec) is the duration that the lunge leg is in contact with the surface. A longer contact time would imply a slower movement, which is indicative of decreased functional ability. To perform more complex maneuvers, as well as quick movements associated with athletics, a shorter contact time with the ground is necessary. Impact index, again expressed as a percentage of the individual’s body weight, quantifies the maximum vertical force exerted by the step- ping leg onto the surface during the lunge landing. As with the step-up-and-over test, impact index indicates the eccentric ability of the non-stepping leg. The total work performed by the lunging leg during the landing and thrust phases of the movement is quantified by the force impulse. The force impulse is expressed in units of percentage of body weight (force) multiplied by the time the force is exerted in seconds. An individual with a high force impulse is one that produces a greater amount of force over a shorter period of time, which is indicative of improved functional ability.

Each test was performed three times with each leg, and the mean was used for analysis. Repeated measures analysis of variance (ANOVA) assessed differences in functional tests for the step-up-and-over test and the forward lunge test. Tukey post-hoc analyses were used to determine statistical significance and a probability level of <.05 was considered significant. All statistics were performed using SPSS 10.1 (Chicago, Ill).

**RESULTS**

On both the step-up-and-over and forward lunge tests, the control group demonstrated greater measures of functional ability than the ACL reconstruction group. Two of the three parameters measured during the step-up-and-over test indicated significant differences. A significant main effect was noted for the lift-up index for group (F[1,34]=4.049, [P=.043]), indicating that the control group produced more force during the initial step than the ACL reconstruction group (63.4% body weight versus 54% body weight). Movement time revealed a significant group×extremity interaction (F[1,33]=4.346, [P=.039]), indicating that the uninvolved extremity (1.3 sec) was slower than the involved extremity (1.1 sec) in the ACL reconstruction group (Figure 5). In short, when the ACL reconstruction individuals led with the involved leg, it took them longer to complete the maneuver. No significant differences were noted in the impact index measurements of this test.

Two of the four parameters measured in the forward lunge test revealed significant differences. Although no differences were noted between groups for lunge distance or contact time, significantly different results were noted for the impact index and force impulse. A significant main effect was noted for extremity (F[1,34]=7.300, [P=.011]) as well as a significant group×extremity interaction (F[1,34]=8.541, [P=.006]) for the impact index. The impact index was greater for the uninvolved leg (29.4% body weight) than the involved leg (23.7% body weight) during foot strike for the ACL reconstruction individuals (Figure 6).

During the forward lunge, the contralateral leg eccentrically controls the downward movement of the lunging leg. The significance of these results suggest decreased eccentric control for the ACL reconstruction group.
reconstruction leg. A significant main effect was noted for extremity (F[1,34]=10.33 [P=.003]) and a significant group×extremity interaction (F[1,34]=5.073 [P=.031]). The force impulse was greater for the uninvolved leg (88.6% body weights/sec) than the involved leg in the ACL reconstruction group (82.1% body weights/sec), indicating that the ACL reconstruction leg performed less work overall.

**DISCUSSION**

Many authors have addressed the varying aspects of functional ability following surgical ACL reconstruction.1-3,8,12-21 These parameters have been studied to evaluate the long-term outcome of the surgery and to develop functional clinical assessment techniques. Two main focuses of functional assessments are sensorimotor control and strength. The body’s ability to react to a stimulus, and to react with the appropriate force in the correct direction, is important in prevention of further injury.

As more research is performed following surgical ACL reconstruction, a noticeable shift has occurred from open kinetic chain tests to closed kinetic chain protocols. For the purpose of this discussion, open kinetic chain exercises are those in which the foot is free to move, such as a seated leg extension. Closed kinetic chain exercises are performed in a weight-bearing position in which the foot meets resistance, such as a squat, hop, lunge, step-up-and-over, etc. This shift in testing has occurred following a similar shift in postoperative knee rehabilitation, which now incorporates more functional closed kinetic chain exercises.9

Sensorimotor control in the open kinetic chain has been measured by a variety of techniques. One technique involves judging a given joint angle. This process evaluates an individual’s joint position sense, or his or her ability to know to what degree a joint is flexed. Barrett1 used joint position sense to evaluate sensorimotor control in patients following ACL reconstruction at a mean follow-up of 3.2 years. Patients indicated their perception of the degree of passive flexion to which the knee was placed by examiners. The results of this investigation revealed that the accuracy of sensorimotor control in knees after ACLr correlated well with function outcome (r=.81) and subjective patient satisfaction (r=.9).

Dvir et al5 also used joint position sense to measure sensorimotor control following ACL reconstruction. Participants were asked to reproduce test angles of knee flexion in four different modes of activity: passive, concentric, dynamic, and eccentric. No significant differences were recorded between the involved and uninvolved knees for these patients, whose mean time from surgery to testing was 12.2 months. Risberg et al3 evaluated sensorimotor control by measuring the threshold to detection of passive motion in both ACL reconstruction and healthy individuals. Patients who underwent ACL reconstruction were studied at mean 2-year follow-up, and the results suggest that sensorimotor control in an open kinetic chain returns to normal. Risberg et al3 indicated no significant differences between the ACL reconstruction and uninvolved knees, or between the ACL reconstruction group and the healthy control group.

Recent literature has demonstrated a shift to more functional, closed kinetic chain proprioceptive analysis. These closed kinetic chain protocols have produced varying results. Harrison et al15 investigated single-leg standing balance on a force
plate in patients 10-18 months following ACL reconstruction. Postural sway, which was determined by the dispersion from a mean center of pressure on a force plate, was used as the measure of standing balance. No significant differences were reported between the surgical and nonsurgical legs in both the eyes-open and eyes-closed tests. Hoffman et al\textsuperscript{16} reported similar results for static balance tests, but revealed significantly longer stabilization times for the ACL reconstruction group when responding to a random perturbation of the low leg.

Denti et al\textsuperscript{13} used the KAT 2000 (OEM Medical, Carlsbad, Calif) to measure static balance in bilateral support and unilateral support trials on an unstable surface. The surgical group, which consisted of patients with 5- to 8-year follow-up, scored significantly worse on bilateral and unilateral support trials. Colby et al\textsuperscript{2} reported significantly longer stabilization times for the involved leg compared to the uninjured leg in ACL reconstruction patients performing a 19-cm step-down onto a force plate.

Previous studies have reported that tests evaluating sensorimotor control performed in the open kinetic chain following ACL reconstruction produce results similar to preoperative levels.\textsuperscript{1,3,5} However, several authors have reported decreased sensorimotor control following ACL reconstruction when testing in the closed kinetic chain.\textsuperscript{2,13,15,16} One observation is that whether using an unstable surface, joint perturbations, or complex movements, the more demanding the test, the more apparent the deficits in sensorimotor control become.

Isokinetic strength training and assessment in the open kinetic chain is an accepted and integral component of postoperative rehabilitation. Clinically, patients are considered to have adequate strength to safely participate in unlimited activities when strength values of the involved leg are >85% of the uninjured leg.\textsuperscript{22} Significant strength differences, <80% of the uninjured leg, have been recorded 6 months postoperatively regardless of whether patellar tendon, semitendinosus, or semitendinosus and gracilis grafts were used for the reconstruction.\textsuperscript{23} Risberg et al\textsuperscript{2} evaluated isokinetic strength differences at 3 and 6 months and 1 and 2 years following ACL reconstruction. They concluded that quadriceps muscle performance may take up to 2 years to be fully regained. Jarvala et al\textsuperscript{18} reported significant isokinetic strength differences between the operated and contralateral limb in patients 5-9 years after ACL reconstruction.

Many functional tests have been used to evaluate strength following ACL reconstruction, including single-leg maximal hop, vertical jump, triple jump, drop jump, stairs hopple, figure-of-eight, shuttle run, carioca, timed hop, cross-over hop for distance, sit-to-stand, step-up-and-over, and a forward lunge.\textsuperscript{4,6,8,9,12,17,19-21,24,25} The best choice of functional tests is not clear when compared directly to values obtained with strength training. Wilk et al\textsuperscript{19} both reported that patients were able to score within 85% of the uninjured limb in single-leg hop tests, yet had quadriceps muscle weakness when measured isokinetically.\textsuperscript{6,19} Studies by Delitto et al\textsuperscript{12} and Greenberger and Paterno\textsuperscript{24} also indicated weak relationships between the isokinetic measures of concentric quadriceps peak torque and work when correlated with a single-leg hop and vertical jump tests. Conversely, Jarvala et al\textsuperscript{18} stated that isokinetic strength deficits correlated well to single-leg hop testing.

Isokinetic and functional testing each have a place during rehabilitation of the ACL reconstruction knee. Clinically, isokinetic strength guidelines for a patient’s release for full activities are widely accepted. Isokinetic testing is performed in the open kinetic chain in the frontal plane allowing accurate documentation of knee flexion and extension strength deficits. This practice is justified as isokinetic strength has been reported to have a strong correlation with subjective knee scores.\textsuperscript{6,18} However, activities performed in a closed kinetic chain involve not only the knee, but the hip and ankle as well. The interaction of the musculature above and below the knee is tested, giving clinicians a better idea of overall functional ability. Closed kinetic chain testing evaluates performance in all planes and simultaneously tests both strength and sensorimotor control.

The use of functional tests may be less taxing than eccentric isokinetic testing, which has been suggested to put harmful levels of strain on the ACL.\textsuperscript{26} Eccentric function of the lower extremity is important following ACL reconstruction, as it plays a role in daily activities of living, such as running, sitting down in a chair, and descending stairs. Yoon and Hwang\textsuperscript{27} stated that eccentric quadriceps strengthening is essential to restoring the functional capabilities of the ACL reconstruction knee; therefore, clinicians should use tests that evaluate this parameter of function. The step-up-and-over and forward lunge tests used in this investigation accurately and safely measure eccentric function of the ACL reconstruction leg. For both tests, this is accomplished by evaluating the impact index when the uninjured leg contacts the surface.

The question is not whether to use functional tests, but which tests to use at the different stages of postoperative rehabilitation. Pfeifer and Banzer\textsuperscript{25} have stated that “the choice of tests may influence the detection of positive/negative or false positive/negative results.” Davies\textsuperscript{10,11} developed a progressive functional testing algorithm to help clinicians with these decisions. The functional testing algo-
The functional tests are more challenging than the static loading tests.

The forward lunge and step-up-and-over tests are not maximal tests, such as the single-leg hop for distance or vertical jump; and therefore could be used in the basic kinesthetic segment of the functional testing algorithm. This segment usually is characterized by strength and motor control deficits during which maximal testing would not be recommended. Rudolf et al. reported that maximal tests, such as the single-leg hop test, were not recommended in non-coper ACL deficient patients due to increased quadriceps activation, and therefore, the possibility of increased anterior tibial translation. This same precaution must be adhered to in ACL reconstruction patients, as excessive anterior or translation can be damaging to the fresh surgical graft.

Chmielewski et al. evaluated patients with postoperative follow-up ranging from 1.5-3 months using the step-up-and-over test and three other force platform functional tests. For the step-up-and-over test, they reported significant differences in movement time similar to the results of this study. The authors also found a correlation between movement time and quadriceps strength of the involved leg, suggesting that increased quadriceps weakness results in increased anterior tibial translation. This increased time of movement led to a decrease in the amount that the knee was loaded. The authors reported that the peak of the horizontal ground reaction force during knee extension was significantly lower in the non-copers group, which also recorded the longest movement times. This indicates that by slowing the movement down, this group attempted to decrease the backwards acceleration of the body during knee extension, possibly reducing the load on the knee. The results from the current study revealed no such difference in either con-

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**What is already known on this topic**

- An important rehabilitation consideration is to achieve equal bilateral strength. This is difficult to obtain following ACL reconstruction.

**What this article adds**

- Assessment of functional performance using force platforms provides valuable information when comparing bilateral function.
- One implication from our results is that eccentric control needs to be stressed in rehabilitation programs.
tact time or lunge distance, therefore the ACL reconstruction and control groups created similar initial forces. Because the initial forces were the same, the increased impact index suggests that the ACL reconstruction group was not able to absorb force as well as the healthy control group.

Another possible explanation for the differences in impact index is in how the ACL reconstruction patients, either consciously or subconsciously, guarded their reconstructed knee. Figure 7 illustrates that the ACL reconstruction group not only had increased impact index values for the uninvolved leg, but also had decreased values for the involved leg. They shifted more of their weight to the uninvolved leg when lunging with the reconstructed leg, in an effort to decrease the impact forces on the involved knee. When lunging with the uninvolved leg, ACL reconstruction patients allowed more of the force to be absorbed by the healthy knee.

It took longer for ACL reconstruction patients to complete a step-up-and-over test when the involved leg was compared to the uninvolved leg. During the forward lunge, more force was produced when individuals led with the involved versus the uninvolved leg, suggesting that eccentric control was compromised with the ACL reconstruction limb. The step-up-and-over test and forward lunge are promising functional tests that can be incorporated as rehabilitation and evaluative tools. Both tests provide information for moderately challenging assessment of strength and sensorimotor control.

REFERENCES