A Vertical Jump Force Test for Assessing Bilateral Strength Asymmetry in Athletes

FRANCO M. IMPELLIZZERI1,2, ERMANNO RAMPININI1, NICOLA MAFFIULETTI2, and SAMUELE M. MARCORA3

1Human Performance Lab, Mapei Sport Research Center, Castellanza, Varese, ITALY; 2Neuromuscular Research Laboratory, Schulthess Clinic, Zurich, SWITZERLAND; and 3School of Sport, Health, and Exercise Sciences, University of Wales–Bangor, UNITED KINGDOM

ABSTRACT

IMPELLIZZERI, F. M., E. RAMPININI, N. MAFFIULETTI, and S. M. MARCORA. A Vertical Jump Force Test for Assessing Bilateral Strength Asymmetry in Athletes. Med. Sci. Sports Exerc., Vol. 39, No. 11, pp. 2044–2050, 2007. Purpose: To establish the validity and reliability of a new vertical jump force test (VJFT) for the assessment of bilateral strength asymmetry in a total of 451 athletes. Methods: The VJFT consists of countermovement jumps with both legs simultaneously: one on a single force platform, the other on a leveled wooden platform. Jumps with the right or the left leg on the force platform were alternated. Bilateral strength asymmetry was calculated as [(stronger leg − weaker leg)/stronger leg] × 100. A positive sign indicates a stronger right leg; a negative sign indicates a stronger left leg. Studies 1 (N = 59) and 2 (N = 41) examined the correlation between the VJFT and other tests of lower-limb bilateral strength asymmetry in male athletes. In study 3, VIFT reliability was assessed in 60 male athletes. In study 4, the effect of rehabilitation on bilateral strength asymmetry was examined in seven male and female athletes 8–12 wk after unilateral knee surgery. In study 5, normative data were determined in 313 male soccer players. Results: Significant correlations were found between VJFT and both the isokinetic leg extension test (r = 0.48; 95% confidence interval, 0.26–0.66) and the isometric leg press test (r = 0.83; 0.70–0.91). VJFT test–retest intraclass correlation coefficient was 0.91 (0.85–0.94), and typical error was 2.4%. The change in mean [−0.40% (−1.25 to 0.46%)] was not substantial. Rehabilitation decreased bilateral strength asymmetry (mean ± SD) of the athletes recovering from unilateral knee surgery from 23 ± 3 to 10 ± 4% (P < 0.01). The range of normal bilateral strength asymmetry (2.5th to 97.5th percentiles) was −15 to 15%. Conclusions: The assessment of bilateral strength asymmetry with the VJFT is valid and reliable, and it may be useful in sports medicine. Key Words: STRENGTH IMBALANCE, ISOKINETIC, ISOMETRIC, VALIDITY, RELIABILITY

In the assessment of lower-limb neuromuscular function, bilateral strength asymmetry usually refers to the relative difference in maximal strength between the two legs (6,9,10,12,16,20,24,26,30). Bilateral strength asymmetry of the knee extensors and flexors is widely used in sports medicine to quantify the functional deficit consequent to knee injury and/or surgery, to monitor the effectiveness of sport rehabilitation programs, and to decide whether an athlete is ready to return to competition (9,28). Furthermore, some studies suggest that bilateral strength asymmetry can be a risk factor for musculoskeletal injuries (11–13,20,30). Therefore, its measurement also may be useful to identify athletes at increased risk of incurring lower-limb injuries during training and competition.

Several methods have been proposed to assess bilateral strength asymmetry of the lower limbs (5,6,9,10,24,26,30). By far, the most common is isokinetic assessment, which quantifies bilateral strength asymmetry of specific muscle groups such as the knee extensors and flexors (10). However, it requires very expensive equipment, and its nature (open-chain movement and isokinetic muscle action) is not specific to most sport activities, which are characterized by closed-chain movements and fast muscle actions involving the stretch-shortening cycle (1). For these reasons, functional tests such as the one-leg hop test have been developed (5,6,24). These tests consist of measuring the difference between the injured and uninjured legs in the distance jumped horizontally. The advantages of these functional tests are the lack of expensive equipment and their specificity, because they require the stretch-shortening cycle and force production at relatively high speed. However, force production is not directly measured, and performance is influenced by other factors such as balance and the ability to coordinate a complex movement involving both lower and upper limbs. Furthermore, in our experience, some athletes are reluctant to perform the one-leg hop test during the early phases of sport rehabilitation for fear of reinjury. Therefore, psychological factors may also affect its performance. Indeed, this test is proposed for

Address for correspondence: Samuele M. Marcora, Ph.D., School of Sport, Health and Exercise Sciences, University of Wales–Bangor, George Building, Holyhead Road, Bangor, Gwynedd, LL57 2BZ, United Kingdom; E-mail: s.m.marcora@bangor.ac.uk. Submitted for publication March 2007. Accepted for publication July 2007.

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the assessment of bilateral strength asymmetry only in the final phases of sport rehabilitation (5,28).

In this study, we present a new vertical jump force test (VJFT) for the assessment of bilateral strength asymmetry developed in a large group of athletes (N = 451). This new method consists of vertical countermovement jumping with both legs without any arm movement, and it overcomes some of the previously mentioned shortcomings of the one-leg hop tests: no direct measurement of force production, the influence of balance, high mechanical load on the injured lower limb, and the influence of low- and upper-limb coordination. Furthermore, it requires only one force platform, thus halving the cost of equipment compared with a similar two-leg jump test recently proposed by Newton et al. (23).

The aims of this study were to establish the reliability of the VJFT, to explore its correlation with other measures of bilateral strength asymmetry of the lower limbs, to examine its sensitivity to changes induced by sport rehabilitation programs of knee-injured athletes, and to statistically define cutoff values for abnormal bilateral strength asymmetry of the lower limbs in male soccer players.

METHODS

Subjects and Study Design

The present investigation consisted of five separate studies. In the first study, we examined the correlation between the VJFT and the isokinetic knee extension test, which is the most commonly used method for the assessment of bilateral strength asymmetry. However, this test is open chain and isolates the knee extensor muscles. Therefore, we also examined the correlation between the VJFT and bilateral strength asymmetry calculated from an isometric leg press test. This test, like the VJFT, is closed chain and involves not only the knee extensors, but also the hip extensors and plantar flexors. In the third study, test–retest reliability of the VJFT was determined for protocols with different numbers of jumps. A fourth study examined the sensitivity of the VJFT to rehabilitation programs designed to reduce bilateral strength asymmetry in athletes recovering from unilateral knee surgery. The fifth study was conducted to provide preliminary normative data of bilateral strength asymmetry assessed with this new method by screening a large number of soccer players.

Before participating in these studies, all subjects (N = 451) gave their written informed consent. All studies were approved by the independent institutional review board of MAPEI Sport Research Center, according to the Guidelines and Recommendations for European Ethics Committees by the European Forum for Good Clinical Practice. Data collection started in 2002 and finished in 2006. All participants were already familiar with the countermovement jump test used in this investigation.

Study 1: correlation with isokinetic leg extension test. Fifty-nine (age 26 ± 5 yr, height 180 ± 5 cm, body mass 79 ± 6 kg) male athletes participating in different sports (soccer, track and field, basket, fencing, and alpine skiing) were recruited for this correlational study. Subjects suffering from acute musculoskeletal injury were excluded from the study. Subjects visiting the laboratory once in the morning. During this visit, subjects performed both the VJFT and the isometric leg press test with at least 30 min of rest between the two tests. Testing order was randomly selected to avoid any order effect. Subjects were instructed to avoid strenuous exercise the day before testing.

Study 2: correlation with isometric leg press test. Forty-one (age 25 ± 4 yr, height 178 ± 5 cm, body mass 78 ± 5 kg) male athletes participating in different sports (soccer, track and field, basket, fencing, and alpine skiing) were recruited for this correlational study. Subjects suffering from acute musculoskeletal injury were excluded from the study. Subjects visited the laboratory once in the morning. During this visit, subjects performed both the VJFT and the isometric leg press test with at least 30 min of rest between the two tests. Testing order was randomly selected to avoid any order effect. Subjects were instructed to avoid strenuous exercise the day before testing.

Study 3: test–retest reliability. Reliability of bilateral strength asymmetry as measured by the VJFT was determined in 60 male subjects (age 25 ± 6 yr, height 177 ± 4 cm, body mass 76 ± 6 kg) participating in different sports (soccer, track and field, basket, fencing, and alpine skiing). Subjects suffering from acute musculoskeletal injury were excluded from the study. Repeated testing was completed in a gym. Subjects visited the facility on two consecutive days in the morning, 2–4 h after a light breakfast.

Study 4: effect of sport rehabilitation. Five male soccer players (age 23 ± 2 yr, height 179 ± 4 cm, body mass 76 ± 5 kg), one female fencer (age 23 yr, height 168 cm, body mass 53 kg), and one female volleyball player (age 19 yr, height 175 cm, body mass 61 kg) participating in individualized rehabilitation programs after unilateral anterior cruciate ligament reconstruction were recruited for this study. Bilateral strength asymmetry of the lower limbs was tested with the VJFT 8–12 wk after surgery (pretest). This corresponded to the start of the advanced activity rehabilitation phase according to the Wilk et al. (28) classification. Posttests were performed 7–9 wk later during the return to activity rehabilitation phase. The sport rehabilitation programs included open-chain isokinetic, closed-chain isotonic, and plyometric exercises and were performed in different rehabilitation centers. Subjects were tested at approximately the same time of the day, about 3 h after a light meal.

Study 5: normative data. The VJFT was administered to 313 male soccer players competing in Italy at professional, semiprofessional, and amateur levels (age 25 ± 4.1 yr, height 177 ± 5 cm, body mass 74 ± 7 kg) to provide preliminary reference values for bilateral strength...
asymmetry of the lower limbs. Subjects suffering from acute musculoskeletal injury were excluded from the study. However, most of these subjects had a history of previous mild to severe musculoskeletal injuries of the lower limbs. Participants were tested indoors at their usual training facility during the preseason training period (from July to September) and were instructed to avoid strenuous exercise for 24 h before testing.

Measurements

Vertical jump force test. Vertical peak force (N) produced by either the right or left leg during vertical countermovement jumping performed with both legs and without any arm movement was measured using a portable force platform (QuattroJump, Kistler, Switzerland) at a sampling rate of 500 Hz (Fig. 1). Each participant started from a stationary, erect position, with knees fully extended. The participant then squatted down to about 90° of knee flexion before starting the upward motion. Subjects were instructed to keep hands on the hips to prevent the influence of arm movements. The position of the feet was standardized during all tests at shoulder width. Subjects performed these countermovement jumps while standing with the leg being tested on the force platform and the contralateral leg placed on a wooden platform leveled with the force platform surface. The two platforms were positioned 1 cm apart to avoid contact, and the feet were placed at the same distance from this interplatform space (Fig. 1). Participants were carefully observed before and during the jumps to ensure that the proper placement and jumping technique were used, and only correct trials were accepted. Subjects performed a total of 10 maximal jumps, alternating the left and right legs (five jumps each), with 60- to 90-s rest periods between jumps. The starting leg (left or right) was randomly selected to avoid any order effect. The average of the three highest peak forces measured for each leg was used to calculate bilateral strength asymmetry. Before the VJFT, subjects performed a general warm-up consisting of jogging on a treadmill or on the field for 10 min, and two or three submaximal jumps as specific warm-up and practice. Verbal encouragement was provided during the test. The force platform was regularly checked for accuracy, linearity, and consistency over time in the loaded condition (5 min), using certified weights ranging from 20 to 200 kg, placed in the area of the force platform in which the foot was placed during the VJFT.

Isokinetic knee extension test. Maximal concentric strength of the knee extensor muscles was measured in open chain using an isokinetic dynamometer (Cybex Norm, Humac, CA) at angular velocities of 60 and 240° s⁻¹. After 10 min of warm-up cycling at 100 W, subjects were positioned on an adjustable chair and secured to the equipment with straps across the trunk, hip, and thigh. The axis of the knee joint was aligned with the axis of the dynamometer arm. An antishear system (Humac, CA) was also positioned on the tibia to limit shear stress to the knee. Range of motion was set at 10–90°. Before each test, the gravity-compensation procedure was done according to the manufacturer’s instructions. After five to six submaximal contractions, the subjects were instructed to push as hard as possible against a shin pad secured to the distal tibia. Subjects completed three maximal contractions at 60° s⁻¹ and then three maximal contractions at 240° s⁻¹ with either the left or right leg. The starting leg (left or right) was randomly selected to avoid any order effect. The average of the peak torques (N-m) measured during the three maximal trials of each leg was used to calculate bilateral strength asymmetry. To avoid artifacts, only peak torques in the load range were considered (8). Verbal encouragement was provided during the test.

Isometric leg press test. Similarly to Marcora and Miller (22), peak force (N) developed during closed-chain maximal isometric contractions was measured using a load cell (AIP, Varese, Italy) connected to an A/D converter (Muscle Lab, Rome, Italy) mounted on an horizontal leg press (Technogym, Gambettola, Italy) at a sampling rate of 100 Hz. The load cell was positioned in series with the sliding axis of the leg press so that the direct line of force was registered. Before each trial, the two chains fixing the load cell to the leg press were tensed to obtain a rigid system. Then, the load cell was reset to zero to negate the force produced on it by the two chains. The dynamometer was routinely calibrated using ISO-certified weights. The leg press back, on which the subjects were lying, was inclined 30° from the horizontal plane. The knee angle was set at about 100° and was controlled using an electronic goniometer (Muscle Lab, Rome, Italy). Before the maximal isometric contractions, subjects performed a general warm-up consisting of jogging on a treadmill or on the field for 10 min, and two to three submaximal isometric contractions as specific warm-up and practice. The participants then performed three maximal isometric contractions, with 2–3
min of recovery in between, with either the left or right leg. The starting leg (left or right) was randomly selected to avoid any order effect. Subjects were asked to exert force as hard and fast as possible for 5 s. During isometric leg press test, participants were verbally encouraged. The average of the peak forces measured during the three maximal trials of each leg was used to calculate bilateral strength asymmetry. Verbal encouragement was provided during the test.

Bilateral Strength Asymmetry Calculation

In the literature (19,20,30), relative lower-limb strength asymmetry is calculated in different ways: 1) (injured − noninjured)/injured × 100; 2) (right − left)/left × 100; 3) (stronger − weaker)/stronger × 100. The first method can be applied only to injured athletes and, therefore, was not used in the current study, which includes predominantly healthy subjects. The second method has the disadvantage of providing different values of relative asymmetry when using the right limb as numerator irrespective of its functional status (weaker or stronger). For example, an absolute strength asymmetry of 200 N in a subject with stronger right leg (right leg = 1000 N; left leg = 800 N) would correspond to +20%. If the same subject had a stronger left leg, the relative difference would be −25%. The third method does not suffer from the problem mentioned above, but it always gives positive values. This is a problem when calculating percentiles (skewed distribution) and reliability (there is the possibility that the strong leg will become the weaker one in a subsequent assessment). To overcome these shortcomings, in the present study we decided to calculate bilateral strength asymmetry according to the third method, but a negative sign (−) was arbitrarily assigned when the left leg was the stronger one, and a positive sign (+) was used when the right leg was the stronger one.

Statistical Analysis

Unless otherwise noted, all data are presented as mean ± one standard deviation (SD). The relationship between bilateral strength asymmetry measured by VJFT and bilateral strength asymmetry measured by isokinetic knee extension (study 1) and isometric leg press (study 2) was assessed by Pearson’s product–moment correlation. The following scale of magnitudes proposed by Hopkins (www.sportsci.org) was used to interpret the correlation coefficients: < 0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; > 0.9, nearly perfect. Test–retest reliability (study 3) was examined using two-way, mixed-effects, single-measure models of intraclass correlation coefficient (ICC: 3, 1), and typical standard error of measurement (14). Bland–Altman limits of agreement were also calculated (7). To establish the most practical number of jumps for the calculation of bilateral strength asymmetry, we assessed reliability on bilateral strength asymmetry, calculated not only considering all five jumps for each leg, but also considering only the first one, two, three, and four. The magnitude of differences between duplicate measurements was interpreted by reference to the within-group SD (differences greater than 0.2 SD are considered substantial) (15). The effect of sport rehabilitation on bilateral strength asymmetry of the lower limbs (study 4) was examined by Wilcoxon matched-pairs test (pretest versus posttest). For this statistical analysis, negative values (i.e., left stronger) were converted into positive values. A Wilcoxon test was also used to assess pre–post changes in mean peak force during the VJFT in both the injured and uninjured legs. Normative data collected in study 5 were checked for normality using the Shapiro–Wilk W test and are graphically presented using a frequency-distribution histogram. Normal range was defined by the 2.5th and 97.5th percentiles (2). The probability of type I error (alpha) was set a priori at 0.05 in all statistical analyses.

RESULTS

Study 1: correlation with isokinetic knee extension test. The mean peak torque of the stronger and weaker legs measured during the isokinetic knee extension test at 60°s−1 was 242 ± 59 and 222 ± 56 N•m, respectively. The mean peak torque of the stronger and weaker legs measured during the isokinetic strength test at 240°s−1 was 153 ± 37 and 143 ± 35 N•m, respectively. The mean peak force measured during the VJFT was 1069 ± 218 N for the stronger leg and 984 ± 200 N for the weaker leg. The correlations between bilateral strength asymmetry calculated with the isokinetic leg extension test and the VJFT were moderate but significant for both 60°s−1 (r = 0.48; 95% confidence interval: 0.26–0.66; P < 0.001) and 240°s−1 (r = 0.48; 0.26–0.66; P < 0.001).

Study 2: correlation with isometric leg press test. The mean peak force of the stronger and weaker leg measured during the isometric leg press test was 1318 ± 383 and 1214 ± 363 N, respectively. The mean peak force measured during the VJFT was 1057 ± 221 N for the stronger leg and 975 ± 181 N for the weaker leg. A significant and very large correlation was found between bilateral strength asymmetry calculated with the isometric leg press test and bilateral strength asymmetry calculated with VJFT (r = 0.83; 0.70–0.91; P < 0.001).

Study 3: test–retest reliability. The mean peak force measured during the first trial of the VJFT was 951 ± 114 N for the stronger leg and 887 ± 107 N for the weaker leg. The mean peak force measured during the second trial of the VJFT was 929 ± 128 N for the stronger leg and 869 ± 120 N for the weaker leg. Test–retest reliability of VJFT bilateral strength asymmetry is presented in Table 1. All residuals in the Bland–Altman plots showed no evidence of significant heteroscedasticity (R = 0.02). Changes in the means between test and retest were not substantial, because they were all lower than ± 1.52% (0.2 × within-group SD),
except for VJFT bilateral strength asymmetry calculated from only one jump for each leg. The best test–retest reliability was obtained using the mean value of five jumps per leg.

**Study 4: effect of sport rehabilitation.** There was a significant reduction in bilateral strength asymmetry of the lower limbs between pretest (23 ± 3%) and posttest (10 ± 4%) (P = 0.02). Whereas the mean peak force of the uninjured leg did not change significantly between pretest (938 ± 165 N) and posttest (998 ± 209 N) (P = 0.50), the mean peak force of the injured leg increased significantly from 725 ± 117 to 980 ± 145 N (P = 0.02). Despite being tested only 8–12 wk after surgery, the VJFT was well tolerated by these athletes, and no adverse events occurred during testing.

**Study 5: normative data.** The mean peak force of the stronger and weaker legs measured during the VJFT was 1036 ± 153 and 972 ± 141 N, respectively. The distribution of the individual strength asymmetry values calculated with the VJFT in 313 soccer players was normal (Shapiro–Wilk W = 0.995, P = 0.47). The normal range (95% reference interval) was −15.1% (2.5th percentile) and 15.0% (97.5th percentile). The average lower-limb strength asymmetry value was 0.8%.

**DISCUSSION**

We have presented a new method for the assessment of bilateral strength asymmetry of the lower limbs in athletes. With the VJFT, it is possible to directly measure the force produced by each leg during vertical countermovement jumping. The characteristics of this movement (stretch-shortening cycle, closed chain, and relatively high speed) are similar for most sport activities. Furthermore, the control of arm movement removes its influence on test results, which better reflect lower-limb function. These features of the VJFT ensure its content validity.

The results of the first study demonstrate a statistically significant correlation between the VJFT and the isokinetic leg extension test, the most common method used to quantify bilateral strength asymmetry of the lower limbs in athletes. However, the moderate correlation coefficient between these two tests (only 23% of variance in common) suggests that the VJFT and the isokinetic knee extension test are not interchangeable when assessing bilateral strength asymmetry. This is not surprising, because the isokinetic test isolates the knee extensors, and these, in turn, contribute to only 49% of the total positive work done during maximal vertical jumps (18). Indeed, the correlation between the VJFT and the isometric leg press test, which involves not only the knee extensors but also the muscles acting at the hip and ankle joints, was much more substantial, with 69% of shared variance. This suggests that these two tests measure the same construct, that is, bilateral strength asymmetry of the entire lower limbs. The remaining variance is likely to be explained by factors that influence vertical jump performance but not maximal isometric strength, such as the ability to use the stretch-shortening cycle potentiation during a countermovement jump (21), and rate of force development (22).

Similarly to our results, Newton et al. (23) have found a significant correlation between bilateral strength asymmetry calculated from their two-leg jump test and bilateral asymmetry calculated from their parallel squat test (R = 0.73, P < 0.01). On the contrary, they did not find any significant correlation with the isokinetic knee extension test at 60°s⁻¹ (R = 0.04) and 240°s⁻¹ (R = 0.55). The reason for such a low correlation at 60°s⁻¹ is not apparent. At 240°s⁻¹, however, the correlation coefficient found by Newton et al. (23) is similar to the significant one found in our study. Therefore, their lack of statistical significance may be related to a small sample size (N = 14) and consequent low statistical power. In conclusion, we suggest that open-chain, isokinetic tests should be used when the purpose of the assessment is to quantify bilateral strength asymmetry of specific lower-limb muscles such as the knee extensors and flexors. On the contrary, both the VJFT and other closed-chain tests provide a global measure of bilateral strength asymmetry, and they may be more functionally relevant to daily life and sport activities, because these require the coordinated action of many lower-limb muscles.

Because the best way to assess reproducibility of repeated measurements is a matter of debate, we assessed test–retest reliability using a variety of statistical methods. Our ICC (1,3) analysis suggests that bilateral strength asymmetry calculated from the VJFT is highly reliable (ICC = 0.91) (27). This value is similar to the ICC reported for bilateral strength asymmetry indirectly inferred from differences in one-leg hop test performance in healthy and injured athletes (0.81 < R < 0.98) (4,16). Surprisingly, to the best of our knowledge, there are no reliability studies of isokinetic tests of lower-limb bilateral strength asymmetry in healthy subjects. Therefore, it is not possible to make

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**TABLE 1. Test–retest reliability of the vertical jump force test.**

<table>
<thead>
<tr>
<th>Number of Jumps</th>
<th>Change in the Mean</th>
<th>Limits of Agreement</th>
<th>Typical Error</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>First 1</td>
<td>−0.20 (−2.20 to 1.80)</td>
<td>± 15.2%</td>
<td>5.5% (4.6 to 6.7%)</td>
<td>0.58 (0.28 to 0.72)</td>
</tr>
<tr>
<td>First 2</td>
<td>0.14 (−1.20 to 1.47)</td>
<td>± 10.1%</td>
<td>3.7% (3.1 to 4.5%)</td>
<td>0.77 (0.64 to 0.85)</td>
</tr>
<tr>
<td>First 3</td>
<td>0.20 (−0.83 to 1.23)</td>
<td>± 7.8%</td>
<td>2.8% (2.4 to 3.4%)</td>
<td>0.86 (0.77 to 0.91)</td>
</tr>
<tr>
<td>First 4</td>
<td>−0.13 (−1.10 to 0.83)</td>
<td>± 7.3%</td>
<td>2.6% (2.2 to 3.2%)</td>
<td>0.88 (0.80 to 0.93)</td>
</tr>
<tr>
<td>First 5</td>
<td>−0.40 (−1.25 to 0.46)</td>
<td>± 6.5%</td>
<td>2.4% (2.0 to 2.9%)</td>
<td>0.91 (0.85 to 0.94)</td>
</tr>
</tbody>
</table>

In parentheses are the 95% confidence intervals. ICC, intraclass correlation coefficient.
meaningful comparisons. However, VJFT test–retest reliability compares well with the ICC shown by Hsu et al. (17) for bilateral strength asymmetry of the knee extensors measured in stroke patients at 30°·s⁻¹ (ICC = 0.42) and 90°·s⁻¹ (ICC = 0.81). Because the results of ICC analysis are influenced by sample heterogeneity (3), we have also assessed the agreement between repeated measures of bilateral strength asymmetry calculated from the VJFT. Using the Bland–Altman 95% limits of agreement method (7), we found a nonsignificant bias and a random error of ±6.5%. Therefore, when using the VJFT for the assessment of bilateral strength asymmetry in individual athletes, changes > 6.5% would indicate a very high probability (97.5%) that a true change has occurred. Hopkins (14) argues that a limit of agreement of 95% may be too conservative and suggests that a change corresponding to 1.5 or 2 times the typical error can be acceptable. Therefore, changes > 4.8% (twice the typical error) may be a more realistic cutoff value to be used in sport rehabilitation practice. Nevertheless, the results of study 4 suggest that, even when using the most stringent 95% limits of agreement, the VJFT may be useful for monitoring longitudinal changes in bilateral strength asymmetry in individual athletes. Indeed, we measured individual reductions ranging from 8 to 21% in response to sport rehabilitation programs lasting 7–9 wk. The average reduction in bilateral strength asymmetry (13 ± 4%) is two times the random error, which suggests a good sensitivity (i.e., a high signal-to-noise ratio) of the VJFT. Although we used the mean value of five jumps for each leg to calculate bilateral strength asymmetry in our studies, the data in Table 1 suggest that, in clinical practice, an acceptable reliability might be achievable with only three or four jumps per leg.

To establish preliminary normative data useful for the diagnosis of abnormal bilateral strength asymmetry in athletes, we administered the VJFT to a large group of competitive male soccer players. From these data, we calculated a reference interval between -15.1% (left stronger) and 15.0% (right stronger). Values falling outside this interval can be considered abnormal and, interestingly, are very similar to the 15% cutoff value commonly used to define clinically relevant bilateral strength asymmetry with isokinetic and one-leg hop tests (5,6,12,25,29). Similar investigations need to be conducted in female subjects and athletes competing in other sports, to increase the external validity of these normative data. Furthermore, the significance of these VJFT cutoff values as a risk factor for sport-related injuries needs to be established with prospective epidemiological studies. In clinical practice, reducing the length and intensity of the warm-up should not reduce the usefulness of the normative data obtained in this investigation. Indeed, the well-established positive effect of muscle temperature on power production should affect both legs, thus leaving bilateral strength asymmetry unaltered.

In conclusion, the results of the present investigation suggest that the assessment of bilateral strength asymmetry with the VJFT is valid and reliable. Because the VJFT is performed with both legs, the mechanical load experienced by the injured leg is considerably reduced compared with the one-leg hop tests currently used for functional assessment of injured athletes in the advanced phases of sport rehabilitation. Indeed, the VJFT was well tolerated by our seven athletes tested only 8–12 wk after knee surgery, and it may be useful for monitoring injured athletes during the early phases of sport rehabilitation. Further studies with a large number of athletes recovering from lower-limb injuries are needed to confirm this possibility and to establish clinical guidelines for the assessment of bilateral strength asymmetry using this new method. Epidemiological studies are also necessary to explore whether abnormal VJFT asymmetry (> 15%) could predict future musculoskeletal injuries to the lower limbs in athletes.

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