ANALYZING CHANGE-OF-DIRECTION AND THE LATERALLY RESISTED SPLIT SQUAT: INCORPORATING A LATERAL VECTOR INTO THE SINGLE LEG SQUAT

by

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A thesis

submitted in partial fulfillment

of the requirements for the degree of

Master of Science in Kinesiology

Boise State University

May 2020

BOISE STATE UNIVERSITY GRADUATE COLLEGE

DEFENSE COMMITTEE AND FINAL READING APPROVALS

of the thesis submitted by

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Thesis Title: Analyzing Change-of-Direction and the Laterally Resisted Split Squat: Incorporating a Lateral Vector into the Single Leg Squat

Date of Final Oral Examination: 10 December 2019

The following individuals read and discussed the thesis submitted by student Derek Maddy, and they evaluated their presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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DEDICATION

I would like to dedicate this to my very supportive wife, Jamey. She has been so patient and by my side throughout this whole process. She is a very large reason why this project has finally been completed. I would also like to dedicate this to my loving family and thank them for so much help in reviewing my paper, even though they still do not fully understand kinesiology.

ACKNOWLEDGMENTS

I would like to acknowledge Chance Cooley and his great idea that started this project. He saw a need in the strength and conditioning field and came up with an idea. Now it is on the way for publication. It was a tremendous thing to bring to life that I want to further be apart of throughout my research career. I would also like to acknowledge my Committee Chair, Dr. Shawn Simonson, who brought this idea to me and who really challenged me throughout this whole process. I learned and experienced a lot about the process of a research project because of him.

ABSTRACT

Improving change of direction (COD) with the use of strength training has led to mixed results. To date, the modified single leg squat (MSLS) and the bilateral squat (BS) have been successfully used to improve COD, with equal improvement. COD is primarily performed at a 45-75º frontal plane angle; however, the MSLS and BS are performed at a 90º frontal plane angle. Based on the force vector theory, it is proposed that a more mechanically similar strength training exercise, the Laterally Resisted Split Squat (LRSS), be used. The purpose of this study is to compare COD with the LRSS, MSLS, and the BS via kinetic measurements. Ten healthy and recreationally active female individuals volunteered for this study. Participants were pre-screened using a COD test to verify proper mechanics. Participant's weight was measured and 1RM (using Bryzcki formula/technique) for the LRSS, MSLS, and BS calculated. Peak ground reaction force (GRF) of participant's dominant leg in the frontal plane for COD and the three exercises at 70% 1RM was collected and used to calculate peak magnitude and vector angle. Peak GRF magnitude was significantly larger in COD (2.13 ± 0.52 bodyweight: BW) than the LRSS (0.85 ± 0.07 BW; $p < 0.001$), MSLS (0.99 ± 0.10 BW; $p = 0.001$), and BS (0.52 ± 0.07 BW; $p < 0.001$). COD (66.70° ± 4.98°) vector angle was not significantly difference than the LRSS (74.94° ± 4.11°; $p = 0.057$) as compared to the MSLS (89.04° ± 0.48°; $p < 0.001$) and BS (82.69° ± 4.30°; $p < 0.001$). In an application of the force vector theory, the LRSS more closely matches COD than the MSLS or BS.

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COD	Change of Direction
LRSS	Laterally Resisted Split Squat
MSLS	Modified Single Leg Squat
BS	Bilateral Squat
GRF	Ground Reaction Force
1RM	One-Repetition Max
BW	Bodyweight

CHAPTER ONE: INTRODUCTION

Change of direction (COD) is commonly used in field sports and frequently assessed in athletics to predict performance outcomes.[2, 10, 20, 23] Improving COD has proven to be difficult as results from research attempting to do so are inconsistent.[4, 12, 16, 19] While strength training is commonly used by athletes to improve their performance, some studies have found a correlation between muscular strength and COD, while others have not.[12, 19, 26-27] Thus, strength and conditioning coaches have focused on using power movements such as plyometric exercises or squat jumps to improve COD.[4, 16] However, these techniques and movements may be too advanced for some individuals resulting in an increased risk of injury.[4]

Considering the inconsistent results, the main issue may not have been the use of strength training in agility programs, but the lack of performing exercises in a similar fashion to COD and its unique unilateral, multi-plane movement. In other words, applying the specificity principle.[2] The modified single leg squat (MSLS) appears to be closely related to COD because the muscles are activated in a similar unilateral fashion and strength-training with the MSLS has resulted in improved COD performance. [1, 9, 15, 17, 18, 24] However, training the MSLS was no different than training the bilateral squat (BS) with the BS group showing larger individual improvement times than the MSLS.[24] One possible reason for this discrepancy could be that, even though the MSLS is more specific to the COD task than the BS, the MSLS is still performed in the frontal plane with a vertical load. The force-vector theory suggests that this is not specific enough to the COD task and may not provide adequate stimulus.[5, 11, 13]

The force-vector theory is a refinement of the specificity principle with the intention to improve transfer that states that athletes should perform exercises and drills in the same specific anatomical planes as the athletic skill they are targeting.[5, 11, 13] The practitioner should determine the exercise(s) best suited to simulate not only the muscles involved in the movement, but also the anatomical planes and force vectors that lead to improvements in that particular motion. Contreras et al previously supported the force vector theory by comparing the barbell hip thrust (horizontal force production) and the BS (vertical force production).[5] They concluded that the barbell hip thrust improved sprint times because of the anterior/posterior hip movement while the BS improved vertical jump height because of the cranial/pedal movement; however, the improvement in the horizontal broad jump was similar.[5] Contreras et al suggested that this was due to the broad jump requiring both vertical and horizontal forces, creating an angular force vector. Thus, the recommendation to perform exercises in all of the movement planes in which the targeted movement occurs.

In COD, the athlete eccentrically slows down their momentum (deceleration phase) in the sagittal plane and plants their outer foot, opposite to the intended new direction, eccentrically lowering their hips and their center of gravity, and then applies a concentric force at a 45-75º frontal plane angle through the planted leg and pushes off the ground in the new direction (acceleration phase).[9, 15] The MSLS mimics the movement in the frontal plane, but not the frontal plane angle; thus, it does not optimize the force vector and would not be expected to lead to optimum improvements in COD. Based on the inconclusive results demonstrated to date and by applying the force-vector theory, a new more specific strength-training exercise to improve COD ability is proposed.

The purpose of this study was to determine if a new resistance training movement will more closely mimic COD than previously used movements. Applying the force-vector theory, the movement should be performed in a unilateral, anterior-posterior manner with the addition of lateral forces at an angle similar to COD. The Laterally Resisted Split Squat (LRSS) is similar to the MSLS with the addition of a lateral force that places the planted leg at an angle similar to 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 approximately under the free end of the bar. The lifter picks up the free end of the bar and hugs it to their chest in a Zercher hold (Figure 1). The participant then slowly eccentrically descends on the planted leg to an approximate knee angle of 90˚ and then rapidly concentrically ascends to the starting position, driving into the barbell, creating the frontal plane angle similar to performing COD. It is theorized that the resistive forces applied to the lifter's planted leg are both lateral and vertical forces and while this movement performed in the frontal plane, the barbell's lateral anchor creates a lateral force and angle similar to COD.

Figure 1 Laterally resisted split squat

Thus, it is hypothesized that

Hypothesis Ia: the LRSS will result in a similar peak GRF magnitude to COD and both will be significantly different than the BS.

Hypothesis Ib: the LRSS will result in a similar peak GRF magnitude to COD and both will be significantly different than the MSLS.

Hypothesis IIa: the LRSS will result in a similar frontal plane GRF vector angle to COD and both will be significantly different than the BS.

Hypothesis IIb: the LRSS will result in a similar frontal plane GRF vector angle to COD and both will be significantly different than the MSLS.

CHAPTER TWO: LITERATURE REVIEW

The purpose of the current study is to improve COD performance by using the laterally resisted split squat (LRSS). This review will consider recent as well as significant studies for better understanding of the relationship between muscular strength, athletic performance, COD and designing strength-training movements to target the movement-specific muscles and patterns.

Agility: Physical or Cognitive Training?

Agility is "the ability to efficiently and rapidly change direction or speed in response to a stimulus."[10] Through research, it has been determined that there are two distinct components of agility – physical (COD) and cognitive.[10] The definition of agility has one key factor in it that makes it distinguishable from other athletic skills, "in response to a stimulus." Agility requires the use of an athlete's cognitive skills in recognizing a stimulus, such as a defensive player or obstacle, making a decision about that stimulus, and creating an appropriate response. Agility is important for an athlete to possess in order to be successful in numerous sports.[10]

Using Muscular Strength-Training to Improve Athletic Performance

Strength-training programs are prescribed to increase the physical aspect of an athlete's skill. Suchomel, Nimphius and Stone reviewed strength training programs used for different athletic skills (jumping, sprinting, COD, etc.) across multiple studies.[26] They concluded that strength training programs may enhance an athlete's strength, power, and speed which can then translate to improved athletic performance. They go on to conclude that stronger athletes demonstrate better overall athletic performance, especially when specifically training within the parameters of their sport or event.[26] Thus, strength-training programs should be included in training regimens for athletes to improve physical aspects of their athletic skill. However, some exercises and programs have provided inconsistent results. [4, 12, 16]

Relationship between Muscular Strength and COD

As previously stated, agility has two components, physical and cognitive.[10] Spiteri et al conducted a study measuring the influence of strength on the physical component – COD time.[25] Twenty-four participants (12 males; 12 females) were divided into two groups (stronger group: 8 males, 4 females; weaker group: 4 males, 8 females) based on the isometric strength of each participant's dominant leg. Participants were classified as either strong or weak according to whether they performed above 50-percentile or below 50-percentile in the study's sample. Participants next performed a maximal isometric unilateral squat against an immovable bar for five seconds while standing on a force plate. The participants performed three trials, with the best performance used for calculation of correlation to COD. After a one-hour break, participants performed a COD protocol that consisted of sprinting in a straight-line for 6 meters and cutting on a force plate at a 45° angle to the left and right and sprinting 2.5 meters. The planted foot was the foot opposite of the cut direction. The force plate was used to measure the post-COD stride velocity, which is defined as the first step taken after COD is observed. Spiteri et al found that the stronger group produced a significantly faster post-COD stride velocity (2.50 to 2.28 m/s; $p = 0.01$) and higher braking force (effect size = 1.31; $p = 0.004$) compared to the weaker group.[25] Thus, this study demonstrates the correlation between muscular strength and COD performance.

The findings in Spiteri et al support the use of strength training to improve COD; however, using strength training to improve COD has led to inconsistent results.[4, 12, 16, 25] Jullien et al conducted a study in which 26 elite male soccer players from a French professional club volunteered and were divided into three groups (Reference: individual technical work only; Coordination: circuit training designed to improve agility; and Strength: strength-training using bilateral squats, sprints and circuit training) to determine the effects of each on changes in running speed, agility coordination, reactive speed and acceleration.[12] The strength-training program consisted of participants performing bilateral squats on a concentric squat machine at 90% of their 1-rep max (1RM) for three sets of three repetitions, for three weeks, five times a week. The participants were assessed via four field-based tests (7.32-meter sprint, 10-meter sprint, shuttle test over 11 meters with a 16.50-meter sprint with 2 changes of directions, and a timed circuit test over a distance of 31.10 meters) before and after each of the three weeks of training. Their results showed improvement in the timed circuit completion times for all three groups from their initial testing to their final testing; however, as far as compared between groups, no significant differences between groups were found ($F = 0.39$; $p = 0.881$).[12] Shuttle test results showed that after training, the coordination group had significantly shorter completion times compared to the strength-training group (coordination = 2.76 sec, strength-training = 3.93 sec; $p < 0.01$).[12] It was concluded that concentric strength training does not improve COD performance and agility while coordination training does. An issue with these results is that participants performed concentric squats even though COD has an eccentric component during deceleration.[1, 12, 15] Thus, the muscles may have been improperly trained for COD.

McBride et al conducted an 8-week training program using jump squats with 30% or 80% of each participant's 1RM with 26 male athletes.[16] Both groups demonstrated an equally significant decrease in their COD performance times in the T-test (pre jump squat 30%: 11.10 ± 0.16 sec; post jump squat 30%: 10.91 ± 0.16 sec; pre jump squat 80%: 10.97 ± 0.20; post jump squat 80%: 10.71 ± 0.18 sec) after the training program.[16] However, it had been suggested that these results occurred due to the velocity rate rather than specificity or load weight of the exercises as the lighter 30% load rate enabled the participants to perform at a faster speed, resulting in an improvement to muscle electrical activity and improving COD.[16]

Castillo-Rodriguez et al used counter-movement jumps and drop jumps in a bilateral and unilateral manner to measure the relationship between muscular strength and COD performance of 45 college amateur male soccer players.[4] The study was conducted over a two-day period. Participants performed a 25-minute warm-up before the start of each testing session. Day one consisted of measuring the athletes' jump test scores and day two (after 48 hours of rest) tested COD performance via 3 10-meter sprints using a 180° COD and a left and right 90° COD. A significant negative correlation was found between COD and all jump tests suggesting that greater muscular strength resulted in faster COD times.[4] The unilateral counter-movement jump showed the highest significant correlation with COD performance times ($r = 0.644$).[4] Castillo-Rodriguez et al emphasized the importance of specificity training for improving COD performance and recommended the use of exercises specific to a motor skill instead of generalized movements.[4] During COD, braking forces are observed similar to the counter-movement jump.[10] A complication within this study was that three (6.7 %) of the participants were injured during the study and their results were excluded. Although this study does not describe the injuries and their severity, one may suggest that the jump tests can be risky, especially for athletes with poor mechanics.

A More Specific Exercise?

It has been established that COD ability is correlated to strength; however, improving strength does not always improve COD. Brughelli et al reviewed COD research in which participants participated in traditional strength training; yet, no improvements in COD performance times were found.[2] They suggested the reason for this is the specificity of the COD task, as it is frequently an unilateral movement in multiple planes that requires multi-plane force production and that improving COD performance may require exercises that target the used muscles in a specific unilateral manner with multi-plane force production. In addition, Castillo-Rodriguez et al used unilateral counter-movement jumps and saw a correlation between jump performance and faster COD performance times.[4] However, the complexity of the movement (balancing on one leg and jumping vertically as high as possible and landing on the same leg) might be too advanced for some. Thus, to improve COD, movements should be performed that strengthen the muscles used entering and coming out the cut motion simultaneously in a unilateral multi-plane fashion for better transferability to the athletic skill.

Specific Strength-Training Transferring to Athletic Skills

Training that specifically targets the muscles used during athletic skills is best for direct transferability.[27] Young, McDowell and Scarlett conducted a specificity study using sprint and agility training methods to see if training for one athletic skill transfers to another.[28] 36 men (age: 24.0 ± 5.7 years) with at least one season of experience involving sprinting and/or COD maneuvers volunteered for the study. Participants completed 7 different tests, covering a distance of 30 meters. Test 1 was a straight sprint while the rest of the tests involved at least 2 changes of direction at < 180° angles. Each test increased in complexity as either the number of changes in directions increased or the magnitude of the angles of each change increased. After testing was completed, participants were divided into 3 different groups (speed, agility, control). The control group continued daily activities. The speed and agility group completed 2 training sessions per week, separated by 72 - 96 hours, for a 6-week period. The speed group practiced straightforward sprinting while the agility group performed COD sprints (similar to tests 5-7). Their results showed that although the participants improved their performance time for the athletic skill they were training (speed group test 1 before = 4.47 ± 0.18 sec, after = 4.34 ± 0.18 sec, $p < 0.05$; agility group test 7 before = 9.78 ± 0.31 sec, after = 9.52 ± 0.30 sec, $p < 0.05$), no improvement occurred for the other athletic skill (speed group test 7 before = 9.51 ± 0.52 sec, after = 9.51 ± 0.52 sec, $p > 0.05$; agility group test 1 before = 4.74 ± 0.30 sec, after = 4.72 ± 0.24 sec, $p > 0.05$).[28] Their findings confirm that athletic skills should be trained individually.[28]

This however, only focused on the use of anaerobic sprint training and not on strength training as a way to specifically train transferability to an athletic skill. Young reviewed studies that used specific strength-training protocols to improve athletic performance via transferability.[27] Sprinting and vertical jumping improved when the protocol focused on using the muscles specifically used in the skill, especially in more experienced athletes.[27] With this understanding in mind, improvements in COD may result via the use of a strength training protocol that is specific to COD by focusing on the muscles and vectors used during COD.

Muscles used during COD athletic skills

To optimize specificity and transferability in strength training, exercises should be selected that use the muscles activated during the targeted movement. Besier, Lloyd, and Ackland compared the muscles activated during running and cutting maneuvers under pre-planned or unexpected conditions.[1] Results during a pre-planned condition showed that right before entering the cutting phase, muscle activation is greater in the bicep femoris and semimembranous (hamstrings) than the quadriceps.[1] This suggests that the hamstrings are used to decelerate and reduce external loading on the knee.[1] During cutting, muscle activation was also greater in the medial and lateral gastrocnemius, gracilis, sartorius, vastus medialis, vastus lateralis, and tensor fascia latae when compared to straightforward running.[1] This necessitates higher muscular strength at faster speeds.[1]

Specific Exercises Designed to Target Muscles Used in COD

With the suggestions made by Brughelli et al in mind, the muscles used during the COD task found by Besier et al and the force-vector theory, an exercise should be used to target the muscles in a unilateral fashion while applying a lateral force on the planted leg.[1, 2, 5] McCurdy completed an electromyography (EMG) motion analysis comparing the muscles activated during the bilateral squat (BS) and the modified single leg squat (MSLS) in 11 Division I female athletes from three different sports (3 soccer, 3 softball, 5 track and field).[18] EMG electrodes were placed on the gluteus medius, rectus femoris and bicep femoris on the dominant leg of each participant. The MSLS (**Figure 2**) is a unilateral exercise performed with a barbell on the lifter's posterior shoulders and their feet anterior/posteriorly staggered with the posterior foot elevated on top of a smooth and sturdy object (i.e. bench).[18] Participants completed 3 repetitions of the MSLS and the BS in a random order. Results showed that the MSLS placed greater demand on the gluteus medius ($\bar{x}$ ± SD: = 40.25 ± 7.8 mV to 27.35 ± 7.23 mV, p = 0.003; peak 72.17 ± 9.2 mV to 57.85 ± 22.09 mV, p =0.033) and hamstrings (57.10 ± 7.74 mV to 22.95 ± 1.84 mV, p = 0.004; peak 103.33 ± 18.89 mV to 60.02 ± 11.09 mV, p = 0.004) than the BS.[18] The BS did produce higher muscle activation for the quadriceps (105.44 ± 14.41 mV to 70.6 ± 15.31 mV, p = 0.013; peak 220.22 ± 40.6 mV to 171.23 ± 26.68 mV, p = 0.041).[18] Since the MSLS involves higher muscle recruitment from the gluteus medius and hamstrings than the BS, these findings suggest that the MSLS might result in significantly greater improvements in COD performance compared to the BS.[18]

McCurdy et al also measured gluteus maximus and hamstring activation, via EMG, in the MSLS, BS, and stiff-leg deadlift.[17] Participant's strength was assessed prior to EMG analysis to estimate the participants' maximal load in each exercise.[17] The participants then performed three repetitions of each exercise using their eight-repetition max. The MSLS had significantly greater gluteus maximus (65.6 ± 15.1 mV) and hamstring (40.1 ± 10.8 mV) activation compared to the BS (gluteus maximus: 40.3 ±

17.7 mV; hamstrings: 24.4 ± 10.6 mV) and stiff-legged deadlift (gluteus maximus: 40.5 ± 18.8 mV; hamstrings: 29.9 ± 12.5 mV).[17] McCurdy et al explained the greater activation in the gluteus maximus and hamstring muscles, compared to other studies, may be due to previous studies using body-weight resistance or light loads during exercises compared to this study using higher relative intensities of 8 RM.[17] The MSLS shows promise to improve COD performance as it activates the specific muscles used during COD and is performed in a unilateral fashion.

Figure 2 Modified single leg squat[18]

MSLS and COD Performance

Spiers et al investigated the MSLS and the BS in a five-week study that assessed rugby players' strength, sprinting and COD performance.[24] Before and after conditioning, 10-meter sprint, 40-meter sprint, and pro-agility test performance were measured. The players were randomly assigned either to the unilateral or bilateral groups. Both groups trained two times a week for five weeks (week 1: 4 sets of 6 repetitions at 75%; week 2: 4 sets of 6 repetitions at 80%; week 3: 4 sets of 5 repetitions at 85%; week 4: 4 sets of 4 repetitions at 90%; week 5: 4 sets of 3 repetitions at 92%).[24] No additional lower limb strength exercises were performed. Results were that both tests were equally effective in improving COD performance; however, the MSLS did not significantly improve the rugby players' pro-agility test times more than the BS. The MSLS group did have a tendency toward faster times than the BS (40-meter sprint post times: Unilateral = 5.26 ± 0.16 sec; Bilateral = 5.34 ± 0.23 sec; $p < 0.05$) (pro-agility posttest times: Unilateral = 4.53 ± 0.07 sec; Bilateral = 4.64 ± 0.14 sec; $p < 0.05$), but the BS showed an improvement in pro-agility test times by 1.9% ± 0.8% compared to the MSLS improvement times at 1.74% ± 1.0%.[24] This difference may seem very small; however, it could potentially mean a large difference in success or failure in an elite sport setting.

The MSLS does target the muscles used during the COD task (specifically the hamstrings) and is performed in unilateral fashion, which should aid transferability; however, when further analyzing the MSLS, the exercise is still performed similar to the BS in that the lifter is standing upright and resisting a downward vertical force on the lifter's upper back. COD is not performed in a vertical upright position; thus reducing the transferability from the MSLS to COD.

Analyzing Change of Direction Movement

To enhance transferability in COD, one should consider COD mechanics, rather than simply the muscles used. Marshall et al examined the kinetic and kinematic measures at the ankle, knee, hip joints, pelvis and torso of fifteen elite Gaelic hurling players during a 75° COD.[15] Participants refrained from lower extremity training 24 hours prior to the testing session. A 3D motion analysis system, synchronized with two force plates, was used to collect data. Reflective markers were placed on the landmarks of the lower limbs, pelvis and trunk. Participants undertook a warm-up period consisting of a 3-minute treadmill jog (8km/hour), 5 body weight squats, 5 single-leg squats, 5 drop landings, and 5 hurdle hops. The initial testing phase included 3 repetitions of sprinting 5 meters towards a marker set on a force plate. Participants made a single foot cut, with their dominant leg, on the force plate and performed a 75° COD towards another marker placed 5 meters away from the force plate. To ensure accuracy of the cutting angle, a marker was placed at a 75° angle from the force plate one meter away. Two pre-testing familiarization sessions were completed. Trials were successful if the participant was able to stay inside the "runway." Participants were instructed to complete the task as quickly as possible to ensure maximum effort. One-minute resting periods were used between each trial. After completing the initial testing phase, a retest phase was conducted one week later to ensure reliability. Marshall et al found five biomechanical factors that were key to COD performance (time: 2.28 sec ± 0.011 sec) – peak ankle power (14.7 ± 2.9 W/Kg; $p < 0.01$), peak ankle plantar flexor moment (2.5 ± 0.3 N/Kg; $p < 0.01$), range of pelvis lateral tilt (from initial contact to peak knee flexion = 5.2 ± 3.3°; $p < 0.01$), maximum thorax lateral rotation angle (4.0 ± 10.0°; $p < 0.01$), and total ground contact time (371 ± 59 msec; $p = 0.01$).[15] These results suggest that participants who were able to produce force quickly at the ankle and had greater rotation of their torso, while keeping frontal plane control of the pelvis, produced faster COD times. The common factors seem to be the force produced at the ankle as well as force produced in the transverse plane. Control of the pelvis in the frontal plane as determined by muscle activation of the gluteal muscles, particularly the gluteus medius, is also an important factor.[18] Thus specificity can be increased by activating the muscles used during COD in the same anatomical planes. Marshall et al suggested athletes perform plyometric training (counter-movement jumps and drop jumps) in order to improve COD; however, plyometric training is considered advanced training and has a greater injury risk, as seen in Castillo-Rodriguez et al. [4, 15]

Dos'Santos et al also analyzed mechanical determinants to improve COD in athletes.[9] It was hypothesized that greater braking forces (deceleration phase) and higher propulsive forces (acceleration phase) would result in faster COD performance.[9] 40 young, male participants with resistance training experience and free from lower limb injuries, participated in this study.[9] Testing was conducted over one session and consisted of 6 trials of the 505 test using left and right lower limbs in an alternating pattern as the planted leg. A force plate was placed where participants would be performing a 180° COD to collect ground reaction force (GRF) data as the participant initially contacted, planted and propelled himself in the new direction. Ground contact time and vertical and horizontal braking/propulsive forces were calculated. Forces were normalized for body mass for analysis (GRF/BM). Correlations between completion times and mechanical variables were calculated. Results showed ground contact time was a main determinant of faster performances in COD (49.1 – 57.3% of variance).[9] However, horizontal propulsive forces were also a determinant of faster COD performance (32.7 – 37.3%).[9] This finding suggests that a greater horizontal force applied when changing directions resulted in faster COD performance. In addition, slower participants had greater vertical impact forces (Slow Left = 19.24 ± 4.29 N/kg, Fast Left = 18.1 ± 4.0 N/kg, $p = 0.007$; Slow Right = 20.3 ± 5.4 N/kg, Fast Right = 16.5 ± 4.2, $p = 0.017$) and smaller horizontal braking forces [except for when testing the right side, which resulted in a non significant difference] (Slow Left = 11.3 ± 2.5 N/kg, Fast Left = 14.2 ± 2.9 N/kg, $p = 0.027$; Slow Right = 12.4 ± 3.1 N/kg, Fast Right = 12.4 ± 3.3, $p > 0.05$) during the initial deceleration while also showing smaller horizontal propulsive forces (Slow Left = 9.8 ± 1.9 N/kg, Fast Left = 12.4 ± 1.3, $p = 0.002$; Slow Right = 10.1 ± 1.0 N/kg, Fast Right = 13.2 ± 1.7 N/kg, $p < 0.001$) during the acceleration phase.[19] The results lead to the conclusion that the faster COD performers were able to perform better because they were able to manipulate their change in momentum and apply muscular forces towards their new intended direction more soundly than slower performers. Thus, correct force application throughout the phases of COD is a big determinant of COD speed.[9, 15] In order for athletes to apply greater forces in their sport-specific tasks, they should perform strength-training movements using the same muscles in the specific anatomical planes of the tasks.

Force Vector Theory

Specificity of exercises is important for athletes to increase performance outcomes.[25, 27, 28] However, specificity is not limited to only the muscles activated during an exercise or athletic skill. The force vector theory has been introduced, refining specificity of exercise in relation to the anatomical plane(s) that the athletic skill is performed in as well as the muscles activated.[20-22] It is proposed that training adaptations may be direction-specific in that exercises should exhibit concentric and eccentric loads in the same anatomical plane(s) as performed in the athletic movement. [5, 11, 13]

For example, Contreras et al hypothesized that the barbell hip-thrust would enhance hip horizontal force production because the movement is performed in the horizontal plane in relation to the body's anatomical position.[5] The hip thrust (**Figure 3**) is a resistance exercise performed while supine with a barbell placed across the pelvis and the barbell lifted using the hip muscles (gluteus maximus, hamstrings, etc.).[5] According to the force vector theory, since the barbell hip-thrust enhances horizontal force production, it will also increase performance to tasks related to the horizontal plane (i.e. sprint performance).[5] Contreras et al compared the effects of a six-week program using the barbell hip-thrust and front squat, a resistance exercise performed in the frontal plane, in a training programs on 10 meter and 20-meter sprint times, horizontal jump distance (a movement occurring in both the horizontal and frontal plane), and vertical jump height (a movement occurring in the frontal plane) in 24 adolescent males who were enrolled in a New Zealand rugby and rowing development program.[5] The athletes had at least one year of experience performing the front squat but no prior experience in performing the hip thrust. After familiarization with the hip thrust, participants performed a 10-minute lower-body dynamic warm-up that consisted of two sets of ten repetitions of the following exercises: standing sagittal plane leg swings, standing frontal leg swings, body weight squats, and hip thrusts. Participants then performed baseline testing for the front squat, hip thrust, vertical and horizontal jump, 10-meter and 20-meter sprints, and isometric mid-thigh pull. Participants were randomly assigned to either the front squat or hip thrust training groups. Training was six-weeks with two sessions, scheduled 72-hours apart, per week (week one: four sets of 12 repetitions, week two – three: four sets of ten repetitions, week four – five: four sets of eight repetitions, week six: four sets of six repetitions). Lower body training was specific to the movements. Each group also performed upper-body exercises (incline press or standing military press, bent-over rows, and bench pull or seated rows) and core exercises (unspecified) for four sets each for an unspecified amount of repetitions. Post-test was conducted after the six-week training program. Results were analyzed within-groups and between the groups. The vertical jump (effect size = -0.47 [-1.20 to 0.23]) showed a significant correlation to the front squat, while the 10-meter (effect size = 0.32 [-0.39 to 1.03]) and 20-meter (effect size = 0.39 [-0.31 to 1.09]) sprint times a significant correlation to the barbell hip-thrust. The horizontal jump (effect size = 0.15 [-0.57 to 0.87]) did not correlate to either specific exercise, as predicted.[5] These results suggest that the front squat yields better performance for vertical movements while the barbell hip thrust yields better performance for horizontal movements. Thus, supporting the force vector theory in that exercises performed in the same anatomical plane(s) as the athletic task, have higher transferability and greater performance improvements compared to exercises that use the same muscles but occur in a different plane.

Figure 3 Barbell hip thrust[5]

Loturco et al also applied the force vector theory.[13] They calculated the correlation between performance outcomes of the barbell hip-thrust, half-squat, and vertical jump to performance outcomes in the different phases of sprinting.[13] When an elite sprinter comes off a block at the start of the race, they accelerate in the horizontal plane for the first 50 meters as they keep their bodies parallel to the ground and gradually transition to a vertical upright position. Because of the different planes and positions used when sprinting, Loturco et al hypothesized that athletes that have a stronger barbell hip-thrust will have a faster velocity in the first 50 meters of a 150-meter sprint, while athletes who have greater half-squats, weighted jump squats, squat jumps, and countermovement jumps will have a higher velocity in the later stage of a sprint.[13] Sixteen elite (Olympic, world championship, or national level) sprinters and jumpers (9 males; 7 females) participated in this study. Day one consisted of five trials of two forms of the vertical jump (squat jump and countermovement jump) with the highest jump used for analyses. They then performed two 60-meter sprints with cameras set at 0 meters, 10 meters, 20 meters, 40 meters and 60 meters, with 8 minutes of rest between each trial. The fastest time was used for analyses. Day two of the study consisted of the athletes performing a 150-meter sprint, with three cameras set at 0 meters, 100 meters and 150 meters. After the sprinting protocol was completed, the athletes were assessed for their mean propulsive power (maximal velocity) outputs of the jump squat, half-squat, and hip-thrust. The initial testing of each exercise started with a load of 40% of each athlete's body mass. The athletes performed each exercise for three repetitions at maximal velocity. If the athlete was able to perform the three repetitions, they rested five-minute before the load was increased by 10% of their body mass. This process continued until a clear loss in maximal velocity was observed. Correlations for each exercise to the different sprint velocities at each distance were calculated. Results were that the hip-thrust had a significantly higher correlation (10 meters = 0.86; 20 meters = 0.91; and 40 meters = 0.91) than the squat jump (10 meters = 0.60; 20 meters = 0.86; and 40 meters = 0.86) and the countermovement jump (10 meters = 0.60; 20 meters = 0.85; and 40 meters = 0.90) during the first 50 meters.[13] However, the squat jump (60 meters = 0.92; 100 meters = 0.88; and 150 meters = 0.86) and countermovement jump (100 meters = 0.86; 150 meters = 0.81) showed higher correlation to the later phase of sprinting than the barbell hip thrust (60 meters = 0.89; 100 meters = 0.72; 150 meters = 0.74).[13] These results support the force vector theory and Loturco et al concluded that coaches and athletes should focus more on training force vectors , rather than creating a generalized strength program targeting the specific muscles used in an athletic skill.[13]

Gonzalo-Skok et al completed a force-vector theory study as well.[11] They divided 20 highly trained, young (13-14 years) male basketball players from an elite club into two groups. This study was different from the previous force-vector theory studies in the use of plyometric training. Before the start of the study, pre-training data were collected for several athletic tasks (forward sprint, countermovement jump, unilateral countermovement jump, unilateral horizontal jump, V-cut test, 180° COD, weight-bearing dorsiflexion, modified star excursion balance test). Participants then performed two plyometric training sessions per week for six weeks using movements specific to their assigned group (unilateral-horizontal or bilateral-vertical training). The unilateral-horizontal training program consisted of performing drop jumps from 10 cm, standing long jumps, standing long jumps without countermovement, unilateral jumps and triple jumps in the same order each week. The bilateral-vertical training program consisted of performing drop jumps from 20 cm, squat jumps with arm swings, countermovement jumps with arm swings, tuck jumps, and hurdle jumps in the same order each week. Both programs followed the same sets and repetitions with week one and two equaling 60 jumps per session (3 x 5, 2 x 5, 2 x 5, 5 x 2, 3 x 5), week three and four included 80 jumps per session (4 x 5, 3 x 5, 3 x 5, 5 x 2, 4 x 5), and week five and six increased to 100 jumps per session (4 x 5, 4 x 5, 4 x 5, 5 x 4, 4 x 5). Post-testing results were that the unilateral-horizontal training group achieved greater improvements in multiple COD tests (Horizontal V-cut Pre = 7.25 ± 0.22 sec, Horizontal V-cut Post = 7.01 ± 0.19 sec; Vertical V-cut Pre = 7.37 ± 0.41 sec, Vertical V-cut Post = 7.21 ± 0.40 sec; Horizontal COD180° Pre = 2.72 ± 0.05 sec, Horizontal COD180° Post = 2.72 ± 0.07 sec; Vertical COD180° Pre = 2.79 ± 0.17 sec, Vertical COD180° Post = 2.77 ± 0.16 sec).[11] These findings support the force vector theory further as well as applying it to COD tasks. Thus, according to the force vector theory, performing exercises in the same anatomical planes as COD will improve COD. However, this study used plyometric training, which was previously mentioned by Castillo-Rodriguez et al as advanced with a greater injury potential.[4]

Applying the force vector theory to COD, a force in the transverse plane is required to result in improvement in performance, similar to what was suggested by Brughelli et al.[2] At this time, the closest muscle-specific strength-training exercise for COD is the MSLS; however, it is performed only in the frontal plane. Thus, further modifications should be implemented.

CHAPTER THREE: MANUSCRIPT

Abstract

The purpose of this study was to determine if a new resistance training movement, the laterally resisted split squat (LRSS) will more closely mimic change of direction (COD) than previously used movements. Ten healthy and active female participants had 1RM for the LRSS, modified single leg squat (MSLS), and bilateral squat (BS) measured and then peak ground reaction forces (GRF) for the dominant leg recorded when performing a COD task and LRSS, MSLS and BS at 70% 1RM. Peak frontal plane GRF magnitude and angle were calculated for each task and submitted to repeated measure ANOVA. Peak GRF magnitude was significantly larger for COD (2.13 ± 0.52 bodyweight: BW) than the LRSS ($p < 0.001$), MSLS ($p = 0.001$), and BS ($p < 0.001$). Peak GRF angle was not significantly different between COD and the LRSS ($p = 0.057$), while the MSLS ($p < 0.001$) and BS ($p < 0.001$) vector angles were significantly greater than COD. In an application of the force vector theory, the LRSS more closely matches COD than the MSLS or BS. Thus, the LRSS may be a more beneficial resistant training movement for improving COD performance.

Keywords: Force vector theory, unilateral, strength training

Introduction

Change of direction (COD) is commonly used in sports and frequently assessed in athletes to predict performance outcomes.[2, 10, 20, 23] Improving COD has proven to be difficult as athletes exhibit inconsistent COD improvements following training.[4, 12, 16, 19] While strength training is commonly used by athletes to improve their performance, it is currently inconclusive whether muscular strength correlates to COD performance.[12, 19, 26-27] Thus, strength and conditioning coaches have focused on using power movements such as plyometric exercises or squat jumps to improve COD performance.[4, 16,] However, these techniques and movements may be too advanced for some individuals resulting in an increased risk of injury.[4]

Considering the inconsistent results, the main issue with improving COD performance may not have been the usage of strength training in agility programs, but lack of exercise specificity. In other words, applying the specificity principle[2], or performing exercises that mimic COD and its unique unilateral, multi-plane movement may be necessary to improve COD performance. The modified single leg squat (MSLS) appears to be closely related to COD because the muscles are activated in a similar unilateral fashion and reportedly improves COD performance following training. [1, 9, 15, 17, 18, 24] However, training with the MSLS did not produce greater improvements in COD performance than training with the bilateral squat (BS).[24] One possible reason for this discrepancy could be that, even though the MSLS replicates the muscular activation of the COD task, it provides inadequate stimulus to produce meaningful improvement in COD performance. The MSLS is performed in the frontal plane with a vertical load while COD occurs in multiple planes with both vertical and horizontal loads. The force-vector theory suggests that MSLS neither provides specificity, nor adequate stimulus to improve COD performance.[5, 11, 13]

The force-vector theory is a refinement of the specificity principle that states that athletes should perform exercises and drills in the same specific anatomical planes using the same vectors as the athletic skill they are targeting.[5, 11, 13] Contreras et al previously supported the force vector theory by comparing the barbell hip thrust (horizontal force production) and the BS (vertical force production).[5] The barbell hip thrust improved sprint times because of the anterior/posterior hip movement while the BS improved vertical jump height because of the cranial/pedal movement; however, the improvement in the horizontal broad jump was similar for both movements.[5] Contreras et al suggested that this was due to the broad jump requiring both vertical and horizontal forces.[5] Thus, the authors recommended that athletes perform training exercises that mimic both the movement plane and angle of force production in which the athletic skill occurs.

During a COD, the athlete plants their outer foot (foot opposite to the intended new direction) to eccentrically lower their hips and center of gravity and decelerate their momentum in the sagittal plane, and then applies a concentric force through the planted leg at a 45-75º frontal plane angle to push off the ground and accelerate their momentum in the new, intended direction.[7,9, 15] The MSLS mimics this movement in the frontal plane, 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 one foot at 45-75º frontal plane angle), with the lifter eccentrically lowering their hips then applying a concentric force through the planted foot (creating an addition of lateral force at an angle similar to COD) to produce a meaningful improvement of performance for the task. Based on the inconclusive results demonstrated to date and by applying the force-vector theory, we propose a new more specific strength-training exercise, the laterally resisted split squat (LRSS) to improve COD ability.

The LRSS is similar to the MSLS with the addition of a lateral force and placing the planted leg at an angle similar to 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 approximately under the free end of the bar and the lifter picks up the free end of the bar and hugs it to their chest in a Zercher hold (Figure 1). The participant then slowly eccentrically descends on the planted leg to an approximate knee angle of 90˚ and then rapidly concentrically ascends to the starting position, driving into the barbell, creating the frontal plane angle similar to performing COD. It is theorized that the resistive forces applied to the lifter's planted leg are both lateral and vertical forces and while this movement is still performed in the frontal plane, the barbell's lateral anchor creates a lateral force and angle similar to COD.

Figure 4 Laterally resisted split squat

The purpose of this study was to determine if the LRSS more closely mimics both the movement plane and angle of force production of the COD than the MSLS and BS movements. It was hypothesized that the LRSS would result in a peak GRF magnitude and angle that is not statistically different than COD, but significantly different than the BS and MSLS, respectively.

Methods

Experimental approach to the problem

To test the main hypothesis, participants performed COD, LRSS, MSLS, and BS with their dominant limb on a force plate. GRF was collected and GRF magnitude normalized to participant's body weight. Peak GRF magnitude and its vector angle from the horizontal axis was analyzed through repeated measure ANOVA to determine significant difference in peak GRF and vector angle between COD and the three exercise movements.

Participants

Ten healthy and recreationally active females (Age: 23.8 years ± 5.37 years, Body Mass 70.35 kg ± 14.31 kg, primary sport: four lacrosse, two volleyball, two hiking, one Nordic skiing, and one power lifting) participated in this study. To be included, participants were required to successfully complete the COD mechanics field test (**Appendix A**). The COD field test involved the participant sprinting for 10-meters and performing a 90° turn off their dominant limb. During COD test, mechanics were assessed on a 3-point scale to ensure participants could adequately control their lower extremity via mechanically sound patterns when performing the study movements and evaluated with the following criteria: shortening of stride length and lowering of center of mass when decelerating, shin angle visually estimated less than 90° sagittal plane and between 45-75° in the frontal plane shin angle during COD, and rotation of hips during push-off towards the new intended direction.[7, 14] Participants had to score at least a 2 on each criteria to be included. All participants successfully completed the COD screening.

Potential participants were excluded if they exhibited knee valgus or ankle eversion during COD field test, reported current lower extremity injury or history of lower extremity surgery. The Institutional Review Board of Human Subjects at Boise State University approved this study (186-MED19-002). Participants provided written consent and a completed health history prior to testing. The dominant lower limb was first established by asking the participant "Which leg do you kick a soccer ball with?" This was then verified with an actual kick. All participants were right leg dominant.

Table 1 Descriptive statistics of participants

Participants (Female)	Age (years)	Mass (kg)
10	23.8 ± 5.37	70.35 ± 14.31

Experimental Procedures

Strength Assessment

The LRSS was demonstrated and participants practiced the movement using a free-weight standard barbell (20.45 kg) with a 4.55 kg bumper plate for five or more repetitions. Corrective feedback was provided until the participant accurately performed the LRSS. After adequate recovery, 1RM estimates for the LRSS, MSLS and BS were assessed in a random order to determine loads for kinetic testing. The participants then performed the first randomly selected exercise for five to ten repetitions at a predetermined percentage of body weight (LRSS = 50%; MSLS = 50%; BS = 80%). If ten repetitions were performed correctly, additional weight (up to 9.09 kg based upon participant's perception of the weight) was added for another attempt. Once the participant could no longer perform the exercise with correct form for more than ten repetitions, the number of correct repetitions and final weight were recorded. The Bryzcki formula was then used to estimate the participant's 1RM.[3, 8]

Predicted 1RM = weight lifted/1.0278 – 0.0278(repetitions)

This procedure was repeated for the other two exercise movements.

Kinetic Assessment

After an adequate rest (3 – 5 min) following the strength assessments, kinetic (GRF) data was recorded with one in-ground force platform (OR-6, AMTI, Watertown, MA) as the participant performed the study (COD, LRSS, MSLS and BS) tasks. The COD task required participants run 10-meters at their own chosen speed, before planting their dominant leg on the force platform and performing a 90º COD pivot and running 10 meters in the newly established direction. After completing the COD, participants randomly performed one of the three resistance movements (LRSS, MSLS, and BS) with their dominant foot on the force plate using 70% of their calculated 1RM **(Figure 2)**. The LRSS required the participant to have the barbell in the Zercher squat hold position and leaning into the weight, while also having the non-dominant foot resting on top of the leg rest behind them before starting. The MSLS required the participant to place the barbell on the participant's upper back and place their non-dominant foot on top of the leg rest behind them before starting. The BS required the participant to place the barbell on the participant's upper back and place their non-dominant foot shoulder width apart from their dominant foot before starting. For each resistance movement, participants performed as many repetitions as possible at a self-selected consistent speed for 15 sec. Participants were required to rest for three minutes between performances of each study task.

This process was repeated until sufficient data was collected from each participant for all three movements. Only one trial was analyzed in this study, with the repetition having the highest peak GRF magnitude value was further analyzed.

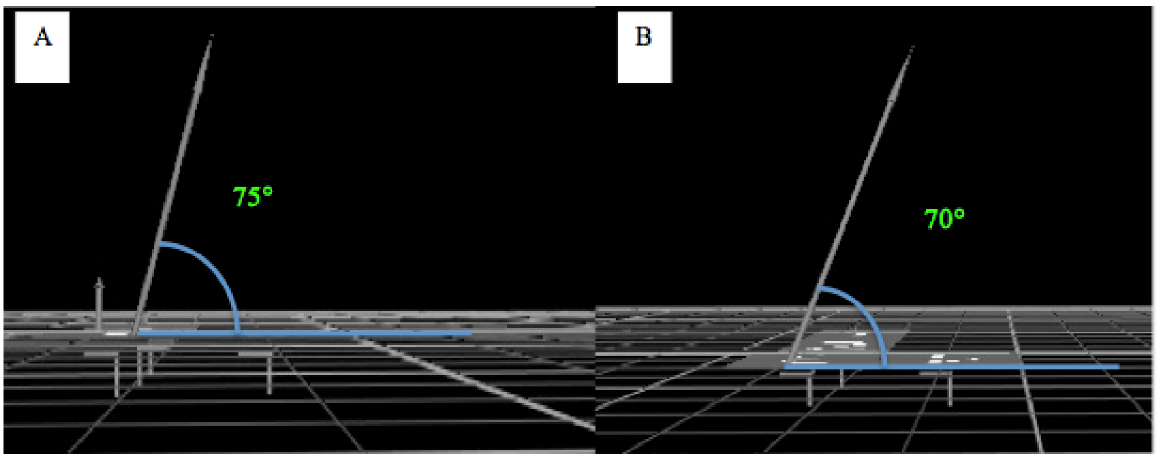

Figure 5 Representative of LRSS (A) and COD (B) vector angles in Nexus. Angles were measured from horizontal axis.

Provocative Measures

Custom MATLAB script (version 2019a, Mathworks, Inc. Natick, MA) was used to calculate peak frontal plane GRF magnitude and angle according to Creaby and Dixon.[6] The peak frontal plane GRF magnitude and angle were calculated using the standard following trigonometry equations:

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

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

Fz represents the vertical GRF and Fx the mediolateral GRF, respectively. GRF magnitude was normalized to participant body weight plus weight lifted (in Newton's) and GRF angle was calculate as the angle from the horizontal axis.

Statistical Analyses

The dependent variables include body mass, 1RM for LRSS, MSLS, and BS, and peak frontal plane GRF magnitude and angle for all study tasks. Prior to analysis 1RM data was tested for outliers using the box and whiskers technique with interquartile range (IQR) method[22] and one participant was removed from the subsequent analysis. Next, peak frontal plane GRF magnitude and angle were submitted to a repeated measure ANOVA to test main effect of study task (COD, LRSS, MSLS and BS). Effect size was calculated in SPSS by squaring the partial eta squared for each variable. To reduce probability of committing Type I error a Bonferroni correction was used for post-hoc comparisons. All analysis was conducted in SPSS 25 (IBM Corporation; Armonk, NY), with alpha level was set at 0.05.

Results

Descriptive statistics (mean ± SD) for participants' 1RM (kg), peak frontal plane GRF magnitude and its corresponding vector angle for COD, LRSS, MSLS, and BS are presented in **Table 2**.

Table 2 Descriptive statistics of participants' 1RM, GRF_{mag} and GRFΘ

Variable	1RM (kg)	Peak Frontal Plane GRF_{mag} (BW)	Frontal Plane GRFΘ (Degrees)
COD	N/A	$2.13 \pm 0.52^{\$¥¢}$	$66.70 \pm 4.98^{¥¢}$
LRSS	$43.18 \pm 8.27^{¢}$	$0.85 \pm 0.37^{\#¥¢}$	$74.94 \pm 4.11^{¥¢}$
MSLS	$37.63 \pm 7.96^{¢}$	$0.99 \pm 0.10^{\#\$¢}$	$89.04 \pm 0.48^{\#\$¢}$
BS	$58.08 \pm 19.39^{\$¥}$	$0.52 \pm 0.07^{\#\$¥}$	$82.69 \pm 4.30^{\#\$¥}$

$^{\#}$ - 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

There was a significant main effect of task for 1RM (F = 10.41, p = 0.001; ES = 0.32). Post Hoc testing revealed 1RM was significantly greater for BS compared to LRSS (p = 0.026) and MSLS (p = 0.025), but no significant difference was evident between LRSS and MSLS (p = 0.413). Thus, in terms of 1RM, BS > LRSS = MSLS.

There was a significant main effect of task for GRF magnitude (F = 65.10, p < 0.001; ES = 0.79). Post Hoc testing revealed significant differences in peak frontal plane GRF magnitude. Specifically, COD had a significantly larger peak GRF magnitude compared to LRSS (p < 0.001), MSLS (p = 0.001), and BS (p < 0.001), and GRF magnitude was significantly greater for MSLS compared to LRSS (p = 0.005) and BS (p < 0.001), and for LRSS compared to BS (p < 0.001). Thus, in terms of GRF magnitude, COD > MSLS > LRSS > BS.

There was a significant main effect of task for peak GRF angle ($F = 50.14$, $p < 0.001$; $ES = 0.74$). The post hoc analysis reveal no significant difference in peak GRF angle between COD and the LRSS ($p = 0.057$), but the peak GRF angle was significantly smaller for both COD and LRSS compared to MSLS (both: $p < 0.001$) and BS ($p < 0.001$; $p = 0.047$), and for BS compared to MSLS ($p = 0.014$). Thus, in terms of GRF vector angles, COD = LRSS < BS < MSLS.

Discussion

The purpose of this study was to determine if a new resistance training movement, the LRSS, would more closely mimic COD than previously used movements. Force plates were used to determine the angle and magnitude of peak GRF vectors for each of the four movements. These results were compared to determine which movement is most similar to COD. It was hypothesized that the LRSS would result in a similar peak GRF magnitude to COD and both will be significantly different than the BS and MSLS. This hypothesis was rejected. It was also hypothesized that the LRSS would result in a similar frontal plane GRF vector angle to COD and both would be significantly different than the BS and MSLS. This hypothesis was accepted

Contrary to our hypothesis, the peak GRF magnitude was significantly greater for COD than the three resistance exercises (LRSS, MSLS, and BS). One reason this could have occurred was the use of 70% of 1RM when testing each movement and comparing these to COD at participant's chosen speed. Measuring GRF with the actual 1RM for each exercise might have resulted in values more similar to the peak GRF magnitude in COD. Even so, GRF magnitude may not be a good indicator for better transferability than the force vector angle used in this study. Jullien et al used the BS on a concentric squat machine set to 90% of their 1RM for three sets of three repetitions for three weeks, five times a week, versus coordination training to demonstrate no effect of strength-training on COD.[12] The coordination training group did see more improvements in the shuttle test than the BS group, therefore the rejection of strength-training for COD.[12] However, this could provide support for using a more specific strength-training exercise (i.e. the LRSS) than performing exercises at high intensities – perhaps the movement pattern is more important than the intensity? The current study found that the MSLS had a higher GRF magnitude compared to the LRSS; however, the GRF angle was dissimilar and may not result in transferability as seen in Spiers et al with the MSLS and BS not differing in improvement.[24] In the Spiers et al study, both the MSLS and BS resulted in similar improvements in COD (training at 75% - 92% 1RM, 4 sets of 3 – 6 repetitions per week for five weeks), as measured via the pro-agility test; thus, a possible reason to use a higher percentage of 1RM.[24] However, just as discussed about in Jullien et al, the specificity may be more important than the intensity.[12] Castillo-Rodriquez et al had participants perform single-leg countermovement and drop jumps.[4] These movements may be seen as too intense and may increase injury risk in athletes, as three participants were reported to be injured from the study and had to be excluded from analysis.[4] Castillo-Rodriguez et al also suggested to “prescribe more rational exercises to improve COD performance” when discussing specificity of movements to predict improvement in performance.[4] Specificity of exercise movements needs to be more than muscle activation patterns. McCurdy et al tested the MSLS using electromyography (EMG) and found higher hamstring and gluteus medius and maximus activation due to the single leg stance in the MSLS compared to the BS, which required higher quadriceps activation. [17, 18] These muscles are highly recruited during COD.[1,15] Thus, the MSLS at a high intensity level should have a significantly greater improvement in COD than the BS. However, this was untrue in Spiers et al, leading to us redefining specificity and use the force vector theory when training to improve athletic tasks.

In agreement with our hypothesis, the frontal plane GRF vector angles in COD and LRSS were not statistically different. This should lead to better transferability per the force vector theory and would be more appropriate in strength-training programs as compared to the MSLS and BS. This fits the findings by Contreras et al using the force vector theory for improving vertical jump height, sprint times and horizontal jump distance using the BS and the barbell hip thrust.[5] The BS (vertical force production) more significantly improved participants' vertical jump height than the barbell hip thrust (horizontal force production), which significantly improved participants' sprint times more than the BS after a six week training program.[5] Neither movement demonstrated greater improvements in the horizontal jump (vertical and horizontal force production) due to the movement being performed in two different planes, creating a force vector angle, similar to COD.[5] The force vector theory suggests using conditioning movements in similar anatomical planes improves transferability to the targeted athletic task.[5, 11, 13] While all three exercises are performed in the frontal plane, the LRSS also requires horizontal force production and results in a resultant vector similar to COD. Therefore, COD and LRSS were not significantly different, but the MSLS and the BS were.

Limitations in this study include the use of 70% 1RM compared to chosen COD speed. Future studies should compare 1RM loads to COD with the use of EMG on muscles primarily activated during COD as to fully understand the LRSS and how it can be the most appropriate movement to improve COD. The LRSS is performed; however, in a similar stance as the MSLS, which according to McCurdy et al, the muscle activation pattern observed was because of the MSLS's unilateral stance. Thus, the same muscle activation pattern would be expected. The gluteus medius, a muscle that highly correlates to better COD performance, may even experience higher activation in the LRSS due to the angular force vector of the movement compared to the MSLS.[1, 15] Further investigation of muscle activation during the LRSS should be conducted. Another limitation was using recreational athletes who have limited weight lifting and COD experience. Advanced and elite athletes may be able to more accurately activate the targeted muscles and use better lifting strategies compared to the athletes used in this study. In addition, testing for 180° COD was not conducted, however it is analyzed in assessing COD and agility speed in several sports (i.e. pro-agility test, NFL combine);[20, 23] thus, a comparison of the LRSS to a 180° might prove interesting. This study only analyzed the LRSS and COD from a peak GRF magnitude and vector angle stand point. While the vector angles of the two tasks were not statistically different, suggesting that the LRSS should improve COD, the LRSS was not actually used in a training module to improve COD. A follow up study in which athletes use an LRSS training module measuring changes in COD would be beneficial in solidifying the LRSS as the most appropriate movement for COD and more support for the force vector theory.

Practical Applications

This study was the first to introduce the LRSS, which resulted in a similar vector angle from horizontal axis to COD. This finding provides force vector theory support for using the LRSS to improve COD performance in athletes. Strength and conditioning coaches can now provide a more effective movement for novice athletes learning new movement patterns or elite athletes trying to break a plateau and increase COD speed. Future work using the LRSS with these populations should be explored.

Acknowledgments

The authors wish to thank the participants for their willingness to join us and the staff of the Boise State University Center for Orthopedics and Biomechanics research for their assistance.

The authors have no conflict of interests.

The results of this study do not constitute endorsement of any product by the authors or the NSCA.

CHAPTER FOUR: CONCLUSION

The purpose of this study was to determine if a new resistance training movement, the LRSS, would more closely mimic COD than previously used resistance training movements, the bilateral squat (BS) and the modified single leg squat (MSLS). Force plates were used to determine the angle and magnitude of peak GRF vectors for each of the four movements. These results were compared to determine which movement is most similar to COD, leading to the possibility of increased transferability. It was hypothesized that the LRSS would result in a similar peak GRF magnitude to COD and both would be significantly different than the BS and MSLS. This hypothesis was rejected. It was also hypothesized that the LRSS would result in a similar frontal plane GRF vector angle to COD and both will be significantly different than the BS and MSLS. This hypothesis was accepted.

Agility has two distinct components – physical and cognitive.[10] The cognitive aspect deals with the ability to be able to respond to a stimulus while the physical aspect is the capability of changing directions. Strength training has commonly shown improvements in athletic tasks, but mixed findings when it comes to COD.[4, 12, 16, 19, 24-27] Spiteri et al did find a correlation between muscular strength and COD, which supported the use of strength training in order to improve COD.[25] However, studies attempting to improve COD via strength training have either been too advanced or too generic.[4, 12, 15, 16]

Specificity training and transferability leads to the supposition of the MSLS being the most suited to improve COD due to the muscle activation pattern of the exercise.[1, 17, [18, 27] However, the BS showed improvements equal to the MSLS in the pro-agility test.[24] It has been suggested that this was due to the vertical force production seen in the two movements, while COD uses both vertical and horizontal forces to create a force vector angle of approximately 67° as seen in the current study. The laterally resisted split squat (LRSS) is a new movement introduced in this study designed with the force vector theory at its core.

The current study found that the LRSS had a similar force vector angle to COD. This should lead to better transferability per the force vector theory and would be more appropriate in strength-training programs as compared to the MSLS and BS. This fits the findings by Contreras et al using the force vector theory for improving vertical jump height, sprint times and horizontal jump distance using the BS and the barbell hip thrust.[5] The BS (vertical force production) more significantly improved participants' vertical jump height than the barbell hip thrust (horizontal force production), which significantly improved participants' sprint times more than the BS after a six week training program.[5] Neither movement demonstrated greater improvements in the horizontal jump (vertical and horizontal force production) due to the movement being performed in two different planes, creating a force vector angle, similar to COD.[5]

The GRF magnitude of the LRSS and COD may have differed, but that could have been due to study design and limitations (i.e. 70% 1RM, recreational athletes). Even so, GRF magnitude may not be a good indicator for better transferability than the force vector angle used in this study. Jullien et al used the BS on a concentric squat machine set to 90% of their 1RM for three sets of three repetitions for three weeks, five times a week, versus coordination training to demonstrate no effect of strength-training on COD.[12] The coordination training group did see more improvements in the shuttle test than the BS group, therefore the rejection of strength-training for COD.[12] However, this could provide support for using a more specific strength-training exercise (i.e. the LRSS) than performing exercises at high intensities – perhaps the movement pattern is more important than the intensity? The current study found that the MSLS had a higher GRF magnitude compared to the LRSS; however, the GRF angle was dissimilar and may not result in transferability as seen in Spiers et al with the MSLS and BS not differing in improvement.[24]

The current study did not investigate muscle activation using electromyography (EMG) in the three exercises in relation to COD. McCurdy et al reported higher hamstring and gluteus medius and maximus activation due to the single leg stance for the MSLS compared to the BS, which required higher quadriceps activation.[17,18] The LRSS features a similar stance to the MSLS, so the same muscle activation pattern can be expected. The gluteus medius, a muscle that correlates to COD performance, may also benefit more from the LRSS compared to the MSLS due to the angular force vector of its movement.[1,15] This could offer more reason to use the LRSS as oppose to the MSLS and should be studied further.

The LRSS may also be a safer exercise for novice lifters as the lifter uses the bar for balance and reduces the proprioceptive load compared to exercises where the barbell is placed on top of the lifter's upper shoulders such as seen in the MSLS and the BS. After completing 1RM assessments, participants were asked "Between the LRSS and MSLS, which exercise was easier and why?" Eight of the ten participants said the LRSS was easier with seven of them saying they "did not have to focus on balance as much and could use the targeted muscles more efficiently for an overall better workout." Since the LRSS does not require as much focus on balance as compared to the MSLS, which has previously shown improvement in COD, it may be superior for novice lifters and adolescent athletes. However, the LRSS may also be beneficial for more advanced and elite athletes as a way to break a plateau by focusing on the specific force vector and muscles more efficiently to improve COD performance. Thus, the application of the LRSS by novice and advanced movers should be further studied.

The LRSS has potential in strength and conditioning and should be studied in different aspects to help introduce its usage to a variety of sports even outside of COD (i.e. hip rotation movements such as baseball pitcher or batter). To further understand the LRSS, more research should examine its unique properties (electromyography, motion capture, etc.) and analyze how the horizontal and vertical force production can lead to possible success in other areas movements. However, based on the force vector theory, it is concluded that the LRSS shows potential for improving COD and should be added into strength training of athletes in sports requiring quick, multi-plane movements.

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APPENDIX A

Table 3 COD screening table chart used to assess COD of participants

<table>
<tr><th colspan="2">COD Screening Score Sheet</th></tr>
<tr><th>COD Mechanics</th><th>Dominant 90°</th></tr>
<tr><td>• Short stride length when decelerating
• Change in COM
• Less than 90° sagittal plane shin angle
• 45-60° frontal plane shin angle
• Rotation of hips during push-off towards new direction</td><td>3</td></tr>
<tr><td>• Change in COM
• Less than 90° sagittal plane shin angle
• 60-75° frontal plane shin angle
• Rotation of hips during push-off towards new direction</td><td>2</td></tr>
<tr><td>• No change in COM
• 90° sagittal plane or larger shin angle
• 90° frontal plane shin angle
• Knee valgus
• Ankle eversion
• No rotation of hips during push-off</td><td>1</td></tr>
<tr><td>Fail

(Score of less than 2 in any category)</td><td>Pass

(Score of at least 2 in every category)</td></tr>
</table>