[Physical Therapy]

Association of the Single-Limb Hop Test With Isokinetic, Kinematic, and Kinetic Asymmetries in Patients After Anterior Cruciate Ligament Reconstruction

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Background: Asymmetries persist after anterior cruciate ligament reconstruction (ACLR). Physical performance tests such as the single-limb hop test have been used extensively to assess return-to-sport criteria, as they reproduce dynamic athletic maneuvers.

Hypothesis: The single-limb hop is associated with muscle strength and kinematic and kinetic asymmetries in ACLR patients 6 to 9 months after surgery.

Study Design: Controlled laboratory study.

Methods: Twenty-two men with ACLR (mean age, 28.8 ± 11.2 years) at 6 to 9 months (mean, 7.01 ± 0.93 months) after surgery completed isokinetic testing in 3 velocities (120, 180, and 300 deg/s) and a kinetic, kinematic, and functional evaluation of the single-limb hop test. Pearson correlation coefficients were used to assess the relationship between the Limb Symmetry Index (LSI) of the single-limb hop distance and each of the outcome variables.

Results: There were significant positive correlations between the LSI of the single-limb hop distance and the LSI of the peak extension torque at 120 deg/s ($P = 0.044$, $r = 0.37$) and the peak extension torque at 180 deg/s ($P = 0.042$, $r = 0.38$) as well as a negative correlation with the peak flexion torque at 180 deg/s ($P = 0.043$, $r = -0.38$). The LSI of the single-limb hop test was not correlated with any kinetic or kinematic variable ($P > 0.05$).

Conclusion: The findings of the present study demonstrate that distance LSI of the single-limb hop test correlates with isokinetic extension peak torque LSI but not kinetic and kinematic asymmetry.

Clinical Relevance: The single-limb hop test can be used as an additional tool for the recognition of muscle strength asymmetries but not for kinetic or kinematic asymmetries 6 to 9 months after ACLR.

Keywords: anterior cruciate ligament reconstruction; hop tests; isokinetics; kinematics; kinetics

Returning athletes to competitive sports in a safe yet timely manner after anterior cruciate ligament reconstruction (ACLR) is a challenging task for rehabilitation professionals and orthopaedic surgeons. Current rehabilitation protocols are based on specific guidelines and objective criteria that allow progression from one phase to the next.[36] The goal of these protocols is to improve neuromuscular and biomechanical control[12,20,30,39] while maintaining knee joint stability for a safe return to preinjury activity level. Despite the use of structured rehabilitation protocols, asymmetries persist

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after ACLR.[26,39] Failure to successfully treat muscle asymmetries may compromise functional recovery[21] and increase the risk of reinjury.[34] Muscle strength is commonly evaluated by isokinetic devices. These have functional limitations and require expensive equipment not always available at physical therapy clinics.

To address these limitations, physical performance tests have been developed[9,13,24] that are able to identify side-to-side differences in dynamic tasks[25] and predict subsequent ACL injury.[27] The single-limb hop test has been used extensively for the assessment of return to sport because it has the advantage of reproducing dynamic athletic maneuvers.[29] The single-limb hop test can be used as a predictor of short-term dynamic stability of ACL-deficient knees.[11,22] After ACLR, the outcome of single-limb hop functional performance has been correlated with isokinetic muscle strength[28,31,37] and with deficits in performance.[22] However, studies have not investigated if performance asymmetries in the single-limb hop test are associated with kinematic and kinetic data asymmetries in ACLR patients. The Limb Symmetry Index (LSI), which quantifies functional performance recovery of the involved leg compared with the uninvolved leg, has been recently developed to assess performance asymmetries.[22] It is unclear if the LSI of the single-limb hop test can identify patients who exhibit large side-to-side muscle strength and kinematic and kinetic asymmetries. Answering this question is of direct clinical importance. If this simple and quick test can serve as an additional tool to identify asymmetries that are currently measured with equipment that is not always available to the clinician, testing could be improved.

Additionally, in recent years, the use of objective, high-fidelity equipment such as optoelectronic motion analysis to study the biomechanics of the single hop in ACLR patients has become more popular.[13,17,22,24] The collective evidence from these studies demonstrates that athletes recovering from ACLR have measurable asymmetries during performance of the hop test.[5] However, no studies have investigated if the performance LSI of the single-limb hop test is associated with kinetic and kinematic asymmetries that are commonly present in ACLR patients. The purpose of this study was to assess the correlation between functional asymmetries of the single-limb hop test with biomechanical and strength asymmetries. We hypothesized that the single-limb hop test is associated with muscle strength, kinetic, and kinematic asymmetries.

MATERIALS AND METHODS

To have a homogenous study group and prevent possible bias that would affect the results, strict selection criteria were used for the study sample. All patients had a complete, unilateral, isolated ACL tear, ACLR with a single bone–patellar tendon–bone (BPTB) autograft in the past 6 to 9 months, no previous injury in either lower limb, male sex, a minimum activity level of 4 as measured by the Tegner activity score, and the ability to jog without a brace. We chose to use a homogenous sample with all patients being male and having undergone surgery with BPTB graft by the same surgeon (ADG), as sex[1] and graft[35] may affect outcomes after ACLR and subsequently may affect hop performance. Exclusion criteria for the ACLR patients included orthopaedic or musculoskeletal conditions affecting the hip or ankle joints of either lower limb, existing or previous injury to the contralateral knee, collateral or posterior cruciate ligament damage at the time of surgery, meniscal damage of more than 25%, serious coexistent chondral lesions (Outerbridge classification III or IV), complications after ACL surgery, persistent abnormal pain, swelling or laxity of the knee at the time of testing (anterior tibial translation more than 3 mm different compared with the healthy knee as measured by a KT1000 arthrometer), cardiorespiratory ailments, vestibular dysfunction, and patellofemoral joint irritability. In 3 patients, meniscal damage was found during the arthroscopic reconstruction, but the level of involved meniscus damage was much less than 25%; therefore, they were included in the study.

According to the above criteria, 22 men (Table 1) were included in this study. All patients completed a postoperative criterion-based rehabilitation program at outpatient physical therapy departments. As in similar research,[27] we did not control the rehabilitation program in an effort to increase the external validity of our findings. The physical therapists were provided with a rehabilitation protocol,[19] but compliance was not measured.

Testing Procedures

All participants were evaluated at the same location and by the same examiner. Participants were asked to wear comfortable clothing and their own athletic shoes, but no brace was allowed. Anthropometric data were collected, and limb dominance was determined by asking them about their preferred limb to kick a ball as far as possible.[22] All participants completed the testing procedure according to the steps below.

Self-Reported Questionnaires

Before the isokinetic and functional evaluation, participants completed the Tegner activity scale and the subjective form of the International Knee Documentation Committee (IKDC 2000).[16,33] The IKDC 2000 is a knee-specific, self-reported measure on a scale of 0 to 100, with higher scores representing better function.

Data processing of self-reported questionnaires. The IKDC Subjective Knee Evaluation Form is scored by summing the scores for the individual items and then transforming the score to a scale that ranges from 0 to 100. Scoring the IKDC was performed only on the questions answered, as in previous research.[2]

Isokinetic Strength

All participants were evaluated using an isokinetic dynamometer (BIODEX System III; Biodex Medical Systems, Shirley, New York) after 5 minutes of warm-up cycling at 40 to 50 rpm on a cycle ergometer. The range of motion (ROM) was set from 90° of flexion to full extension (0°). Isokinetic concentric evaluation

Table 1. Characteristics of ACLR patients

	ACLR
Number	22
Sex	22/22 male
Mean age in years (SD, range)	28.8 (11.2, 17.88-48.39)
Mean height in meters (SD, range)	1.77 (0.04, 1.72-1.86)
Mean body mass in kg (SD, range)	76.75 (10.53, 60-102)
Injured side	11 left, 11 right
Partial meniscectomy	3/22
Time from surgery to evaluation in months (SD, range)	7.01 (0.93, 6.06-9.43)
Time from injury to surgery in months (SD, range)	4.81 (3.88, 1.57-15.35)
Main sport participated before injury (n)	Soccer (11), basketball (2), running (1), skiing (2), indoor soccer (6)
Median Tegner score before injury (range)	7.5 (6-9)
Main sport participated at evaluation (n)	Running and swimming (15), running and cycling (2), soccer (5)
Median Tegner score at evaluation (range)	5 (4-7)
Mean IKDC (SD, range)	72.4 (8.8, 57.4-86.2)

ACLR, anterior cruciate ligament reconstruction; IKDC, International Knee Documentation Committee; n, number; SD, standard deviation.

was performed at 120, 180, and 300 deg/s. Although isokinetic testing at 60 deg/s provides valuable information on strength recovery after ACLR,[8] we elected to test only at higher speeds, as all ACLR patients had BPTB grafts and may be predisposed to patellofemoral pain.[14] All tests were performed on the contralateral limb first followed by the ACLR limb. Before the test, subjects performed a standardized trial session of 4 repetitions with submaximal effort to familiarize themselves with the equipment, followed by a 1-minute pause before the test, which consisted of 5 maximal repetitions. The exact same procedure was performed on the other limb.

Data processing of isokinetic strength. We used the mean peak torque value of the 5 repetitions to calculate the LSI as per the following formula: involved limb/uninvolved limb × 100%.[22]

Functional Evaluation

After the isokinetic evaluation, each participant rested for 5 minutes. The functional task used in this investigation was the single-limb hop test (Figure 1), as described by Noyes et al.[23] Reliability of the hop test is excellent, with intraclass correlation coefficients ranging from 0.92 to 0.96.[3,4] A hop was only deemed successful if the participants landed on 1 foot without losing their balance (ie, no extra hops for balance correction were allowed) until the investigator had marked the position of the heel on the floor. The test was performed until 3 successful hops were made with each limb. Each participant performed 3 practice and 3 real hops for each limb. Testing for each hop began with the contralateral limb, followed by the ACLR limb.

Data processing of functional evaluation.

Distance: The distance (in centimeters) was measured from the toe in the starting position to the heel in the landing position for the 3 successful hops and calculated by the protocol of Noyes et al.[23]

Kinematic: An 8-camera system (VICON, Oxford, United Kingdom) was used to capture (100 Hz) the coordinates of 16 reflective markers placed on selected bony landmarks of the lower limbs and the pelvis according to Davis et al.[7] The same clinician placed the skin markers on all subjects. Using the algorithms described by Davis et al,[7] we calculated the 3-dimensional joint angle for hip flexion, knee flexion, and ankle dorsiflexion. We only report sagittal plane joint angles here as this is the plane that absorbs most of the impact in forward hops. Before each kinematic and kinetic collection, calibration was made until the mean residuals that represent accuracy of the system were below 2.0 mm. Kinematic data were smoothened with a Woltring filter at a cutoff frequency of 6 Hz. The mean peak hip, knee, and ankle flexion angles

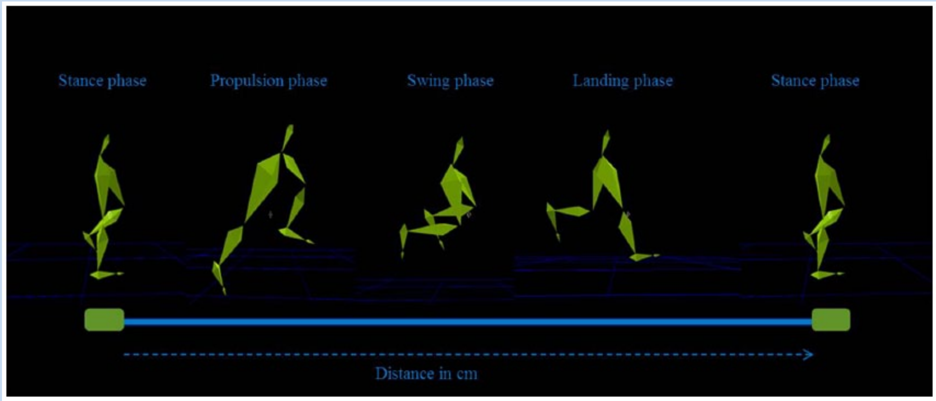

Figure 1. Single hop by 3-dimensional analysis.

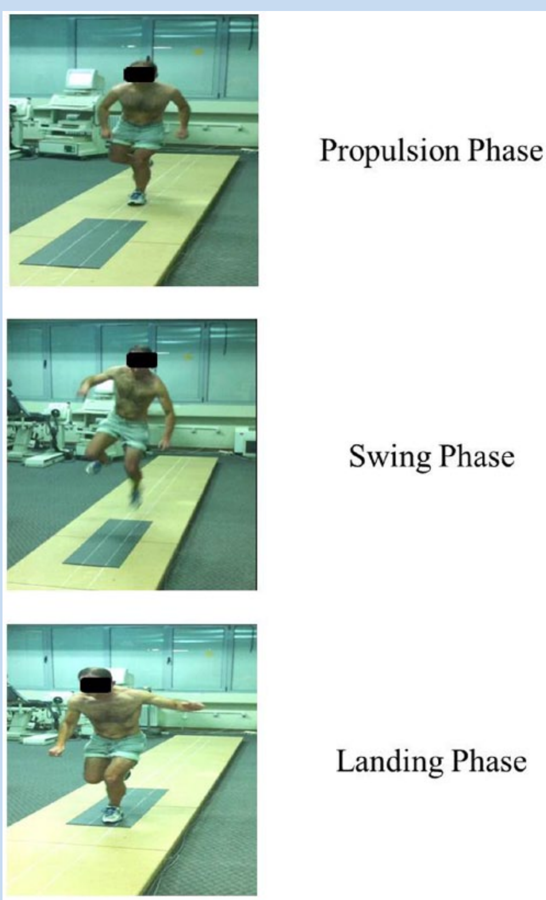

Figure 2. Single-limb hop test.

of the 3 successful trials during the landing phase of the hop test were used to calculate LSI and were entered into the statistical analysis.

Kinetic: The kinetic evaluation of both limbs was performed on a force platform (type 4060; Bertec, Columbus, Ohio). Kinetic data were collected at a sampling frequency of 1000 Hz and were synchronized with the Vicon system. Kinetic data of both limbs were analyzed for the landing phase of the single hop (Figure 2), and peak moments were calculated for the hip, knee, and ankle to determine the LSI.

Statistical Analysis

Means and standard deviations were calculated for all variables (Table 2). Pearson correlation coefficients were calculated between the LSI of the distance of the hop tests and the LSIs of the isokinetic peak torques, peak flexion angles, and peak internal moments.

Statistical analysis was conducted using SPSS version 17.0 (SPSS Inc, Chicago, Illinois). Statistical significance was established a priori at $P \leq 0.05$. Pearson r lower than 0.1 was defined as "none," higher than 0.1 and lower than 0.3 as "small," higher than 0.3 and lower than 0.5 as "medium," and higher than 0.5 as "large."[6]

RESULTS

Self-Reported Questionnaires

Overall, the subjective assessments revealed that the ACLR group had a mean IKDC score of 72.4 (range, 57.4-86.2). The median Tegner activity level score was 5 (range, 4-7) (Table 1).

Correlations

There were significant positive correlations (see Appendix 1, available at http://sph.sagepub.com/content/suppl) between the LSI of the single-limb hop distance and the LSI of the peak extension torque at 120 deg/s ($P = 0.044$, $r = 0.37$) (Figure 3), the peak extension torque at 180 deg/s ($P = 0.042$, $r = 0.38$) (Figure 4), and a negative correlation with the peak flexion torque at 180 deg/s ($P = 0.043$, $r = -0.38$).

The LSI hop distance was not correlated (see Appendix 1, available at http://sph.sagepub.com/content/suppl) with any kinetic or kinematic variable ($P > 0.05$). However, the LSIs for isokinetic knee extension at 3 speeds were all positively

Table 2. Means and standard deviations of the Limb Symmetry Index (LSI) of the tested variables

	Mean	Standard Deviation
LSI hop	82.0611968	12.39731574
LSI peak extension torque at 120 deg/s	75.6883419	12.07036012
LSI peak extension torque at 180 deg/s	79.699936	12.03985627
LSI peak extension torque at 300 deg/s	82.3978976	11.25493158
LSI peak flexion torque at 120 deg/s	103.4651499	12.26808831
LSI peak flexion torque at 180 deg/s	102.273578	10.72285154
LSI peak flexion torque at 300 deg/s	101.807184	26.98620428
LSI peak hip flexion angle	106.6923511	29.7548114
LSI peak knee flexion angle	93.5623442	41.8955178
LSI peak ankle dorsiflexion angle	88.1868927	32.26575499
LSI peak hip flexion moment	98.0875343	40.87205978
LSI peak knee flexion moment	56.21587	27.4004695
LSI peak ankle dorsiflexion moment	120.7350763	51.46211881

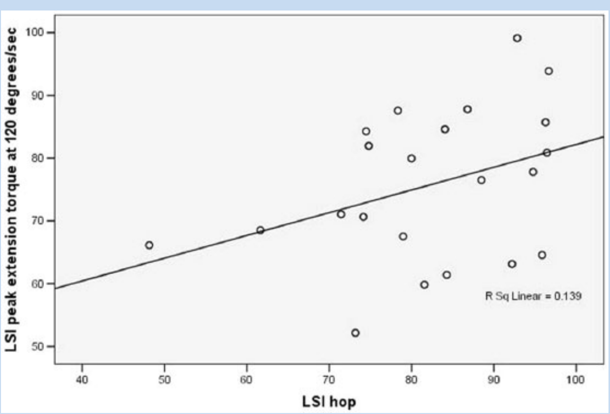

Figure 3. Correlation between the Limb Symmetry Indices of hop distance and peak torque at 120 deg/s.

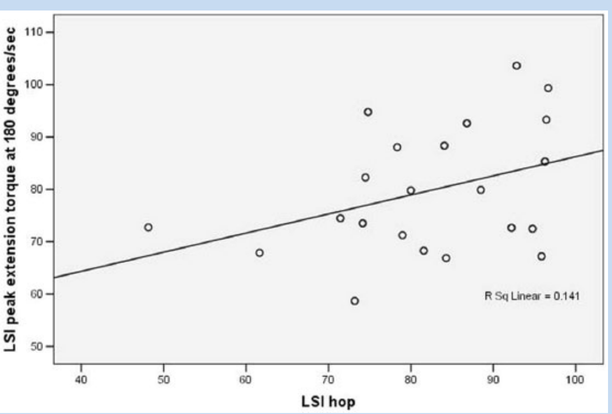

Figure 4. Correlation between the Limb Symmetry Indices of hop distance and peak torque at 180 deg/s.

correlated with each other with large effect sizes. The LSI for isokinetic knee flexion at 180 deg/s was positively correlated to the other 2 knee flexion speeds with medium to large effect sizes. The peak knee flexion angle was positively correlated to hip ($P = 0.02$) and ankle ($P = 0.026$) peak flexion angles with medium effect sizes. Additionally, the peak hip flexion moment was positively correlated to the peak ankle dorsiflexion moment ($P = 0.015$) with a medium effect size but negatively correlated to the peak knee flexion moment ($P = 0.016$), also with a medium effect size. Finally, the peak ankle dorsiflexion angle was positively correlated with peak knee flexion moment ($P = 0.031$) with medium effect size (see Appendix 2, available at http://sph.sagepub.com/content/suppl).

DISCUSSION

The main finding is that patients with ACLR and with BPTB graft had single-limb hop test asymmetries correlate moderately to knee extensor muscle strength asymmetries at velocities of 120 and 180 deg/s but not with kinematic or kinetic asymmetries. The practical implication for clinicians is that performance on the single-limb hop test may be an additional method for evaluating muscle strength asymmetries when isokinetic devices are not available. However, the single-limb hop test cannot be used for evaluating kinetic and kinematic asymmetries—a 3-dimensional motion analysis systems would be needed for this.

It is of great interest to rehabilitation professionals to identify easy, economic, safe, and reliable measurement tools for functional outcomes after ACLR that allow for the accurate measurement of neuromuscular and biomechanical deficits. The single-limb hop test can be easily used for in-field or clinical evaluation and constitutes an excellent measure of asymmetries in ACLR patients.[5] Furthermore, the single-limb hop test is a functional activity that simulates athletic maneuvers and provides objective information for existing neuromuscular deficits after ACLR.[28,29] The single-limb hop test is a reasonable substitute for isokinetic devices.

The correlations in the present study were moderate, suggesting the single-limb distance asymmetries may be influenced by other factors in addition to muscle strength, such as psychological confidence, balance, and proprioception.[27,34]

A novel finding of this study is that single-limb hop asymmetries were not correlated to kinetic or kinematic asymmetries during landing. This suggests that the compensatory mechanism after ACLR can be attributed to a much more complex process than to muscle. A potential explanation may be that isokinetic strength was measured as an open kinetic chain activity while landing from a hop is a closed kinetic chain activity. It is unclear if the findings would be different if strength was also measured as a closed kinetic chain activity.[10] The current study suggests that there are patients who have symmetrical muscle strength but land with kinetic and kinematic asymmetries because of faulty neuromuscular patterns or psychological factors.[5,18,34] This underscores the need for careful and objective evaluation of biomechanical asymmetries prior to clearing athletes for return to sport. Biomechanical asymmetries can predict index ACL injury[15] and reinjury in ACLR patients.[27] This study demonstrates that the single-limb hop test can detect the contribution of muscle strength asymmetries to the ability to generate power, but it cannot detect kinetic or kinematic asymmetries.

Hip, knee, and ankle flexion angle asymmetries positively correlate to each other. This suggests that asymmetry in one joint relates to asymmetry in the other major lower extremity joints. Clinicians need to pay particular attention to the joints distal and proximal to the knee, especially in those patients with persisting knee asymmetries. The rehabilitative solution may be restoring hip and ankle asymmetries.

In terms of joint moments, knee and hip asymmetries are negatively correlated. Clinical experience with ACLR patients indicates that patients who do not have full confidence or strength in the knee muscles tend to protect the knee from high flexion moments by distributing it to the hip, allowing successful landing without collapsing. However, this pattern is pathological and should be corrected prior to the athlete's return to sports to avoid reinjury to the knee. ACLR patients land with lower peak hip flexion compared with healthy controls.[38]

Several limitations for this study should be noted. Only male patients with ACLR using BPTB autograft were included. Outcomes cannot be generalized to all ACLR patients. Furthermore, we did not evaluate the isokinetic muscle strength at 60 deg/s, which is widely used. Additionally, we used only flexion angles and moments for the correlation with the single-limb hop test. Recent research has suggested that frontal plane knee motion is a predictor of ACL injuries.[32] The validity of the LSI for the kinematic and kinetic alterations after ACLR is still in question, as well as the correlation of the LSI of the hop tests to biomechanical variables in addition to peak flexion angles and moments. Finally, compliance to the rehabilitation protocol was not measured.

CONCLUSION

The findings of the present study demonstrate that performance LSI of the single-limb hop test correlates to isokinetic extension peak torque LSI but not to peak flexion angles and moment asymmetry. These results suggest that the single-limb hop test has the potential to identify muscle strength asymmetries but not kinetic or kinematic asymmetries 6 to 9 months after ACLR.

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