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The Force-Vector Theory Supports Use of the Laterally Resisted Split Squat to Enhance Change of Direction

Chance Cooley,[1] Shawn R. Simonson,[2] and Derek A. Maddy[2]

[1]Crunch Fitness, Boise, Idaho; and [2]Department of Kinesiology, Boise State University, Boise, Idaho

Abstract

Cooley, C, Simonson, SR, and Maddy, DA. The force-vector theory supports use of the laterally resisted split squat to enhance change of direction. *J Strength Cond Res* 38(5): 835–841, 2024—The purpose of this study was to challenge the conventional change of direction (COD) training methods of the modern-day strength and conditioning professional. A new iteration of the modified single-leg squat (MSLS), the laterally resisted split squat (LRSS), is theorized to be the most effective movement for enhancing COD performance. This study lays out a rationale for this hypothesis by biomechanically comparing the LRSS, bilateral back squat (BS), and MSLS with a COD task (90-degree turn). One repetition maximum (1RM) for LRSS, MSLS, and BS was measured for 23 healthy active female subjects. Peak ground reaction forces (GRF) for the dominant leg were recorded when performing COD and the LRSS, MSLS, and BS at 70% 1RM. Peak frontal plane GRF magnitude and angle were calculated for each task and submitted to repeated measures ANOVA. Peak GRF magnitude was significantly larger for COD (2.23 ± 0.62 body weight) than the LRSS, MSLS, and BS ($p \leq 0.001$). Peak GRF angle was not significantly different between COD and the LRSS ($p = 0.057$), whereas the MSLS and BS ($p < 0.001$) vector angles were significantly greater than COD. In this application of the force-vector theory, the LRSS more closely matches COD than the MSLS or BS. Thus, the LRSS has the greater potential to enhance COD.

Key Words: force-vector theroy, unilateral, strength training

Introduction

Change of direction (COD) is one of the most important motor qualities in almost all current sports; therefore, it is frequently assessed to predict performance outcomes (3,11,26,30). Although strength training is commonly used by athletes to improve their performance, it is currently inconclusive whether muscular strength correlates to COD performance (17,25,31–33,35) and improving COD has proven to be difficult because athletes exhibit inconsistent COD results after training (5,17,21,25). Thus, strength and conditioning coaches have focused instead on using power movements such as plyometric exercises or squat jumps to improve COD performance (8,11,21,22). However, these techniques and movements may be too advanced for some individuals, resulting in reduced effectiveness and an increased risk of injury (5,29).

Because of plyometrics potentially increasing the likelihood of injury or reduced effectiveness in the pursuit of COD enhancement, what resistance training exercises are strength and conditioning professionals attempting to use to solve this problem? The current research would point to the modified single-leg squat (MSLS) and back squat (BS). The MSLS seems to be closely related to COD because the muscles are activated in a similar unilateral fashion and reportedly improves COD performance after training (1,2,10,20,23,24,31). However, results are inconsistent in that training with the MSLS did not produce greater improvements in COD performance than training with the BS (31). Considering the inconsistent results, the main issue with improving COD performance may not have been the use of strength training in agility programs, but lack of exercise specificity. In other words, applying the specificity principle or performing exercises that mimic COD and its unique unilateral, multiplane pattern may be necessary to improve COD performance (6,13,18). The force-vector theory, a refinement of the specificity principle, suggests that MSLS neither provides specific nor adequate stimulus because it does not occur in the same anatomical plane(s) as COD (1,6,12,13,18,34). Although the MSLS replicates the muscular activation of the COD task, it provides inadequate stimulus to produce meaningful improvement in COD performance because it is performed in the frontal plane with a vertical load, whereas COD occurs in multiple planes with both vertical and horizontal loads.

More specifically, the force-vector theory states that to maximize transfer to performance, athletes should train movements in the same specific anatomical planes using the same vectors as the athletic skill they are targeting (1,6,12,13,18,34). Contreras et al. (6) eloquently demonstrated this theory in a real-world application by comparing the barbell hip thrust (horizontal force production) and the front squat (vertical force production) and their effect on performance outcomes. Contreras et al. (6) found that the hip thrust improved sprint times, whereas the BS improved vertical jump height. It is from this study and the theory that guided it, that the authors theorize that the laterally resisted split

Address correspondence to Shawn R. Simonson, ShawnSimonson@BoiseState.edu.

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squat (LRSS) would enhance COD to a greater degree than other exercises currently used.

Going a step further and comparing COD with other movements through the lens of the force-vector theory illustrates this point. During COD, the athlete plants their outer foot (foot opposite to the intended new direction) to eccentrically lower their hips and center of gravity in the transverse plane and decelerate their momentum in the sagittal plane. There is a brief amortization phase, stopping of momentum, and then a concentric force is applied through the planted leg at a 45–75° angle in the frontal plane to push off the ground and accelerate their momentum in the new, intended direction (8,10,20). The MSLS mimics this movement in the transverse and sagittal planes, but may not mimic the frontal plane angle of force production; thus, it does not optimize the force-vector and would not be expected to lead to optimum improvements in COD. Applying the force-vector theory, the movement should be performed in a unilateral stance (with the leg at 45–75° in the frontal plane), eccentric lowering of the hips, and then application of a concentric force through the planted foot. Based on the inconclusive results demonstrated to date and by applying the force-vector theory, we propose a new more specific strength training exercise, LRSS, to improve COD ability.

The LRSS is similar in nature to the MSLS with the addition of a lateral force by placing the planted leg at an angle comparable with COD. To create the lateral force, a barbell is anchored to the floor at the distal end with a landmine base. Plates are loaded at the free end of the bar. The lifter stands at the free end of the bar oriented at a right angle to the bar, the leg to be worked (planted leg), is opposite/distal to the landmine, and the near/proximal leg is elevated on a platform behind the lifter. The foot of the planted leg is placed just to the outside of the free end of the bar and the lifter picks up this end of the bar and brings it tight to their chest in a Zercher hold (Figure 1). They then eccentrically descend on the planted leg to an approximate 90° knee angle and then concentrically ascend to the starting position, driving into the barbell and creating a frontal plane angle similar to performing COD. It is theorized that this is more similar to COD because, although this movement is still performed in the transverse and sagittal planes, the resistive forces applied to the lifter's planted leg are also in the frontal plane because of the barbell's lateral anchor.

The purpose of this study was to provide a theoretical basis for the inclusion of the LRSS in strength and conditioning programs intended to enhance COD performance. The first step in this process is to determine whether the LRSS more closely mimics both the frontal plane movement and angle of force production of the COD than the frequently used MSLS and BS movements. It was hypothesized that based on the force-vector theory, the LRSS will result in a peak ground reaction force (GRF) magnitude (GRF_{mag}) and angle (GRF_{θ}) that is not statistically different than COD, but significantly different than the BS and MSLS, respectively.

Methods

Experimental Approach to the Problem

The force-vector theory suggests athletes need to perform training exercises that specifically mimic both the movement plane and angle of force production of a targeted athletic skill to improve performance (6). Force plate analysis was used to test the specificity of the LRSS to COD. The magnitude and vector angle of the GRF in the frontal plane were quantified and compared for LRSS, MSLS, BS, and COD.

Subjects

Ten healthy and recreationally active female subjects (age: 23.8 ± 5.37 years, body mass 70.35 ± 14.31 kg, height: 164.85 ± 8.42 cm, and 3.4 ± 1.8 years of resistance training experience) and 13 female varsity collegiate soccer players participating in preseason conditioning (age: 19.8 ± 1.3 years, body mass 67.12 ± 5.30 kg, height: 170.92 ± 5.12 cm, and 3.1 ± 1.0 years of resistance training experience) completed this study. Because subsequent analysis indicated no significant differences between the 2 subject groups, data were combined (Table 1). All subjects provided written consent and a completed health history before testing. Because testing was of short duration and of limited scope, there was no control for diet or menstrual cycle phase. This study received prior Boise State University Institutional Review Board approval.

Subjects' dominant lower limb was first established by asking the subject, "Which foot do you kick a soccer ball with?" and then verified with an actual kick. All 23 subjects were right leg dominant. After a suitable warm-up, subjects were then required to successfully complete a COD mechanics field test to ensure adequate control of the lower extremity and reduce injury potential. The test involved sprinting 10 m and performing a 90° turn off the dominant limb. Mechanics were assessed on a 3-point scale: shortening of stride length and lowering of center of mass when

Figure 1. The laterally resisted split squat (LRSS) at the top (left panel) and bottom (right panel) of the movement. The distal end of the barbell is anchored by a landmine base (not shown).

Table 1
LRSS study subjects.*

Subjects (female)	Age (y)	Mass (kg)	Height (cm)	Sport/physical activity (*n*)
23	21.4 ± 3.0	68.50 ± 8.98	168.44 ± 6.47	Soccer (13) Lacrosse (4) Hiking (2) Volleyball (2) Downhill skiing (1) Weightlifting (1)

*LRSS = laterally resisted split squat.

decelerating, shin angle visually estimated at less than 90° sagittal plane and between 45 and 75° in the frontal plane, and rotation of hips during push-off toward the new intended direction (8,10,19,20). Subjects had to score at least a 2 on each criterion to be included.

Procedures

All screening and data collection occurred in 1 test session. After completing screening, the LRSS was demonstrated, and subjects practiced the movement using a free-weight standard barbell (20.45 kg) with a 4.55-kg bumper plate for 5 or more repetitions. Corrective feedback was provided until the subject appropriately performed the LRSS.

Strength Assessment. After adequate recovery, 1 repetition maximum (1RM) estimates for the LRSS, MSLS, and BS were assessed in a random order through a roll of a die (1,4: LRSS; 2,5: MSLS; and 3,6: BS). To assess 1RM, the subject performed 5–10 repetitions of the randomly selected exercise at a predetermined percentage of body weight (BW) (LRSS = 50%; MSLS = 50%; and BS = 80%). If 10 repetitions were performed correctly, additional weight (up to 9.09 kg based on subject's perception of the weight) was added and the movement repeated. Once the subject could no longer perform the movement with correct form for more than 10 repetitions, the number of correct repetitions and final weight were recorded. The Bryzcki formula was then used to estimate the subject's 1RM (4,9,15). This maximal strength testing procedure was then repeated for the other 2 movements in random order.

Kinetic Assessment. After adequate rest after the strength assessments, kinetic (GRF) data were recorded with an in-ground force platform (OR-6, AMTI, Watertown, MA) as the subjects performed the various tasks (COD, LRSS, MSLS, and BS). The COD task was a 10-m run up to the target on the force platform, planting the dominant leg, performing a 90° COD pivot, and running an additional 10 m in the new direction.

After completing the COD, subjects randomly performed one of the 3 resistance movements (LRSS, MSLS, and BS) using 70% of their calculated 1RM with their dominant foot on the force plate (Figure 2). As previously described for the LRSS, the subject stood with the landmine base placed laterally to them and their dominant, outside, foot just under the free bar end. The near foot was elevated behind them on a leg rest. They used a Zercher hold to pin the barbell to their chest and leaned into the weight. For the MSLS, the subject placed their nondominant foot on the same posteriorly placed leg rest and then stood up under the bar so that it was resting across their back just above the shoulder blades in a typical BS position. For the BS, the nondominant foot was placed parallel to the dominant (approximately shoulder width away) and off the force plate with the barbell in a traditional position resting across their back just above the shoulder blades.

For each resistance movement, subjects performed up to 10 repetitions at a controlled and consistent speed for 15 seconds. This process was repeated, and data were collected for all 3 tasks with at least 3-minute rest between each movement. The repetition with the highest peak GRF_{mag} within each movement was used for analysis.

Ground Reaction Force Measures. Custom MATLAB script (version 2019a, MathWorks, Inc., Natick, MA) was used to calculate peak frontal plane GRF_{mag} and GRF_{θ} according to Creaby and Dixon using trigonometric equations (7).

$$GRF_{mag} = \sqrt{F_x^2 + F_z^2},$$

$$GRF_{\theta} = \tan^{-1}\frac{F_x}{F_z},$$

where F_z represents the vertical GRF and F_x the mediolateral GRF. GRF_{mag} was normalized to subject BW plus weight lifted (in

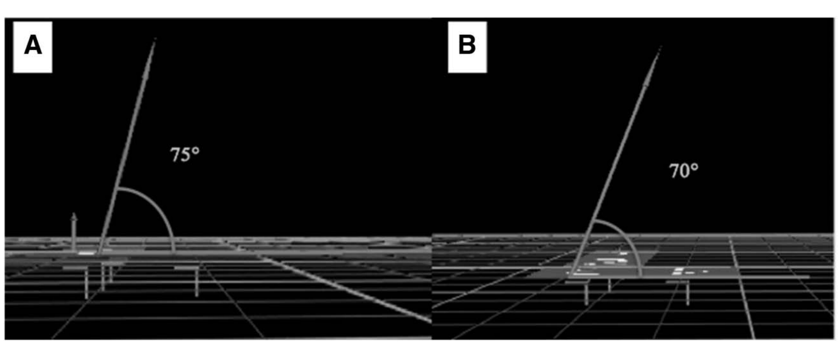

Figure 2. Representative LRSS (A) and COD (B) force vectors as seen in Nexus. Angles are measured from the horizontal axis. LRSS = laterally resisted split squat; COD = change of direction.

Newton's), and GRF_θ was measured as the angle from the horizontal axis.

Statistical Analyses

The dependent variables included body mass, 1RM for LRSS, MSLS, and BS, and peak frontal plane GRF_{mag} and GRF_θ for all tasks. Before analysis, 1RM data were tested for outliers using the box and whiskers technique with interquartile range method, and all subjects were included (28). Peak frontal plane GRF_{mag} and GRF_θ for the subjects were submitted to repeated measures ANOVA to test main effect of task (COD, LRSS, MSLS, and BS). To reduce probability of committing type I error, a Bonferroni correction was used for post hoc comparisons. Effect size was calculated using partial eta-squared values according to Hopkins (16). All analysis was conducted in SPSS 25 (IBM Corporation; Armonk, NY), with alpha level 0.05.

Results

Figure 3 indicates the BS-to-body mass ratio for the subjects and shows a general linear trend. Figure 3B indicates that, although the soccer athletes were more narrowly clustered, there was no significant difference in strength-to-body mass ratios for the BS and LRSS. Descriptive statistics (mean ± *SD*) for subjects' peak frontal plane GRF_{mag} and corresponding GRF_θ for COD, LRSS, MSLS, and BS are presented in Table 2. Figure 4B indicates that, although there was a trend for the female soccer players to have smaller angles in both the 90° cut and LRSS, these were not significantly different from the female recreationally active subjects.

There was a significant main effect of task for GRF_{mag} ($p < 0.001$; ES = 0.94). Specifically, COD had a significantly larger peak GRF_{mag} compared with LRSS ($p < 0.001$), MSLS ($p = 0.001$), and BS ($p < 0.001$), and GRF_{mag} was significantly greater for MSLS compared with LRSS ($p = 0.005$) and BS ($p < 0.001$) and for LRSS compared with BS ($p < 0.001$). Thus, in terms of GRF_{mag}, COD > MSLS > LRSS > BS.

There was a significant main effect of task for peak GRF_θ ($p < 0.001$; ES = 0.96). There was no significant difference in peak GRF_θ between COD and the LRSS ($p = 0.057$), but peak GRF_θ was significantly smaller for both COD and LRSS compared with MSLS (both: $p < 0.001$) and BS ($p < 0.001$; $p = 0.047$) and for BS compared with MSLS ($p = 0.014$). Thus, in terms of GRF vector angles, MSLS > BS > LRSS ≈ COD (Figure 4).

Discussion

According to the force-vector theory, the current training movements used by many strength and conditioning professionals may not adequately replicate the movement plane and vector angle of

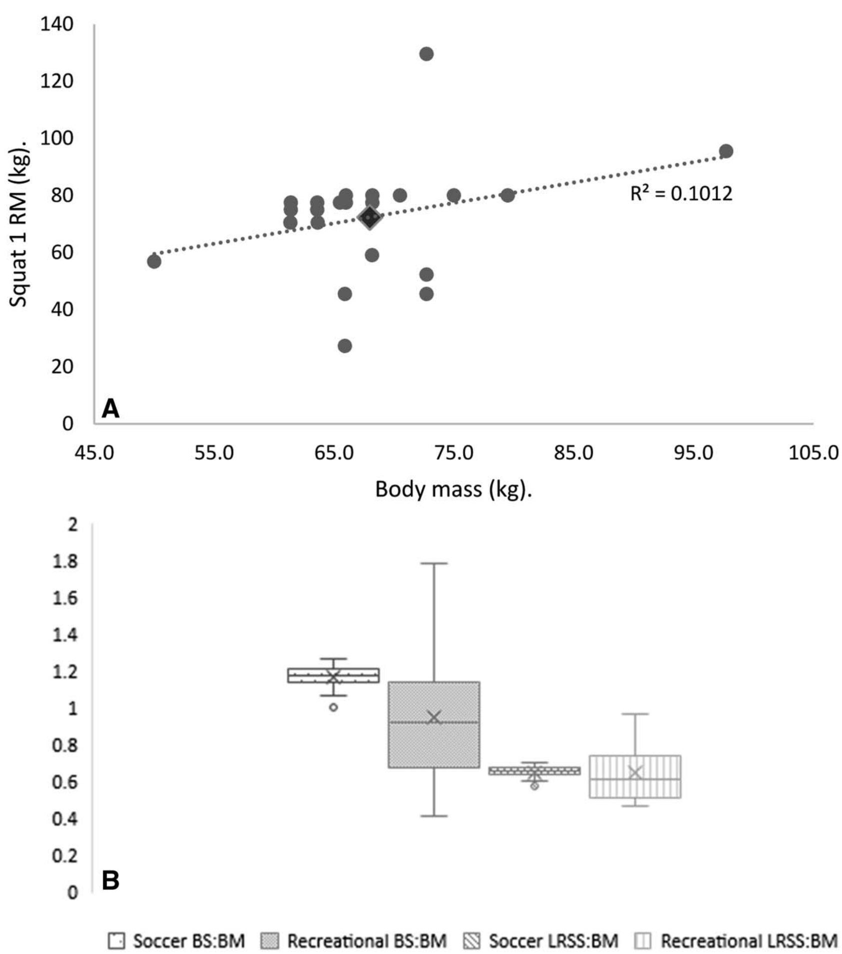

Figure 3. (A) Comparison of BS 1RM with body mass for 23 female LRSS subjects. (B) Comparison of the ratio between the BS 1RM and body mass and the ratio between the LRSS 1RM and body mass for female college soccer players and female recreational athletes. BS = back squat; 1RM = 1 repetition maximum; LRSS = laterally resisted split squat.

Table 2
Relationship between strength, peak ground reaction force, and frontal plane angle (1RM, GRF_{mag}, and GRF_{Θ}) for 23 female LRSS subjects.*

Variable	Peak frontal plain GRF_{mag} (multiple of body weight)	Frontal plane GRF_{Θ} (°)
COD	2.23 ± 0.62‡,§,||	65.33 ± 4.98§,||
LRSS	0.95 ± 0.47†,§,||	72.84 ± 5.64§,||
MSLS	1.09 ± 0.20†,‡,||	89.04 ± 0.48†,‡,||
BS	0.72 ± 0.17†,‡,§	82.69 ± 4.30†,‡,§

*1RM = 1 repetition maximum; GRF = ground reaction forces; LRSS = laterally resisted split squat; COD = change of direction; MSLS = modified single-leg squat; BS = back squat.
†Mean significantly different from COD at 0.05 level.
‡Mean significantly different from LRSS at 0.05 level.
§Mean significantly different from MSLS at 0.05 level.
||Mean significantly different from BS at 0.05 level.

force production required during COD to produce a meaningful improvement in COD performance. The purpose of this study was to provide a theoretical basis for the inclusion of the LRSS in COD training regiments. The first step in doing this was to biomechanically determine whether the LRSS more closely resembles COD. The current results support this theoretical rationale as the hypothesis that the LRSS will result in a similar frontal plane GRF vector angle to COD was accepted. However, the hypothesis that the LRSS will result in a similar peak GRF_{mag} to COD was rejected.

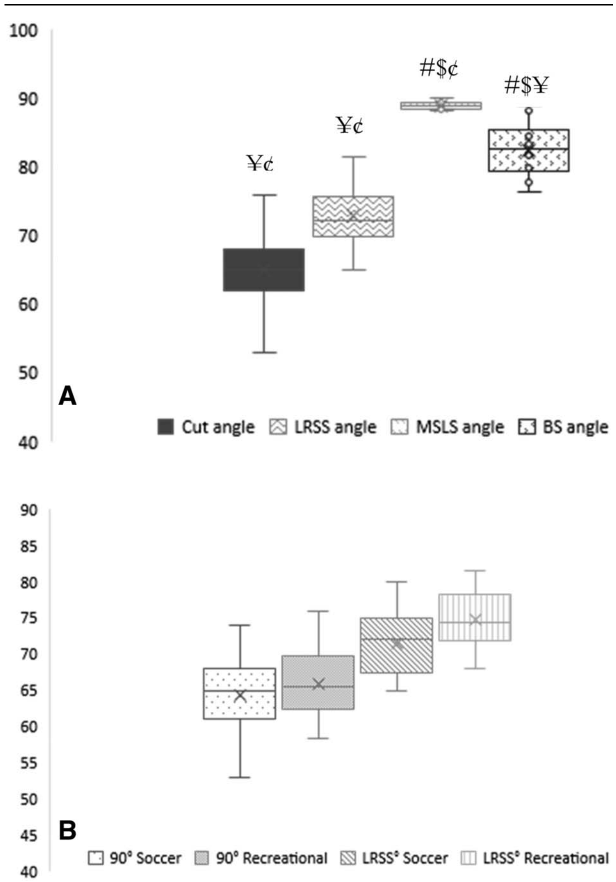

Figure 4. (A) Comparison of ground reaction force angles during the 90° cut and the LRSS, MSLS, and BS for 23 female LRSS subjects. (B) Comparison of ground reaction force angles during the 90° cut and the LRSS for female college soccer players and female recreational athletes. LRSS = laterally resisted split squat; MSLS = modified single-leg squat; BS = back squat.

Contrary to one aspect of our hypothesis, the peak GRF_{mag} was significantly greater for COD than the 3 resistance exercises (LRSS, MSLS, and BS). The peak GRF_{mag} of the COD was 1.14–1.51 BWs greater than the resistance exercises in general and 1.28 BWs greater than LRSS specifically. This makes sense as peak GRF_{mag} reported when running 3.6 m/s was 2.49 ± 0.19 BW, approximately 15% greater than the 2.23 ± 0.62 observed during the COD task (7). None of the subjects had a 1RM approaching 2 times their BW, and so, the magnitude must be lower. However, in the current study, resistance exercises were performed at 70% of 1RM and the COD at a sprint. Measuring GRF with the 1RM for each resistance exercise might have resulted in values more similar to the COD GRF_{mag}. However, considering a 30% increase in peak GRF_{mag} for the resistance exercises would only result in peak GRF values of 0.68–1.29 BWs, still much less than 2 BW. Although training at the same absolute load may not be feasible, this does suggest that training at higher intensities may be warranted, and that further study is needed to determine training loads to best enhance COD performance.

Thus, GRF_{mag} may not be a good indicator of the specificity required for meaningful COD performance gains after training. Training with the MSLS and BS (at 75–92% 1RM for 5 weeks) resulted in similar improvements in COD assessed through the pro-agility test (31). The MSLS requires nearly 50% greater magnitude of peak GRF compared with BS as well as greater hamstring, gluteus maximus, and gluteus medius activation, highly activated muscles during performance of a COD task (2,20,23,24). If peak GRF_{mag} was a good indicator of the specificity required for training improvements, in theory, performing MSLS exercises should lead to greater improvements in COD than the BS. However, Jullien et al. (17) reported that multidirectional locomotor training (i.e., running, hurdling, and shuffling in various directions) produced an approximately 5% greater improvement of COD performance on the shuttle test than BS training. Thus, as suggested by Contreras et al. (6), it may not be training the targeted muscles at a greater magnitude that is important for improving performance; rather, it maybe the plane in which the movement produces force.

In agreement with our hypothesis and justifying the inclusion of the LRSS in COD training, the frontal plane GRF_{Θ} recorded for COD and LRSS was not statistically different. All 3 resistance exercises produced force in the frontal plane. But, the GRF_{θ} of the LRS was approximately 17.4 and 23.7° more medially directed than during the BS and MSLS tasks, respectively. Applying the force-vector theory, the LRSS is the most appropriate of the currently chosen resistance exercises for COD training. Numerous studies demonstrate that individuals produce meaningful performance improvements by training exercises that require force production in the anatomical planes of the targeted athletic task (1,6,12,13,18,34).

Case in point, on further review of the data collected from this study, it is demonstrated that the BS required force production that was directed approximately 6° more medially than the MSLS tasks. By using the force-vector theory as our guide, one would hypothesize that BS training would produce greater improvements in COD performance than training with MSLS (27). Through research conducted by Speirs et al. (31), this hypothesis was validated. The BS and MSLS both improved agility performance, and the BS group did demonstrate a greater, albeit nonsignificant, improvement in COD performance than the MSLS group (31). Studies demonstrating more medially directed exercises enhance COD were not limited to Speirs et al., and Henry et al. demonstrated that the factors involved in producing superior lateral jump performance in the dominant leg were predictive of COD performance in that leg, whereas vertical and horizontal jumps were not predictive of COD performance (14). McCormick et al. (22) furthered this argument by showing medially directed plyometrics were more effective at enhancing a COD task than vertically directed plyometrics.

Medially directed exercises seem to enhance COD to a greater degree than vertical and horizontally directed exercises (12,14,24,30). According to the findings of this study, the LRSS is a more medially directed exercise. This satisfies step one in the creation of a theoretical basis for the LRSS's inclusion in a COD training program and provides it with the potential of enhancing COD more because it is medially directed (12,14,22,31). But, how is this potential going to be assessed? The second step in the construction of the theoretical rationale for the LRSS's inclusion is to determine whether the LRSS can enhance COD as the BS and MSLS did through a conditioning study (31). If its capacity to enhance COD is determined, the next step would then be to explicitly delineate whether medially directed LRSS training produces greater improvements in COD compared with vertically directed exercises such as the BS, MSLS, or horizontally directed exercises such as the hip thrust. If each step hypothesis is accepted, a sound theoretical basis will be provided for the LRSS's inclusion in the COD enhancement programs for athletes of various sports.

Two seemingly different populations were assessed in this study. Although there was a trend for the soccer players to have smaller angles for the COD and LRSS, it was not significant; thus, the data for all subjects were combined. What this might indicate though is that as strength and athleticism improve, it may be worthwhile to have the subject place the base foot beyond the bar end, further from the landmine base, to create a smaller angle when performing the LRSS. A longer bar might also be necessary when working with taller individuals and when the amount of weight being added to the bar interferes with the Zercher hold.

Practical Applications

To produce a meaningful improvement in COD performance and increase the likelihood athletes achieve success in competition, strength and conditioning professionals need to choose training exercises that replicate the movement plane and angle of force produced during the specific motor ability. Biomechanical analysis confirms that the LRSS closely resembles the frontal plane vector angle of a COD task in accordance with the force-vector theory. Thus, we suggest that strength and conditioning professionals implement the LRSS into their training programs to produce a superior improvement in COD performance.

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