The Relationship Between Isokinetic Quadriceps Strength Test and Hop Tests for Distance and One-Legged Vertical Jump Test Following Anterior Cruciate Ligament Reconstruction

Renate Petschnig, MD[1]
Ramon Baron, MD[2]
Michaela Albrecht, MD[3]

Isokinetic measurements and functional tests are often used to assess function following knee ligament reconstruction using the opposite limb as a control. However, the question of whether the uninvolved leg may serve as a reference on functional tests has not been adequately answered. In particular, the one-legged rebound vertical jump has not been used to assess functional levels following surgery of the cruciate ligament. The purposes of this study were: 1) to determine whether the uninvolved leg is within normal range of an age- and weight-matched group, 2) to determine differences between the involved and uninvolved leg in patients after anterior cruciate ligament reconstruction, 3) to examine the relationship between knee extensor strength and four functional performance tests, and 4) to determine if the one-legged rebound vertical jump yields more information in the assessment of knee function than the other functional tests with respect to two time-frames. Fifty healthy subjects (group A, mean age = 28.1 years) and 55 anterior cruciate ligament patients (groups B and C) participated in dynamometric measurement, one-legged and two-legged vertical jump, and the single- and the triple-hop test. Mean time for testing was 13 weeks following surgery for group B (N = 30, mean age = 27.8 years) and 54 weeks following surgery for group C (N = 25, mean age = 29.9 years). Pearson product moment correlation coefficients between peak torque and single and triple hop were r = .45, r = .48, r = .51, and r = .55 for groups B and C, respectively. Pearson product moment correlation coefficients between peak torque and the height of the vertical jump was r = .51 for group C. Results for group A revealed limb symmetry indices of 95% or more on all functional performance and isokinetic tests. In group B, all patients showed a limb symmetry index of less than 85% on all tests. In group C, the index for the vertical jump was the only functional test that fell below the level of 85%. Regardless of whether the dominant or nondominant leg is involved, the uninvolved leg can be used adequately as a reference guide for outcome from rehabilitation using these measurements. The one-legged vertical jump test is capable of detecting functional limitations of the lower limb following knee ligament reconstruction up to 54 weeks postoperatively.

Key Words: *anterior cruciate ligament, muscle strength, functional tests, one-legged vertical jump*

[1] Coordinator in Physical Medicine, Rehabilitation, and Sports Medicine, Institute for Physical Medicine and Rehabilitation, Donau Hospital, Vienna, Austria
[2] Professor and Chairman, Institute of Exercise Physiology and Sports Medicine, Department of Prevention and Rehabilitation, University of Vienna, Auf der Schmelz 6, A-1150 Vienna, Austria
[3] Assistant in Physical Medicine and Rehabilitation, Institute for Physical Medicine and Rehabilitation, Donau Hospital, Vienna, Austria

Traditionally, evaluation following anterior cruciate ligament (ACL) reconstruction has focused on physical characteristics and measurements of knee stability, such as strength, laxity, and range of motion (26,27,29). Open kinetic chain evaluation has been used as the primary tool to assess a patient's strength, readiness to proceed to a higher functional level, and return to sports (26,27). Recently, reliance on such criteria has been refuted based on the lack of a strong relationship between the results of these measurements and the patient's perception of knee function (11) or readiness to return to sports (16). As a result, tests which are more specific to functional capacity have been designed.

Closed kinetic chain activities have been developed for patients as an alternative to evaluate strength and to determine the suitability of progress to a higher functional level (1,28). These activities or functional tests should be considered in the clinical examination of the patient for accurate assessment of knee function. Quantitative assessment using the hop tests for distance, with comparisons between the uninvolved and the involved leg, has been recommended as a useful method to evaluate functional limitations (3,17).

The hop test, developed by Daniel et al (6), was designed to assess both strength and confidence in the involved leg. Various one-legged tests for distance (3,20,30), two-legged tests, including the figure-of-eight test (23,30), the stair-running test (23,30), the carioca test (17), and the vertical jump (1,3) have also been established as measurements of the return to a functional level and the patient's perception of knee function (20,23). Patients with inadequate one-legged hop test indices were considered at an increased risk for giving way during functional activities (3,20,32). The two-legged tests provide a quantitative assessment of a "daily life" function (23), and the one-legged tests provide assessment of functional stability (strength/stability) of the involved leg (23). The one-legged hop tests for distance have been established as valid and reliable measurements (3,9,12,20,30).

Several authors have studied the reliability of the one-legged and two-legged vertical jump (3,5,19,24,33). The findings of Barber et al (3) and Risberg et al (24) did not support the reliability of the one-legged and two-legged vertical jump test. They found that a large percentage of normal subjects scored outside of the normal limb symmetry range, and that a significant difference existed between test and retest for the vertical jump. They stated that the vertical jump did not detect functional limitation in a reliable manner.

In contrast, some authors do support the reliability of the one-legged (19) and two-legged (5,33) vertical jump in healthy subjects when using a contact mattress (5,33) or a Kistler platform (19). Evaluation of two-legged tests also implies measurements of the uninvolved leg that may affect the test result.

Therefore, we are introducing a new test protocol consisting of one-legged vertical jumps measured over 10 seconds using a contact mattress interfaced to a computer called "Jumpergometer". Up to now, there have been no investigations on patients using the rebound one-legged vertical jump with maximal jump frequency on the Jumpergometer. Maximum jump frequency means as many jumps/minute as possible.

The purposes of this study with ACL patients were: *1)* to determine if the uninvolved leg may be assumed to be within a normal healthy range and may further be used as a reference for the purpose of making comparisons with respect to isokinetic measurement, the hop tests for distance, and the one-legged vertical jump test; *2)* to determine differences between the involved and uninvolved leg in patients after ACL reconstruction; *3)* to determine the relationship between peak torque of the quadriceps muscle and the one-legged hop tests for distance and the one-legged vertical jump test and to determine the relationship between the one-legged and two-legged vertical jump tests; and *4)* to determine if the one-legged rebound vertical jump yields more information in the assessment of knee function than the other functional tests with respect to two time frames following ACL reconstruction.

Hypotheses

Altogether, we had five hypotheses: we hypothesized that the uninvolved leg would measure in the normal range, regardless of dominance, with respect to peak torque (4), hop tests for distance, and the one-legged vertical jump test, and that the uninvolved leg can be used as a control.

As suggested by the literature (3,6,20), we hypothesized that the vertical jump test would produce similar results with regard to the limb symmetry index as well as for the hop test for distance, and that a limb symmetry index of 85% or greater would be within the normal range.

We further hypothesized that the one-legged vertical jump test would have the lowest sensitivity rate in detecting lower limb limitations (3,20), but that the one-legged vertical jump would be highly reliable (5,33).

The fourth hypothesis was that the contact time (landing and single-leg standing on the mattress) of the one-legged vertical jump on the involved leg would remain inadequate (less than 85% of the value of the uninvolved leg) for a longer amount of time than the height of the jump would remain inadequate (37).

Our last hypothesis was that there would be a correlation between the height of the one-legged vertical jump and peak torque performed at a slow speed (9,20,35).

MATERIALS AND METHODS

Subjects

Fifty healthy males with no prior history of knee injury (group A, mean age = 28.1 ± 6.4 years, mean height = 180.3 ± 4.9 cm, mean weight = 79.3 ± 6.9 kg) and 55 males with ACL reconstruction (group B, N = 30, mean age = 27.8 ± 9.0 years, mean height = 176.0 ± 6.9 cm, mean weight = 78.1 ± 11.6 kg, and group C, N = 25, mean age = 29.9 ± 5.8 years, mean height = 176.4 ± 6.9 cm, mean weight = 73.1 ± 8.7 kg) participated in the study.

To be included in the study, subjects (group A) had to meet the following criteria: only occasional exercise and no regular strength or endurance training and no prior history of pain, injury, or surgery to either hip, knee, or ankle. Persons who performed vigorous exercise one to two times/week or more were excluded. Leg dominance was assessed by asking the subject to kick a soccer ball twice which was rolling toward them (9). Eighty-eight percent were right-leg dominant.

The 55 patients in groups B and C had similar surgical ACL reconstruction procedures using an autograft with the middle third of the patella tendon. All underwent a similar postoperative rehabilitation program. The mean follow-up period was 12.9 ± 3.0 weeks for group B and 53.9 ± 13.2 weeks for group C. Patients were seen at that time because 16 weeks after surgery, the rehabilitation program is generally concluded and patients returned for clinical evaluation at a minimum of 9 month postoperatively. In 88% of the patients, the right leg was dominant and in 12% the left leg was dominant. Sixty-three percent had surgery of the right leg and 37% had surgery of the left leg. To be included in the study, patients had to meet the following criteria: no pain, no joint effusion, range of motion = 0–110°, and they could unilaterally mini-squat with a knee angle of 30° in the involved leg. The subjects had no prior knee surgery and no evidence of ligament injury in the opposite knee. Postoperatively, all patients were fitted with a brace (Don Joy, Carlsbad, CA) for 6 weeks. The range of motion was set at 0–60° for 2 weeks and 0–100° thereafter. Increased weight bearing as tolerated was permitted from the eighth day onward and full weight bearing from the 14th day onward.

Rehabilitation began on the day after surgery with passive, active-assisted, and active motion without resistance in the brace. All patients underwent an accelerated intensified rehabilitation program (28,32) from the second day postoperatively. Maintaining full knee extension and active quadriceps control was the first goal. Two weeks after surgery, we began with a program developed by Tippett and Voight (32). Their functional program of rehabilitation places primary importance on the three Cs: carriage, confidence, and control. The ability to shift weight, the ability to stand on one foot, and symmetry of movement are indicators of carriage. Confidence is indicated by the speed and deliberateness with which a skill is performed. Control is exemplified by precise performance of a given task which the patient no longer needs to think about in order to perform. Besides leg press exercises and exercises on the balance board, patients performed bilateral mini-squats with a range of 0–30°. In the final stages, patients also perform hopping and running, which facilitate feedback from the mechanoreceptors located in proximal and distal joint structures (32,38).

Instrumentation

Vertical jump The Jumpergometer (Fitronic, Bratislava) measures contact and flight times during rebound jumps by means of the special contact mattress interfaced to a computer. The measuring equipment consisted of a platform which functioned as the contact switch of an electric circuit. A computer permitted recording of the contact and flight time of every single jump. Using these data, the system calculates the height of a jump, mean acceleration during active phase of take-off, mean power in the active phase of take-off, velocity in the final moment of take-off, and mean power during the entire jump cycle (33). The test protocol used is a modification of the two-legged vertical jump test described by Tkac et al (33). All participants had to perform three 10-second jumping trials and were instructed to jump as high as possible and to keep contact with the platform as short as possible, as if it were a hot plate. Participants had to stand on one leg/two legs and perform vertical jumps and were required to land on the same leg/both legs. They were instructed to keep both hands on their hips to eliminate their use in generating momentum. The position of the upper body was also standardized (15), so that a minimum of flexion and extension of the trunk occurred. Thus, it is believed that the leg extensors were the main contributors to the performance in the jumps. A 2-minute recovery phase was inserted between the test series. Height in centimeters, contact time (seconds), and frequency (jumps/minute) were determined for the one-legged and two-legged vertical jump tests using the Jumpergometer. The best trial was used for data analysis. The parameters are expressed as means of the three highest values of the best trial. The best trial was used because the closest test-retest correlation is described by Tkac et al (33) between means of three maximum values.

Hop tests for distance Two one-legged functional tests, the single hop and the triple hop, were assessed for distance (cm) (9,23). Participants stood on one leg and performed one hop or three hops as far as possible along a straight line, landing on the same foot. They were instructed to keep both hands behind their backs to eliminate their use in generating momentum. This test was performed three times, and the average of the three values was calculated.

Dynamometric measurement Testing of the quadriceps muscle was performed at a velocity of 15°/sec in a concentric isokinetic mode on the Cybex 6000 (Brady, Vienna, Austria) in a seated position. We used a slow speed because in the literature (20) the best correlation between limb symmetry indices on peak torque and on functional tests was found at slow speeds. A 4-minute warm-up period on the cycle ergometer, Dynavit Meditronic 40 (Siemens, Vienna, Austria), at the level of one W/kg body weight at 70–80 rpm was performed prior to the test. After three warm-up repetitions at an intermediate speed (90°/sec), each participant performed three submaximal test trials (15°/sec) to get accustomed to the measuring procedure. Following a 2-minute rest period, three maximal concentric extensions were performed. Torque for angles between 20° and 100° were registered. Peak torque from this range of motion was taken as a criterion for the strength of the knee extensor muscles. The test series for the left and right extremities were separated by a 15-minute recovery period.

To obtain the limb symmetry index for the one-legged vertical jump, the single hop, the triple hop, and the peak torque, the mean of the involved limb was divided by the mean of the uninvolved limb, and the result was multiplied by 100. A limb symmetry index of less than 85% was considered inadequate for the vertical jump and for the hop tests for distance (3,6,20), and a limb symmetry index of less than 90% was considered inadequate for peak torque (2,4,14,16,21,25).

Procedure

In order to examine the reliability of the one-legged vertical jump on the Jumpergometer, group A was evaluated twice (test-retest) at a 72-hour interval. Attempts were made to retest each subject at the same time of day as their initial test. We followed the same procedure for testing that is described for vertical jump in this study. An intraclass correlation coefficient (ICC 2,1) was used to examine the reliability of the measurements of the jumping frequency, the contact time, and the jumping height obtained on two different days. The ICC for between-day comparisons for all measurements was above .89. The ICC values indicated that the measurements obtained in this study were reliable.

On three consecutive days prior to testing, all participants received instructions for the jump tests and were able to familiarize themselves with the protocol and practice under the direct supervision of a physical therapist. The test was carried out on the second day following the last set of instructions. All data for each participant were collected by the same physician. Variables included results of the one-legged and two-legged vertical jump, the single- and the triple-hop test, and the dynamometric measurement. The hop tests and the isokinetic test were separated by at least 48 hours of rest. The leg to be tested first was randomized as well as the order of testing. On the first day before testing, all patients filled in the Lysholm score (18) in order to record their self-assessment of parameters of limping, weight bearing, stair climbing, squatting, instability, pain, swelling, and locking. Maximum score was 100. Scores below 68 were considered poor; from 68–76, fair; from 77–90, good; and above 90, excellent (23). Prior to any testing, informed consent forms were signed by all participants.

Statistical Analysis

Statistical analysis conducted on Statgraphics (Version 5, Statistical Graphics Corporation) included mean values ±1 standard deviation, Wilcoxon's rank-sum test for paired samples, and Pearson product moment correlations. The level of significance was set at $p < 0.05$ for all statistical analysis. A binary table (20) was used to determine the specificity, the sensitivity, false-negative, and false-positive rates for the hop tests for distance, the vertical jump, and isokinetic testing.

RESULTS

The Wilcoxon test showed no significant differences among the groups concerning age, height, and weight. Results for group A (Table 1) revealed no significant differences between the dominant and nondominant leg on any of the tests. There were no significant differences for the uninvolved leg between group B and C and both legs in group A on any of the tests. There were significant differences between groups B and C on the involved leg with respect to the follow-up period ($p < 0.0001$), Lysholm score ($p < 0.0001$), functional tests ($p < 0.0001$), and dynamometric measurement ($p < 0.0001$) (Table 1). Results in group B indicate that a significant difference existed between the involved and uninvolved leg on all functional performance ($p < 0.0001$) and isokinetic tests ($p < 0.0001$). Results in group C revealed significant differences between the involved and uninvolved leg on isokinetic tests ($p < 0.02$), on vertical jump for height ($p < 0.0001$), and on the single- ($p < 0.008$) and triple-hop test ($p < 0.05$) for distance. Pearson product moment correlations between peak torque and six variables are given in Table 2. In addition, there was a correlation between the one-legged and two-legged vertical jump in groups A ($p < 0.001$, $r = .6932$), B ($p < 0.001$, $r = .7149$), and C ($p < 0.001$, $r = .7351$). The height of the one-legged vertical jump was found to be 50% of the two-legged vertical jump in group A. The height of the two-legged vertical jump was the sum of the one-legged jump height of the involved and uninvolved leg. The limb symmetry indices are outlined in Table 3. Table 4 shows the specificity, the sensitivity, false-negative, and false-positive rates for the hop tests for distance, the vertical jump, and isokinetic testing.

DISCUSSION

Results revealed that the peak torque of the extensor muscles of both legs in healthy men (group A) and the peak torque of the uninvolved leg in patients (groups B and C) is within normal healthy range (4). The results indicate that the uninvolved leg, regardless of dominance, can serve as a control when using dynamometric measurement in patients following knee ligament reconstruction. In our study, the distance of hopping in the uninvolved leg, regardless of dominance, in groups B and C did not differ from the distance of hopping in healthy men (group A). This suggests that the uninvolved leg may be used for reference when using hop tests for distance.

Variable	Group A		Group B		Group C		Differences B-C
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	
TL-VJ h (cm)	28.9	2.5	21.6	3.7	26.0	3.2	*
OL-VJ h non-dom (cm)	14.1	1.7					
OL-VJ h dom (cm)	14.3	1.3					
OL-VJ h uninvolved (cm)			14.1	2.7	15.1	2.1	NS
OL-VJ h involved (cm)			6.7	2.5	11.3	2.6	*
OL-VJ tc non-dom (sec)	0.285	0.04					
OL-VJ tc dom (sec)	0.284	0.03					
OL-VJ tc uninvolved (sec)			0.283	0.04	0.278	0.04	NS
OL-VJ tc involved (sec)			0.347	0.06	0.292	0.03	*
OL-VJ fr non-dom (j/min)	96.5	5.8					
OL-VJ fr dom (j/min)	95.8	4.6					
OL-VJ fr uninvolved (j/min)			98.8	7.4	97.5	6.1	NS
OL-VJ fr involved (j/min)			109.0	8.9	102.5	8.8	*
SH non-dom (cm)	190.0	16.4					
SH dom (cm)	195.0	15.9					
SH uninvolved (cm)			181.0	25.7	195.2	20.2	NS
SH involved (cm)			137.3	25.6	172.5	21.6	*
TH non-dom (cm)	570.4	62.0					
TH dom (cm)	479.7	59.3					
TH uninvolved (cm)			557.2	64.0	582.7	59.4	NS
TH involved (cm)			402.3	78.0	525.2	80.8	*
PT non-dom (Nm)	228.5	29.6					
PT dom (Nm)	234.1	31.2					
PT uninvolved (Nm)			222.0	35.0	229.0	34.3	NS
PT involved (Nm)			121.0	23.8	199.0	28.0	*
Lysholm (%)			86.8	5.5	95.7	4.0	*

$p < 0.05$ indicates a significant difference between groups B and C.
NS = Not significant; Dom = Dominant leg; Non-dom = Non-dominant leg; OL = One-legged; TL = Two-legged; VJ = Vertical jump; h = Height of a jump; tc = Contact time; fr = Frequency (jumps/minute); SH = Single hop; TH = Triple hop; PT = Peak torque.

TABLE 1. *Mean values of variables.*

Presently, normative data exist for the two-legged vertical jump (10) but not for the one-legged vertical jump. Therefore, we used the healthy males as a control group to determine if the uninvolved leg was within the normal range in groups B and C. This was found to be the case.

Factor	Group B (N = 30) Peak Torque	Group C (N = 25) Peak Torque
	r	r
Single hop	0.45*	0.51*
Triple hop	0.48*	0.55*
Vertical jump	0.01	0.51*
Contact time	0.27	0.17
Lysholm score	0.01	0.37
Follow-up period	0.04	0.29

$p < 0.05$ indicates a significant correlation.
Group B = Patients' follow-up period 13 weeks.
Group C = Patients' follow-up period 54 weeks.

TABLE 2. *Pearson product moment correlations between peak torque and six variables of the involved leg.*

Hence, we concluded that the uninvolved leg also can be used for reference when using the vertical jump in patients following knee ligament reconstruction. From these findings, we conclude, regardless of the leg injured, the uninvolved leg can be used as an outcome standard from rehabilitation. But, in accordance with Elliot (7), we suggest that if the uninvolved leg has a history of injury or surgery, the uninvolved leg can be used as a reference only with caution. The values of the uninvolved leg may either be lower as a result of decreased physical activity due to generalized immobility (7) or higher because of increased loading if the body weight is shifted to the uninvolved leg for a long time (22). In this case, standard values relative to age and gender are necessary for a meaningful interpretation of these tests.

Group	LSI VJ (%)		LSI SH (%)		LSI TH (%)		LSI PT (%)	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Group A (N = 30)	95.2	8.5	97.4	3.4	98.3	4.1	97.1	8.4
Group B (N = 30)	46.3	12.9	73.0	9.9	71.0	12.9	54.7	8.8
Group C (N = 25)	74.9	13.3	88.4	8.4	89.5	12.0	87.2	5.4

Limb symmetry indices (LSI) on vertical jump (VJ), single hop (SH), triple hop (TH), and peak torque (PT). For side-to-side comparison, deficits were expressed as a percentage of the results of the involved and uninvolved sides for patients (group B = 13 weeks and group C = 54 weeks following surgery) and as a percentage of the results of the nondominant and dominant sides for the control group (group A).

TABLE 3. *Mean values of variables.*

	Vertical Jump		Single Hop		Triple Hop		Peak Torque	
Specificity	96		98		96		94	
False-positive rate	4		2		4		6	
	Group B	Group C	Group B	Group C	Group B	Group C	Group B	Group C
Sensitivity	100	72	93	28	90	16	100	64
False-negative rate	0	28	7	72	10	84	0	36

TABLE 4. *Specificity, sensitivity, false-negative, and false-positive rates for the vertical jump, hop tests for distance, and the isokinetic testing. Results are percent of study population [group B (N = 30), group C (N = 25)].*

Results supported the hypothesis that the vertical jump test would produce similar results for the limb symmetry indices as the hop test did for distance, and that a limb symmetry index of 85% or greater would be within the normal range. Group A demonstrated that limb symmetry of equal to or greater than 90% was normal on all tests. In agreement with the literature, a limb symmetry index of less than 90% was considered inadequate for peak torque (2,4,14,16,21,25), and a limb symmetry index of less than 85% was considered inadequate for the hop test for distance (3,6,20).

All patients in group B and 64% of the patients in group C had an inadequate peak torque limb symmetry index (Table 3). This supports the findings of other authors (16,28, 31) who demonstrated that regaining quadriceps muscle strength after patellar tendon autograft reconstruction may take 1–2 years. Our findings do not support those of Shelbourne and Foulk (27), who reported that 50% of the patients had achieved 80% quadriceps muscle strength 4 months postoperatively. The differences between the two studies may be related to a faster velocity (180°/sec) used by Shelbourne and Foulk.

Isokinetic strength testing alone may provide insufficient data for the assessment of a patient's functional level. Several authors (9,17) previously stated that dynamic functional capacity cannot be ascertained from isokinetic strength performance. Since we know that the functions of standing, walking, and running are governed by the biomechanics of a closed kinetic chain, isolated muscle testing does not give enough information on a patient's functional ability.

Hop testing appears to be valuable as a general screening assessment. For group B, almost all of the patients had an inadequate limb symmetry index on the single hop and triple hop for distance, but in group C only 28% of the patients had an inadequate limb symmetry index on the single hop and 16% on the triple hop (Table 3). Thus, the hop test for distance had returned to normal in approximately 75% of the patients between week 13 and week 54. More than 1 year was needed before all patients had returned to adequate limb symmetry indices on the hop tests for distance after ACL reconstruction. Our study supports previous findings (16,23) which found a limb symmetry index for the hop test for distance within the normal range only 18 months after surgery. Aside from the horizontal jump test, the vertical jump test was found to be a good tool to develop standards for the evaluation of lower extremity strength and power and to assess a functional profile (9).

According to the literature (3,20), the one-legged rebound vertical jump test would have the lowest sensitivity rate in detecting lower limb limitations. The results of our study do not confirm this finding. All patients in group B and 72% in group C had an inadequate limb symmetry index on vertical jump (Table 3). Considering that 54 weeks after surgery 28% of the patients had an inadequate limb symmetry index for single hop and 16% had an inadequate limb symmetry index for triple hop, the one-legged vertical jump had a greater number of abnormal cases than the hop tests for distance. Therefore, we concluded that the one-legged vertical jump is sensitive enough to detect functional limitations of the lower limb following knee ligament reconstruction even greater than 54 weeks after surgery (Table 4). As already mentioned, this is in contrast to our hypothesis which was based on the findings of Noyes et al (20), who stated that vertical jump tests had the lowest sensitivity rates in detecting lower limb limitations, and

The one-legged vertical jump is sensitive enough to detect functional limitations of the lower limb following knee ligament reconstruction.

to the findings of Barber et al (3), who found a large percentage of normal subjects scored outside the normal limb symmetry range for the vertical jump test. This may be due to the different test protocols which are used in the various studies to evaluate the height of the jump. When measuring vertical height, the starting position must be repeatable as well as the method of measuring the height of a jump. Varied starting positions, especially the positions of knee flexion and the position of the arms, may influence the result. Normally, the patient performs only two jumps and the mean is calculated. According to Tippett and Voight

(32), a test-retest protocol has to be accurate and consistent. In our opinion, this can only be guaranteed by using a computer-interfaced system (19,32).

The sensitivity of the vertical jump decreases, however, when both legs are used. Therefore, it is better to perform the vertical jump on one leg. For the two-legged jump, patients may compensate with the uninvolved leg, and this may affect the test result. Therefore, standard values are necessary for meaningful interpretation of the test results of the two-legged vertical jump. Furthermore, the findings of Risberg et al (24) and Barber et al (3) do not support the reliability of the vertical jump. Unfortunately, there are different methods in the literature used to perform the vertical jump (3,8,15,19,24,32), and often the test description is inaccurate.

The Jumpergometer is a device for the accurate recording of vertical jump performance. Among other methods of vertical jump testing, Bosco et al (5) described a test based on repeated rebound vertical jumps. This test, which lasted 60 seconds, used a frequency of 60 jumps per minute. The reliability stated by the author was $r = .95$. However, an investigation of the test-retest correlation by Tkac et al (33) at different frequencies of jumps demonstrated a low reliability of measurement at frequencies of 60 ($r = .55$) and 80 ($r = .83$) per minute. A modified protocol described by Tkac et al (33) demonstrated a reliability of $r = .88$ when jumping with a maximal frequency (jumps/minute). In our study, the ICC for between-day comparisons on the one-legged vertical jump was above .89, which indicated good reliability. The results in pretests (test-retest) on healthy subjects showed that the height of the two-legged vertical jump is the sum of the jump height of both legs. In the patients, the height of the two-legged vertical jump is also the sum of the height of both legs (involved and uninvolved). Estimation of the two-legged jump height minus the height of the one-legged jump with the uninvolved leg yields the height of the jump in the involved leg. This is important in the early rehabilitation phase if patients are not allowed to perform one-legged vertical jumps or they simply refuse to use the involved leg for simple exercises.

The vertical jump provides an assessment of strength, power, and the patient's willingness to accept weight on the affected leg (32). To control normal physiologic loads during vertical jumps, agonist, antagonist, and synergistic muscle groups have to be activated. The dynamic stabilization process needs a co-contraction about the joint in as short a time as possible. The assessment of lower limb function encompasses many variables that may affect the test results, including neuromuscular coordination, strength, and confidence in the involved leg (34). Apart from the significantly lower height of the jumps of the involved leg in groups B and C, the results revealed a dramatically longer contact time and a higher frequency of jumps per minute for group B but not for group C. We attribute the contact time to dynamic stabilization (37). This indicated that not only the strength of jumping as demonstrated by the lower height of a jump may be affected but also the dynamic stabilization of the joint. The contact time at the 54-week follow-up was no longer significantly different between the involved and uninvolved leg, but the significant difference in the jump height remained. The improvement of the contact time may be attributed to the accelerated intensified rehabilitation program which began 2 weeks postoperatively and was designed to restore functional stability about the joint. The increased similarity over time of the contact times between the involved leg and the uninvolved leg is indicative of an improved dynamic stabilization. However, we might attribute the differences in the heights of the jumps to impaired strength. This statement is supported by our last hypothesis that there is a significant correlation between the peak torque and the height of a jump on one-legged vertical jump in group C. Thus, during rehabilitation, the parameter's height of a jump and contact time may help to determine whether stabilization or strength of jumping or both are impaired.

Several studies (3,9,16) examining the relationship between knee extensor strength and functional performance found a low correlation between isokinetic testing and functional tests but no significant correlation between isokinetic testing and vertical jump. Results of other investigations (13,36) demonstrated significant positive correlations between kinetic parameters of the active muscle groups (knee extensors) and jumping height. A positive correlation between the jump height on vertical jump and the peak torque of the quadriceps muscle in male physical education students is reported by Jaric et al (13). This report is confirmed by our study, which showed a correlation between peak torque and jumping height on the vertical jump in groups A and C. The study by Jaric et al substantiates our findings that the height of the vertical jump can be attributed to the strength of the extensor muscles.

Clinical Relevance

1) Regardless of whether the dominant or nondominant leg is involved, the uninvolved leg can be used adequately as a reference guide for functional outcome measures in rehabilitation; *2)* The one-legged vertical jump is sensitive enough to detect functional limitations of the lower limb following knee ligament reconstruction even longer than 54 weeks after surgery; *3)* If patients, in the early phase of their rehabilitation, are not allowed to perform one-legged vertical jumps or they simply refuse to use the involved leg, the height of the involved leg can be calculated: $\text{Height}_{\text{involved leg}} = \text{Height}_{\text{two-legged}} - \text{Height}_{\text{uninvolved leg}}$ to assess functional limitation; and *4)* By measuring the parameters of jump height and contact time over the course of rehabilitation, it might be possible to determine whether stabilization, strength, or both are still impaired.

SUMMARY

Based on our findings, the uninvolved leg is in normal range, regardless of dominance, and can be used as a control for the hop tests for distance, the one-legged vertical jump test, and the isokinetic strength test. The vertical jump test produces similar results for the limb symmetry index as the hop test for distance, and a limb symmetry index of 85% or greater is within the normal range. The one-legged vertical jump is highly reliable. There is a correlation between the height of the one-legged vertical jump and peak torque performed at a slow speed. In contrast to our hypotheses, the one-legged rebound vertical jump test has the highest sensitivity rate in detecting lower limb limitations, and the contact time of the one-legged vertical jump on the involved leg does not remain inadequate for a longer time than the height of a jump. Based on our finding that 1 year after surgery, out of all functional tests, only the index for the vertical jump was less than 85%, we recommend that the one-legged rebound vertical jump test be used to assess a functional profile. The results of our study underscore that the one-legged rebound vertical jump yields more information in the assessment of knee function than the other functional tests, even more than 54 weeks after surgery. JOSPT

ACKNOWLEDGMENTS

We express sincere thanks to Daniel Rosenfels, PT, for his assistance.

REFERENCES

1. *Anderson MA, Gieck JHG, Perrin D, Weltman A, Rutt R, Denegar C: The relationships among isometric, isotonic, and isokinetic concentric and eccentric quadriceps and hamstring force and three components of athletic performance. J Orthop Sports Phys Ther 14(3):114–120, 1991*
2. *Bach BR, Jones GT, Sweet FA, Hager CA: Arthroscopy-assisted anterior cruciate ligament reconstruction using patella tendon substation. Am J Sports Med 22(6):758–767, 1994*
3. *Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W: Quantitative assessment of functional limitation in normal and anterior cruciate ligament deficient knees. Clin Orthop 255:204–214, 1990*
4. *Baron R: Normative data for muscle strength in relation to age, knee angle and velocity. Wiener Medizinische Wochenschrift 145(22):600–605, 1995*
5. *Bosco C, Luhtanen P, Komi PV: A simple method for measurement of mechanical power in jumping. Eur J Appl Physiol 50(2):273–282, 1983*
6. *Daniel DM, Stone ML, Riehl B: A measurement of lower limb function. Am J Knee Surg 1:212–214, 1988*
7. *Elliot J: Assessing muscle strength isokinetically. JAMA 240:2408–2412, 1978*
8. *Eloranta V: Effect of postural and load variation on the coordination of the leg muscles in concentric jumping movement. Electromyogr Clin Neurophysiol 36:59–64, 1996*
9. *Greenberger HB, Paterno MV: Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. J Orthop Sports Phys Ther 22(5):202–206, 1995*
10. *Hamar D: Die Erfassung der maximalen alaktaziden Leistung mit Hilfe eines einfachen Sprungergometers. Presented at the Congress "Quantifizierung rehabilitativer Prozesse," Vienna, Austria, May, 1994*
11. *Harter RA, Osternig LR, Singer KM: Long-term evaluation of knee stability and function following surgical reconstruction for anterior cruciate ligament insufficiency. Am J Sports Med 16:434–443, 1988*
12. *Hu HS, Whitney SL, Irrgang JJ, Janosky J: Test-retest reliability of the one-legged vertical jump test and the one-legged standing hop test. Presented at the annual Combined Sections Meeting of the American Physical Therapy Association, San Francisco, CA, February, 1992*
13. *Jaric S, Ristanovic D, Crocos D: The relationship between kinetic parameters and kinematic variable in a complex movement. Eur J Appl Physiol 59(5):370–376, 1989*
14. *Kannus P: Isokinetic evaluation of muscular performance. Int J Sports Med 15: S11–18, 1994*
15. *Komi PV, Bosco C: Utilization of stored elastic energy in leg extensor muscles by men and women. Med Sci Sports Exerc 10(4):261–265, 1978*
16. *Lephart SM, Kocher MS, Harner CD, Fu FH: Quadriceps strength and functional capacity after anterior cruciate ligament reconstruction. Am J Sports Med 21(5):738–743, 1993*
17. *Lephart SM, Perrin DH, Fu FH, Geick JH, McCue FC, Irrgang JJ: Relationship between selected physical characteristics and functional capacity in the anterior cruciate ligament insufficient athlete. J Orthop Sports Phys Ther 16(4): 174–181, 1992*
18. *Lysholm J, Gillquist J: Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale. Am J Sports Med 10(3):150–154, 1982*
19. *Mair J, Mayr M, Müller A, Koller A, Haid C, Artner-Dwozak E, Calzolari C, Larue C, Puschendorf B: Rapid adaptation to eccentric exercise-induced muscle damage. Int J Sports Med 16:352–356, 1995*
20. *Noyes FR, Barber SD, Mangine RE: Abnormal lower limb symmetry determined by functional hop tests after anterior cruciate ligament rupture. Am J Sports Med 19(5):513–518, 1991*
21. *Noyes FR, Mooar PA, Matthews DS: The symptomatic anterior cruciate deficient knee. J Bone Joint Surg 65A: 154–162, 1983*
22. *Petschnig R, Baron R, Kotz R, Ritschl P, Engel A: Muscle function after endoprosthetic enplacement of the proximal tibia. Acta Orthop Scand 66(3):261–265, 1995*
23. *Risberg MA, Ekland A: Assessment of functional tests after anterior cruciate ligament surgery. J Orthop Sports Phys Ther 19(4):212–217, 1994*
24. *Risberg MA, Holm I, Ekland A: Reliability of functional knee tests in normal athletes. Scand J Med Sci Sports 5(1): 24–28, 1995*
25. *Sapega AA, Nicholas JA, Sokolow D, Saraniti A: The nature of torque "over-*

shoot" in Cybex isokinetic dynamometry. Med Sci Sports Exerc 14(5):368–375, 1982
26. Seto JL, Orofino AS, Morrissey MC, Medeiros JM, Mason WJ: Assessment of quadriceps/hamstrings strength, knee ligament stability, functional and sport activity levels five years after anterior cruciate ligament reconstruction. Am J Sports Med 16(2):170–181, 1988
27. Shelbourne KD, Foulk DA: Timing of surgery in acute anterior cruciate ligament tears on the return of quadriceps muscle strength after reconstruction using an autogenous patellar tendon graft. Am J Sports Med 23(6):686–689, 1995
28. Shelbourne KD, Nitz P: Accelerated rehabilitation after anterior cruciate ligament repair. Clin Orthop 227:238–250, 1988
29. Sherman MF, Lieber L, Bonamo JR, Podesta L, Reiter I: The long-term follow-up of primary anterior ligament repair. Am J Sports Med 19(3):243–255, 1991
30. Tegner Y, Lysholm J, Lysholm M, Gillquist J: A performance test to monitor rehabilitation and evaluate anterior cruciate ligament injuries. Am J Sports Med 14(2):156–159, 1986
31. Tibon JE, Antich TJ, Fanton GS, Perry J: Functional analysis of anterior cruciate ligament instability. Am J Sports Med 14:276–284, 1986
32. Tippett SR, Voight ML: Functional Progressions for Sport Rehabilitation, Champaign, IL: Human Kinetics Publishers, 1995
33. Tkac M, Hamar D, Komadel L, Kuthanova O: Measurement of anaerobic power of the lower limbs by a method of repeated vertical jumps. Sports Training Med Rehabil 1(3):317–325, 1990
34. Voight ML, Cook G: Clinical application of closed kinetic chain exercise. J Sport Rehabil 5(1):25–44, 1986
35. Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR: The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL reconstructed knee. J Orthop Sports Phys Ther 20(2):60–73, 1994
36. Wilson G, Murphy A: The efficiency of isokinetic, isometric and vertical jump tests in exercise science. Aust J Sci Med Sport 27(1):20–24, 1995
37. Zätterström R, Friden T, Lindstrad A, Moritz U: The effect of physiotherapy on standing balance in chronic anterior cruciate ligament insufficiency. Am J Sports Med 22(4):531–536, 1994
38. Zimny M: Mechanoreceptors in articular tissues. Am J Anat 182:16–32, 1988