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DETERMINATION OF FUNCTIONAL STRENGTH IMBALANCE OF THE LOWER EXTREMITIES

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ABSTRACT. Newton, R.U., A. Gerber, S. Nimphius, J.K. Shim, B.K. Doan, M. Robertson, D.R. Pearson, B.W. Craig, K. Häkkinen, and W.J. Kraemer. Determination of functional strength imbalance of the lower extremities. *J. Strength Cond. Res. 20(4): 971–977. 2006.*—The purposes of this study were (a) to determine whether a significant strength imbalance existed between the left and right or dominant (D) and nondominant (ND) legs and (b) to investigate possible correlations among various unilateral and bilateral closed kinetic chain tests, including a field test, and traditional isokinetic dynamometry used to determine strength imbalance. Fourteen Division I collegiate women softball players (20.2 ± 1.4 years) volunteered to undergo measures of average peak torque for isokinetic flexion and extension at $60°\cdot s^{-1}$ and $240°\cdot s^{-1}$; in addition, measures of peak and average force of each leg during parallel back squat, 2-legged vertical jump, and single-leg vertical jump and performance in a 5-hop test were examined. Significant differences of between 4.2% and 16.0% were evident for all measures except for average force during single-leg vertical jump between the D and ND limbs, thus revealing a significant strength imbalance. The 5-hop test revealed a significant difference between D and ND limbs and showed a moderate correlation with more sophisticated laboratory tests, suggesting a potential use as a field test for the identification of strength imbalance. The results of this study indicate that a significant strength imbalance can exist even in collegiate level athletes, and future research should be conducted to determine how detrimental these imbalances could be in terms of peak performance for athletes, as well as the implications for injury risk.

KEY WORDS. injury, performance, isokinetic, field test, softball

INTRODUCTION

Multiple contributing factors, such as handedness, previous injury, or specific sport demands, could result in the development of muscle strength imbalances among athletes. Such imbalances not only may affect performance but also could increase incidence of injury (1, 6, 15, 23). In contrast, a few studies have also indicated that there is no relationship between strength imbalances and injury (2, 3, 8, 20, 22). With such contradictions in the literature, it is important to gain more knowledge in the area of strength imbalance in athletes and its indication for sport performance and ability to predict injury. In addition, the common methodologies used to determine the aforementioned strength imbalances have mostly involved the use of expensive laboratory methods, principally isokinetic or isometric dynamometry. Therefore, it is important not only to investigate muscle imbalance, both contralateral and antagonist/agonist, but also to investigate the methods by which we measure these variables and how they may or may not relate to sport performance and injury risk.

A few studies have demonstrated that individuals have a dominant (D) limb that produces more force and power or performs more work. In one study investigating contralateral differences in competitive swimmers, it was reported that power output of the arms during simulated swimming exercise was significantly higher for the left arm, at 54.0 ± 3.87% of the total power output. The imbalance increased as the swimmers approached exhaustion and was higher in unilateral breathers (16). Another study revealed a significant difference of 11.6 ± 8.31% when comparing peak torque production of the hip abductors (10). Further, an important study investigating contralateral limb imbalances revealed that there was a trend for higher injury rates to be associated with knee flexor or hip extensor strength imbalances of 15% or more on either side of the body in female collegiate athletes (11). Therefore, contralateral strength imbalances, although not as commonly investigated as agonist/antagonist strength imbalances, could pose a similar risk for injury.

Lower-body strength differences with regards to knee flexor and extensor strength and correlation to hamstring injury have been reported in various athletes using isokinetic dynamometry (1, 4, 15). The knee flexor-extensor ratio is commonly reported because of a possible relationship to hamstrings and anterior cruciate ligament (ACL) injuries. For example, hamstrings to quadriceps torque ratio has been measured in gymnasts in an attempt to explain the comparatively high incidence of ACL injuries. The authors stated that the relatively weak hamstrings could be one cause of the increasing incidence of ACL injuries in that sport (18). Further, contralateral differences, expressed as the percentage difference between the right and left hip extensors, were predictive of whether treatment for low-back pain was required over the ensuing year (13).

Despite such research, the link between imbalance and injury remains inconclusive, with one study (2) of 102 Australian Rules football players finding no significant differences for any of the variables when comparing the injured and noninjured legs in players with unilateral hamstring strains ($n = 9$). Neither the injured nor the noninjured leg of injured players differed from the mean of left and right legs in noninjured players for any isokinetic variable. The hamstring to opposite hamstring ratios also did not differ between injured and noninjured players. A hamstring to opposite hamstring ratio of less than 0.90 and a hamstring to quadriceps ratio of less than 0.60 were not associated with an increased risk of hamstring injury. The authors' conclusion was that isokinetic dynamometry was not able to directly discriminate Australian Rules football players at risk for hamstring injury (2).

Isometric measures of hip and knee flexion and extension strength have been used to assess imbalances in track and field athletes, who were then followed over the subsequent 2 years. Among the 64 subjects, 24.2 percent had suffered from hamstring strains, and, when subjects were divided into injured and uninjured groups and compared using the various strength measures, the injured group had a greater bilateral imbalance, relatively weak hamstrings, and a lower knee flexion-extension ratio at the start of the study. The authors concluded that the imbalances were related to the occurrence of hamstring strains (23).

In another study involving track and field athletes, different methods of assessing muscle imbalance were compared, and it was revealed that, despite quite different protocols, isotonic, isometric, and isokinetic bilateral as well as flexion-extension imbalances could be detected and were comparable across methods even though absolute force measures were not (12). Few studies have investigated the relationship between quadriceps and hamstring strength index through open chain isokinetic testing and its relationship to closed kinetic chain tests, such as the single-leg hop (9, 19). Greenberger and Paterno (9) presented results demonstrating that isokinetic strength did not correlate to functional testing, specifically a 1-leg hop for distance. However, Sekiya et al. (19) indicated that there was a positive correlation between the hop index (mean distance hopped by the involved leg/mean distance hopped by the noninvolved leg) and muscle strength. Such contradicting findings give reason to further investigate the relationship between other closed chain tests and isometric dynamometry, which could equally determine possible strength imbalances among athletes.

The purposes of this study were: first, to determine whether a significant strength imbalance existed between the left and right or D and nondominant (ND) legs; and second, to investigate possible correlations among various unilateral and bilateral closed kinetic chain tests and traditional isokinetic dynamometry used to determine strength imbalance, as well as to evaluate the effectiveness of a simple field test (the 5-hop test) for possible validity in assessing contralateral lower-limb imbalance.

METHODS

Experimental Approach to the Problem

This study was designed to measure strength and power performance during bilateral and unilateral movements involving the lower extremities. During various performance tests, the contribution of each leg was discerned for subsequent comparison of left to right and D to ND legs for the purpose of examining imbalances between the legs. A cross-sectional design was implemented using female collegiate softball players as subjects. Testing was conducted over several sessions. Subjects were required to warm up by riding a stationary bicycle for 5–10 minutes. Any static stretching that subjects felt necessary to be done to assist them in performing the tests was also permitted. On the first day, back squat and vertical jump testing were completed, and on the second day, at least 3 days later, isokinetic testing was performed and 5-hop performance was measured.

Subjects

Volunteers from the university women's softball team competing in National Collegiate Athletic Association Division 1 were chosen to participate in this study. Subjects ranged in age from 18 to 23 years and had at least 1 year of weight training experience, with some having as many as 4–5 years (at the collegiate level of competition). The mean (*SD*) age, height, and weight of the subjects were 20.2 (1.4) years, 166 (6.7) cm, and 67.2 (9.1) kg, respectively. The procedures and possible risks and benefits were explained to all potential subjects, and they were asked to read and sign the informed consent document prior to participation. All procedures and the informed consent document were reviewed and approved by the Internal Review Board of the university.

Procedures

Squats. A Kistler in-ground force plate (Type 9281B, Kistler Instrument Corporation, Amhurst, NY) and a Kistler portable force plate (Type 9286A, Kistler) were sampled simultaneously for data collection. The force plates were connected to separate 8-channel charge amplifiers (model number 9865A, Kistler) and the Bioware software program (version 3.0 for Windows 95, Kistler) was used to record the vertical ground reaction force (VGRF) independently from each foot. Both force-measuring systems were calibrated and then checked for balance (i.e., equivalent measurement of known force) before each testing session.

Following the warm-up, each subject's weight was measured while the subject stood on a single force plate, and was recorded in newtons of force. Warm-up for the squat exercise was then performed, involving 1 set each of 8, 6, 4, and 3 repetitions at 60, 65, 70, and 75% of the subject's 1 repetition maximum (1RM), respectively, as estimated by current university weight room strength records. Sets were separated by a 2-minute recovery period. Subjects were then instructed to step off the force plate, and voltage channels were offset to 0. Subjects were then given a signal to step back onto the force plates to begin their squats. Three consecutive squats at 80% of 1RM were performed to parallel depth. Subjects would rerack the weight on the squat rack after finishing each set. Two minutes' rest between sets was enforced to give subjects proper recovery time. A total of 3 sets were performed at this load. The VGRF for each foot was recorded during both the concentric and eccentric phases of movement. Peak force (PF) for each repetition was recorded as the highest force output during the concentric phase. Average force (AVGF) was recorded as the average force output over the entire concentric phase.

Vertical Jump. Subjects performed a total of 6 jumps. Two jumps were double-leg vertical jumps (DVJ), and 4 were single-leg jumps (SVJ) (2 off the right leg and 2 off the left). For the DVJ, subjects stood erect on the force plates (configured as outlined above for squats) and performed a countermovement jump with maximal effort.

TABLE 1. Mean ± *SD* peak and average vertical force during back squat with comparisons for left vs. right and dominant vs. nondominant.

	Right leg (N)	Left leg (N)	Imbalance (%)	Dominant leg (N)	Nondominant leg (N)	Imbalance (%)
Peak	764 ± 78	789 ± 109	−3.16 ± 8.39	802 ± 103	752 ± 80*	5.94 ± 5.05
Average	642 ± 64	664 ± 98	−3.27 ± 7.34	674 ± 91	632 ± 69*	6.02 ± 3.80

* Significant difference ($p < 0.05$) between dominant and nondominant legs.

TABLE 2. Mean ± *SD* of peak and average vertical force during 2- and 1-leg vertical jump (VJ) with comparisons for left vs. right and dominant vs. nondominant.

	Right leg (N)	Left leg (N)	Imbalance (%)	Dominant leg (N)	Nondominant leg (N)	Imbalance (%)
2-Leg VJ						
Peak Force	761 ± 119	785 ± 116	2.97 ± 6.49	796 ± 118	750 ± 113*	5.68 ± 3.95
Average Force	482 ± 78	497 ± 77	2.76 ± 8.03	505 ± 73	474 ± 79*	6.28 ± 5.15
1-Leg VJ						
Peak Force	1.101 ± 190	1,141 ± 107	3.82 ± 10.73	1,167 ± 139	1,074 ± 155*	8.05 ± 7.16
Average Force	748 ± 102	787 ± 65	4.93 ± 9.67	794 ± 69	741 ± 95	6.67 ± 8.35

* Significant difference ($p < 0.05$) between dominant and nondominant force (N).

Subjects were allowed to use their arms to obtain additional upward momentum. Single-leg jumps were performed in the same manner for both right and left legs. The VGRF was recorded for later analysis, which involved calculation of the PF and AVGF as described for the squat test.

Isokinetic Testing. A Cybex Norm dynamometer (Cybex International Inc., Ronkoma, NY) was used to measure knee flexion and extension torque. The dynamometer was calibrated prior to each test session by attaching known weights to the calibration arm and verifying the torque measurement. Subjects were secured with straps over the shoulders and fastened midchest. The shin pad was adjusted to fit the subject comfortably, and the thigh strap was secured approximately 3 cm proximal to the quadriceps-patella tendon junction. Protocols were programmed into the computer prior to testing. Knee extension (IKE) and flexion (IKF) movements were performed at preset speeds of $60^\circ \cdot s^{-1}$ and $240^\circ \cdot s^{-1}$. Four sets of 3 repetitions with 2 minutes' rest between sets were performed. Protocols were completed for both right and left legs. All trials were randomized with respect to speed and leg tested first within each subject and from subject to subject. Peak torque was recorded for each repetition. Average peak torque of the repetitions (AVGPTQ) was calculated as the mean of the peak torques for each repetition of the set.

5-Hop Test. This test has not been described previously to our knowledge but is used in various forms in a range of sports. Markers were placed on the floor to give the starting position for the subjects. Beginning on both feet, subjects hopped out onto 1 foot and then performed 4 consecutive hops on 1 leg, landing on both feet on the fifth hop. Subjects attempted to maximize the distance covered. Distance hopped was measured in centimeters from the subject's starting point (toes) to the end point (heels). Three trials were performed for both right and left legs. Because this was a novel test, intraclass correlation was calculated to assess test reliability, and the result was 0.892.

Statistical Analyses

All data were initially analyzed using Microsoft Excel (Microsoft, Redmond, WA). Statistical analysis was completed using SPSS Version 10.0 (SPSS Inc., Chicago, IL). Right to left ratio of the various measures was determined using the formula (right leg score − left leg score)/right leg score × 100. Dominant to ND ratio of the various measures was determined using the formula (strong leg − weak leg)/strong leg × 100, which has been previously reported (8, 14, 23). Mean and *SD* were calculated for all variables. Repeated measures analysis of variance was used to determine whether significant differences existed between right and left or D and ND legs. Correlation coefficients using the Pearson method were used to evaluate relationships between D and ND imbalances determined by the various tests. The criterion for significance was set at $p \leq 0.05$.

RESULTS

Significant differences were found when comparing D and ND legs for all tests, except in AVGF production during single-leg jumps. However, no consistent difference was found in test performance when comparing left and right legs. In addition, some of the D:ND ratios were found to correlate between tests. The specific results are as follows.

Squats

There was no significant difference between right and left legs for either PF or AVGF during the squat. However, there was a significant difference between D and ND legs in PF and AVGF (Table 1).

Vertical Jump

There was no significant difference found between the right and left legs for DVJ in PF or AVGF (Table 2). However, there were significant differences between D and ND legs during DVJ in PF as well as in AVGF. The SVJ revealed no significant difference in PF or AVGF when

Table 3. Mean ± *SD* isokinetic knee extension and flexion peak torque at $60^\circ \cdot s^{-1}$ and $240^\circ \cdot s^{-1}$ with comparisons for left vs. right and dominant vs. nondominant.

	Right leg (Nm)	Left leg (Nm)	Imbalance (%)	Dominant leg (Nm)	Nondominant leg (Nm)	Imbalance (%)
$60^\circ \cdot s^{-1}$						
Flexion	93.4 ± 13.4	89.5 ± 14.8	3.28 ± 16.02	97.8 ± 12.4	85.1 ± 12.9*	13.00 ± 7.00
Extension	129.5 ± 13.0	133.1 ± 24.2	−3.18 ± 18.21	140.8 ± 15.8	121.8 ± 17.8*	13.51 ± 8.37
$240^\circ \cdot s^{-1}$						
Flexion	63.5 ± 13.0	56.3 ± 9.3	8.07 ± 19.99	65.6 ± 11.7	54.2 ± 8.5*	16.01 ± 13.65
Extension	82.3 ± 17.2	81.1 ± 12.7	−0.62 ± 17.33	87.8 ± 16.3	75.6 ± 10.6*	13.06 ± 8.13

* Significant difference ($p < 0.05$) between dominant and nondominant legs.

Table 4. Mean ± *SD* of hamstrings to quadriceps average peak torque ratios for left, right, dominant, and nondominant legs tested at $60^\circ \cdot s^{-1}$ and $240^\circ \cdot s^{-1}$. No significant differences were found between right and left or dominant and nondominant legs.

	Left leg	Right leg	Imbalance (%)	Dominant leg	Nondominant leg	Imbalance (%)
$60^\circ \cdot s^{-1}$	0.681 ± 0.092	0.726 ± 0.126	4.78 ± 15.64	0.697 ± 0.073	0.708 ± 0.119	−7.41 ± 18.91
$240^\circ \cdot s^{-1}$	0.705 ± 0.124	0.779 ± 0.131	7.33 ± 20.77	0.757 ± 0.128	0.721 ± 0.099	6.71 ± 22.68

Table 5. Results of 5-hop test reported as mean ± *SD* distance in centimeters with comparisons for left vs. right and dominant vs. nondominant.

Right leg (cm)	Left leg (cm)	Imbalance (%)	Dominant leg (cm)	Nondominant leg (cm)	Imbalance (%)
771 ± 106	781 ± 114	0.92 ± 5.34	792 ± 108	759 ± 110*	4.24 ± 2.61

* Significant difference ($p < 0.05$) between dominant and nondominant legs.

Table 6. Pearson correlation analysis ($n = 14$) for dominant to nondominant ratio in each test.*

	SQUAT-PK	SQUAT-AVG	VJBIPK	VJBIAVG	VJUN-IPK	VJUNAVG	IKF60	IKE60	IKF240	IKE240	HOP
SQUATPK	1.000										
SQUATAVG	0.947†	1.000									
VJBIPK	0.734†	0.500	1.000								
VJBIAVG	0.367	0.224	0.652‡	1.000							
VJUNIPK	−0.268	−0.176	−0.616	−0.680	1.000						
VJUNAVG	−0.054	−0.011	0.041	−0.062	0.893†	1.000					
IKF60	0.674‡	0.618‡	0.592	0.180	−0.011	−0.013	1.000				
IKE60	0.439	0.495	0.037	−0.333	0.650	0.646	0.532	1.000			
IKF240	0.418	0.410	0.768†	0.482	−0.444	−0.301	0.710†	0.168	1.000		
IKE240	0.231	0.018	0.550	0.043	−0.249	−0.052	0.327	0.259	0.374	1.000	
HOP	0.498	0.526	0.628	0.532	0.257	0.422	0.573	0.365	0.381	−0.147	1.000

* SQUATPK = squat peak force; SQUATAVG = squat average force; VJBIPK = 2-legged vertical jump peak force; VJBIAVG = 2-legged vertical jump average force; VJUNIPK = 1-legged vertical jump peak force; VJUNAVG = 1-legged vertical jump average force; IKF60 = knee flexion at $60^\circ \cdot s^{-1}$; IKE60 = knee extension at $60^\circ \cdot s^{-1}$; IKF240 = knee flexion at $240^\circ \cdot s^{-1}$; IKE240 = knee extension at $240^\circ \cdot s^{-1}$; HOP = 5-hop test.

† Correlation is significant at the 0.01 level (2-tailed).

‡ Correlation is significant at the 0.05 level (2-tailed).

comparing right and left legs. In addition, no significant difference was found in AVGF production between D and ND legs. However, there was a significant difference in PF between D and ND legs during SVJ.

Isokinetic Testing

Results of the isokinetic testing are presented in Table 3. No significant difference in AVGPTQ was found between right and left legs at either $60^\circ \cdot s^{-1}$ or $240^\circ \cdot s^{-1}$ for flexion or extension. In contrast, there was a significant difference between D and ND legs for AVGPTQ in flexion and extension at both $60^\circ \cdot s^{-1}$ and $240^\circ \cdot s^{-1}$. No significant difference was found in the hamstring to quadriceps strength ratio in either left to right or D to ND comparisons (Table 4).

5-Hop Test

There were no significant differences between the right and left legs in 5-hop performance. In comparison, there was a significant difference in 5-hop performance when comparing D and ND legs (Table 5).

Correlation Analysis

Pearson correlation analysis revealed significant relationships in D:ND imbalance for several tests, as presented in Table 6. Specifically, significant relationships were found between squat PF and squat AVGF, squat PF and DVJ PF, squat PF and IKF AVGPTQ at 60°·s^{-1}, and squat AVGF and IKF AVGPTQ at 60°·s^{-1}. With regard to vertical jump performance, a significant correlation was found between DVJ PF and IKF AVGPTQ at 240°·s^{-1}. The IKF AVGPTQ values at 240°·s^{-1} and 60°·s^{-1} were significantly correlated, but IKE at 240°·s^{-1} and 60°·s^{-1} were not significantly correlated.

DISCUSSION

This study assessed strength imbalances between the lower extremities through traditional, open kinetic chain laboratory techniques as well as more sport-specific, laboratory-based, closed kinetic chain testing protocols and a field test. Significant differences were found between D and ND legs for all variables measured in the tests performed, except AVGF for the SVJ. No significant differences were seen when comparing right and left legs.

The absence of strength imbalance when comparing right and left legs could be attributed to the fact that some people are right leg–dominant whereas others are left leg–dominant, therefore nullifying strength differences when these are averaged across the group. Of the subjects tested, all 14 subjects were right-handed throwers; however, 9 were considered right-handed batters, 4 were considered left-handed batters, and 1 was considered a switch hitter. Keeping this in mind, despite all subjects' being right-handed throwers, preferred leg side may be different based on preferred batting side. Dominance of a side could therefore still be attributed to repeat emphasis of 1 leg being a drive leg for hitting or baserunning; hence, the development of a D leg. In fact, there was considerable variation in right to left dominance across the various tests. The findings of this study are in contrast to those of 2 studies that found no significant bilateral strength differences in jumping track athletes, running track athletes, or elite basketball players (20, 22). This may be a result of the athletes' playing and training experience in softball, which does tend to emphasize 1 side of the body over the other in skills such as batting and baserunning. Because of limited research on bilateral strength differences in athletes, it is unclear whether these imbalances are a result of sport-specific training or of other factors such as difference in leg length or injury. Given the resistance training background of the athletes, it was surprising that such imbalances existed. It is an important finding of the study that even with extensive bilateral squat, vertical jump, and other leg extensor training, significant contralateral imbalances in strength persist. Without further research, it can only be hypothesized that the dominance of movement of 1 side of the body during skills training and competition perpetuates these imbalances, and specific resistance training targeting the weaker side may be required.

It was somewhat surprising to observe a difference in force production of around 6% during the back squat and DVJ. Both are very symmetric bilateral activities that the athletes have considerable experience in performing, but still a significant and meaningful difference was evident. When comparing D to ND for SVJ, the difference increased to around 8%, indicating considerable imbalance in power output as well as strength. The fact that SVJ reflected the imbalance observed in squat and DVJ provides support for the use of SVJ for assessing imbalance. The advantages are that this test could be performed with only 1 force plate, or perhaps by even less sophisticated measurement devices, such as a contact mat timing system or jump and reach equipment. However, this was not the purpose of this study, and further investigation into the use of jump height or flight time to assess imbalance would be required.

When comparing hamstring to quadriceps strength ratios, isokinetic testing is prevalent as the method to identify imbalances, typically in an effort to identify risk or recovery from injury (1–3, 6, 8, 9, 12, 21–23). This study revealed significant strength differences at both tested speeds (60 and 240°·s^{-1}) between D and ND legs for flexion and extension. However, no significant difference was found in hamstring to quadriceps ratio. This is similar to the data presented by Theoharopoulos et al. (22) who reported that no significant difference existed in flexor-extensor ratio of elite basketball players between contralateral limbs, therefore indicating that despite bilateral differences' being prevalent in these athletes, the agonist-antagonist relationship remains satisfactory.

In the past, open kinetic chain exercises were used to help determine an athlete's readiness for returning to play after injury (17). Isokinetic testing has been thought of as the primary assessment tool in helping to determine an athlete's progression after injury, mainly because it isolates the muscles more effectively (9, 12, 21). Recently, an increasing number of researchers have been pursuing the use of closed kinetic chain exercises or activities to determine this readiness or to assess an athlete's strength level, as closed kinetic chain movements are more functional in nature and more related to actions performed on the playing field (5, 7, 17).

Sekiya et al. (19) found positive correlations between hop index (mean distance hopped by the involved leg/mean distance hopped by the noninvolved leg) and muscle strength. The above study used subjects who had suffered ACL injuries and had received surgery, with an average time from surgery to testing of 24 months. Subjects began on 1 leg (the test leg) and hopped as far as possible, landing on the same leg. Greenberger and Paterno (9) also used a 1-leg hop test in a study that assessed knee extensor strength and hopping test performance. The hop protocol mirrored that used in the study of Sekiya et al. (19) and similarly found significant correlations between average torque for the D and ND legs and distance hopped. The current study consisted of healthy (injury-free) collegiate athletes completing a 5-hop test in which the athlete started on both feet, hopped out to land on 1 foot, and would then perform 4 consecutive hops (total of 5 hops), landing on both feet on the final hop. When comparing D:ND ratios, there were no significant correlations with imbalance determined by the 5-hop test or any other tests, but the low n size for correlation analysis may have been a factor. There were moderate relationships (0.257–0.628) with the squat and vertical jump force measures of imbalance, suggesting that this simple field test may have potential for assessment of leg strength imbalance. In particular, D:ND imbalance in the hop test was reflected in PF measured in the DVJ ($r = 0.628$) and PF and AVGF in the back squat ($r = 0.498$ and 0.526 respectively). Although these are only moderate relationships, it is notable that the essentially unilateral field test has some shared variance in terms of D:ND imbalance with the bilateral squat and jump tests. The positive though weak relationship with the unilateral jumps was surprising, given the apparent greater similarity of movement; anecdotally, however, the subjects had difficulty performing the SVJ, and this lack of familiarity may have masked D:ND imbalances. The D:ND imbalance in the hop test was also moderately and positively correlated with the D:ND imbalance measured for isokinetic knee flexion. Given the important role of the hamstrings in stabilizing the knee, and in particular in protecting the ACL, the hop test may prove a valuable field test for assessing hamstring functioning, and in particular for assessing imbalance between legs. We suggest that further research with larger subject numbers is necessary to more completely evaluate such potential, because a simple yet valid test would be of great benefit to the strength and conditioning specialist or clinician without access to multiple force plates or isokinetic dynamometers.

A significant correlation existed when comparing squat PF imbalance and AVGPTQ imbalance produced during isokinetic flexion at $60°\cdot s^{-1}$. This finding is helpful when looking at the speed of movement of the squat exercise, as squats tend to be performed relatively slowly. Additionally, significant correlations seen between PF imbalance of the DVJ and isokinetic flexion at $240°\cdot s^{-1}$ could be in large part because of the movement speed of the vertical jump. Most functional activities occur near $300°\cdot s^{-1}$ (9); therefore, testing at $240°\cdot s^{-1}$ could be used to correlate to functional movements.

This study revealed significant differences between D and ND limbs in isometric dynamometry as well as in laboratory and field tests that utilize less expensive and more readily available equipment. Although significant correlations were not found between such parameters as 5-hop distance and isometric dynamometry, all tests revealed significant bilateral differences in the athletes. These findings are important for several reasons. First, even athletes with extensive and quality strength and conditioning training backgrounds exhibit considerable imbalances in lower-limb strength and power performance. Second, when bilateral movements such as the back squat and DVJ are performed, force generation and contribution to the performance can be markedly different between the lower limbs. Third, simple field tests such as the 5-hop test and SVJ test can be used to discriminate unilateral performance and thus provide a measure of lower-limb strength imbalance.

Further research needs to be conducted to determine just how important it is for athletes to possess bilateral strength balance. Although significant differences were found among all tests conducted, it is still hard to determine how much more likely one might be to suffer injury because of that imbalance and how daily performance might be affected.

Practical Applications

A strength imbalance could possibly affect an athlete's performance either by increasing risk of injury or by limiting an athlete to favoring their stronger or D side. Such a limitation or preference is perceived as a weakness in sports such as basketball, softball, tennis, etc. where the ability to utilize both sides equally could enhance performance. Utilizing simple testing methods such as the SVJ or simple field based 5-hop tests could give strength coaches the ability to quickly determine whether an athlete is in need of a training program that emphasizes unilateral exercises in an effort to isolate each side for strength balance improvement. Also, such simple field tests appear to mirror the results of more clinical assessments and may be useful for monitoring recovery following lower-limb injury or surgery. Strength and conditioning specialists should be aware of the importance of assessing their athletes for lower-limb strength imbalance, as the difference may be much larger than expected. Remediation of such imbalance may improve performance and reduce injury risk.

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