OPTIMIZING INJURY RISK ASSESSMENTS: CORRELATION OF GROUND REACTION FORCE ASYMMETRIES IN VERTICAL JUMPS

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ABSTRACT

Sport-related injuries present a complex and costly challenge for athletes, coaches, trainers, athletic programs, healthcare professionals, and communities. Increased injury risk in the lower extremities in athletes may be attributed in part to bilateral asymmetries—measurable imbalances in function or performance between the right and left limbs. To assess bilateral asymmetry, functional movement assessments (FMAs) have been shown to be a valid, reliable method. The goal of this investigation was to examine how closely asymmetry measurements relate to each other in three different movements based on those previously used in FMAs. A cohort of male and female collegiate athletes (n=104) performed drop jump, countermovement jump with rebound, and single-leg countermovement jump assessments on force platforms to measure vertical ground reaction force (vGRF) asymmetries in both concentric and eccentric phases of each movement. Asymmetry correlations were all significant at the p=0.01 level. Correlations between bilateral movements during both concentric and eccentric phases were strong (r=.573-.708), but concentric and eccentric correlations between bilateral and unilateral movements were weak to moderate (r=.278-.350), as were those between concentric and eccentric phases of the same movement (r=.440-.485). Results suggest that no movement included in this assessment correlated strong enough in asymmetry values to justify replacing one movement with another, as each provided unique asymmetry information. Differences in neurological activation and motor control between movements may have contributed to these differences in asymmetry values, as well as anthropometric variables and training unique to each athlete. An understanding of the differences in asymmetry information yielded by different movements can help clinicians optimize FMAs for the most complete picture of an athlete's risk for injury associated with their musculoskeletal biomechanics.

INTRODUCTION

Sports-related injuries have been a large problem for competitive and recreational athletes, coaches, trainers, athletic programs, and communities. Sports injuries are an important economic burden across all ages (Ozturk and Kilic 2013), with studies estimating a cost per injury of $335 USD in 1990 (de Loes 1990) and the cost burden of sports injuries to be 0.07-0.08% of total healthcare costs (Cumps et al. 2008). In the 30 million school-age children alone who participate in organized sports programs, the treatment for acute and overuse injuries (which most commonly include injuries to the ankle and knee followed by the hand, wrist, elbow, lower leg, head, neck and clavicle) has been estimated to cost as much as $1.8 Billion USD/year in 2003 (Adirim and Cheng 2003). In addition, sports injuries can have significant negative psychological consequences for athletes (Schuer and Dietrich, 1997; Crossman, 1997) especially if the athlete had an investment in playing at the elite level (Kleiber and Brock, 1992).

Epidemiological research of collegiate athletes in the NCAA has illuminated the extent and frequency of injuries in competitive sport. An epidemiological study conducted by Yang et al. (2012) examined injury data across 16 teams at one Big 10 institution and found an injury rate of 63.1 per 10000 athletic exposures (games or official practices), or 1317 total injuries across 4 years. Across the 16 teams analyzed, half of overuse injuries were associated with no time loss, while only about a quarter of acute injuries were associated with no time loss. Overuse injuries accounted for a quarter of these injuries (the rest being acute injuries) and about half of each of overuse and acute injuries occurred to the lower extremities. (Yang et al. 2012). Furthermore, descriptive epidemiological studies by the NCAA Injury Surveillance system found that lower extremity injuries account for at least 1/3 of all competitive sports injuries in 15 NCAA sports, with 8 of these sports having lower extremity injuries account for over 50% of total injuries (Dick, Ferrara et al. 2007; Agel, Palmieri-Smith et al., 2007; Agel, Dick, et al., 2007; Agel, Dompier, et al., 2007; Agel, Evans, et al., 2007; Agel, Olson, et al. 2007; Dick, Hertel et al. 2007; Dick, Hootman et al. 2007; Dick, Lincoln et al., 2007; Dick, Putukian et al., 2007; Dick, Romani et al., 2007; Dick, Sauers et al., 2007; Marshall, Covassin et al., 2007; Marshall, Hamstra-Wright et al., 2007).

Increased injury risk in the lower extremities in athletes may be attributed in part to bilateral functional asymmetries—measurable imbalances in function or performance between right and left limbs. A study on 26 male athletes across several sports with a history of hamstring injuries and discomfort found that 18 of the athletes had significant bilateral strength deficits (Crosier et al. 2002). Soccer players with bilateral imbalances were found to be 5 times more likely to sustain a hamstring strain than those without an imbalance (Crosier et al. 2003), and players sustaining non-contact knee sprains had reduced muscle strength in the injured leg (Ekstrand and Gilquist 1983). In collegiate track and field athletes, leg imbalance and hamstring strength was also found to be related to occurrence of hamstring strains (Yamamoto 1993). In female collegiate athletes, it was found that strength and flexibility imbalances in the hip extensor or knee flexors were associated with lower extremity injuries, and that hip muscle imbalances are correlated with lower back pain (Knapik et al. 1991; Nadler et al. 2001). In addition, neuromuscular imbalances were found to be an important contributor to ACL injury (Myer et al. 2004).

Much of the aforementioned literature employed the use of dynamometers to measure bilateral functional asymmetry in athletes, but many research designs use functional movement assessments and the use of vertical ground reaction forces (vGRFs) through force platforms to measure bilateral asymmetry. The trend of sports rehabilitation assessments recently has been to move away from isolated assessments (such as that done by dynamometers, devices used to test the strength of specific muscle groups) toward an integrated, movement-based approach of evaluating athlete biomechanics. Such functional movement assessments evaluate the body as a kinetically linked system of "regional interdependence" where dysfunction or injury in one region can contribute to dysfunction in other regions of the body, thus allowing clinicians to more easily observe inefficient movement patterns that could contribute to injury (Cook et al. 2014). Three categories of functional movement tests have been used in past designs to measure bilateral vGRFs, as they are simple, repeatable, reflect common joint movement patterns and loading, and have been found to be predictive of injury risk and performance. These categories include Drop Jumps (DJs)/Drop Landings, Bilateral Squats/countermovement jumps (CMJs), and Single leg (SL) squats/SL CMJs[1].

Studies of drop landing and DJ vGRFs found that these movements were effective at evaluating functional asymmetry and predicting increased risk of future ACL injuries (Schot et. al. 1994; Paterno et al. 2007). In addition, the DJ was used in a study on high school female athletes to find that increased vGRFs, bilateral leg force asymmetries and kinematic variables such as knee valgus were predictors of ACL injury (Hewett et al. 2005). Measuring vGRFs in drop jump and drop landing tasks were also able to evaluate biomechanical risk factors for patellofemoral pain syndrome (PFP): that is, individuals with PFP syndrome exhibited lower dominant leg vGRFs than healthy controls, among other kinematic differences (Souza et al. 2009; Boling et al. 2009). One study, however, found that none of the vertical DJ assessment variables measured, including peak vGRF of injured limb vs. uninjured limbs in controls, were associated with increased injury risk (Krosshaug et al. 2016).

[1] See Methods for descriptions of the DJ, CMJ with Rebound, and SL CMJ movements under "Test protocol"

There is limited but encouraging literature supporting the ability of bilateral bodyweight (BW) squats and bilateral countermovement jumps (CMJs) to evaluate functional asymmetries using vGRFs. One study found that the BW Squat assessment using wearable inertial measurement units (IMU's) can distinguish with "excellent accuracy" between acceptable and aberrant squat mechanics as defined by the National Strength and Conditioning Association (O'Reilly et al. 2017), and another study found that a BW squat can be used to identify vGRF functional asymmetry caused by injuries to the PCL (Liu et al. 2010). However, another study found no difference in peak vGRFs between ACL-reconstructed and healthy limbs upon performing bilateral squats, even though other kinetic and kinematic variables displayed bilateral asymmetries (Salem et al. 2003). Prior research on the efficacy of CMJ tests to assess bilateral asymmetry has been similarly encouraging but limited: some studies have found that assessment of vertical force parameters such as vGRFs through vertical jump tests has been reliable (Impellizeri et al. 2017; Hori et al. 2009; Peterson et al. 2016), and that the CMJ test has been successfully used to evaluate bilateral vGRF asymmetries in athletes post-ACL reconstruction (Jordan et al. 2015).

Prior research appears to be even more limited for the use of vGRFs in single-leg functional movement assessments, as most measured kinematic variables such as frontal plane projection angles to evaluate human biomechanics. The few studies that have measured vGRFs for these movements provided mixed results: Alenezi et. al. (2014) found that using vGRF data in the SL squat was reliable, though it provided less data variability than kinematic measurements, but a study by Marshall et al. (2016) found that the SL squat assessment did not provide meaningful insight into bilateral loading in athletes with Athletic Groin Pain using vGRF measurements. In addition, a review of SL squat movement analysis studies by Warner et al. in 2019 found that due to variability in methodology of prior research, it was not possible to determine (with the SL squat) the specific biomechanical parameters that distinguish pathological and non-pathological groups. Similarly limited with prior research, the use of the SL CMJ in a functional movement assessment was found by Barber et al. in 1990 to not detect functional limitations (like asymmetries) in a reliable manner. The aforementioned study, however, used jump reach height rather than vGRF measurements to come to that conclusion (Barber et al. 1990). A more recent study on soccer players found that the SL vertical jump was able to find force asymmetries between non-dominant and dominant legs during the impulse phase of the jump but not the landing phase (Yanci and Camara, 2016).

Based on the extent of prior literature, DJ movements appear to be the most reliable and used functional movement assessments for screening lower-extremity biomechanical risk factors like bilateral asymmetry using vGRFs. Bilateral squats and CMJs appear to be reliable for evaluating vGRF functional asymmetry, but with less supporting research, and SL squats and SL vertical jumps appear to have mixed and uncertain reliability for evaluating biomechanical risk factors. Currently, though it is starting to be included with CMJs, performing an immediate rebound jump afterward has not been evaluated. The goal of this study was to examine if countermovement jump rebound movements (CMJRs) and single-leg countermovement jump (SLCMJs) movements, which add more medial/lateral limb complexity to movements used in prior studies, both correlate strongly to bilateral asymmetry vGRF measurements in the DJ. This could help elucidate if CMJRs and SLCMJs are worth including in a functional movement assessment along with the DJ. If they correlate strongly in their asymmetry measures, then perhaps they are less necessary, but if they do not correlate strongly to the DJ, the CMJR and SLCMJ may provide unique biomechanical information not provided by the DJ.

If the aforementioned movement assessments are considered to be 4 individual movements: the DJ, CMJ, rebound jump (RBJ), and SLCMJ, all 4 of these movements could be further divided into an eccentric braking phase followed by a concentric propulsive phase. Unique asymmetry data can then be aquired from each phase. Dividing movements into concentric (muscle shortening under load) and eccentric (muscle lengthening under load) phases, and measuring forces from these individual phases, can possibly give a clinician or trainer a broader picture on an athlete's condition and or performance. Thus, these measurements could be important for crafting testing, rehabilitation, and conditioning techniques for athletes who perform in high-speed concentric and eccentric muscle contractions in their respective sports (Ghena et al. 1991). Past studies have compared concentric and eccentric loading and power in the lower extremities through dynamometer torque output measurements at different contraction speeds, mostly at the quadriceps and hamstrings. This design structure was shown to be reliable (Tredinnik and Duncan, 1988). It was found that hamstring and quadricep torque outputs were significantly higher but neural activation was significantly lower (measured through electromyographic activity) during eccentric movements than concentric movements, and that increasing contraction velocity reduces torque in the hamstrings and quadriceps during concentric contractions but has no effect on torque during eccentric contractions (Ghena et al. 1991; Westing et al. 1991). One study analyzed hamstring torque asymmetry in elite soccer players using dynamometers, finding that eccentric torque asymmetry of over 10% did not identify players with a prior hamstring injury, but concentric hamstring asymmetry of over 10% did correlate with prior hamstring injury with over 90% probability (Dauty et al. 2003). To measure and compare eccentric and concentric force asymmetries in the lower extremities, vGRFs could be utilized. Along with measuring how eccentric average braking force asymmetry compare between movements, average propulsive and braking force asymmetries can be compared within each movement. The magnitude of difference between asymmetry in eccentric and concentric phases of these movements could carry implications for strengthening and conditioning strategies as well as injury risk.

Thus, the purpose of this study was to compare average concentric (propulsive) force asymmetry and average eccentric (braking) force asymmetry between 3 functional movement assessments and 4 total movements: DJ, CMJ, RBJ, and SLCMJ to assess if some jump types yielded different asymmetry information than others. A secondary purpose of this study was to compare eccentric and concentric force asymmetries within each movement to see if they yield any clinically relevant differences. It was hypothesized that vGRF asymmetries (both concentric and eccentric) between the bilateral movements (DJ, CMJ, RBJ) would correlate more strongly than between the (unilateral) SLCMJ and the bilateral movements, and it was hypothesized that the concentric phase asymmetries would correlate poorly with eccentric phase asymmetries across all movements.

METHODS

Participants

A cohort of 104 male and female NCAA Division I athletes at Colorado State University across 11 different sports teams were included in this study, which was collected as part of an ongoing service program for them. These sports included football, men’s and women’s basketball, women’s soccer, women’s volleyball, men’s and women’s track & field, women’s swimming, women’s diving, women’s golf, women’s softball, and women’s tennis. The athletes were primarily freshman and transfer varsity athletes; however, a few additional athletes were included at the request of the Athletic Department training room. Athletes were excluded if their injuries were too severe, had not progressed enough in recovery to safely perform the functional movement tests, or were not available at the time of scheduled testing. For all athletes, this was the first time performing the functional movement assessment.

Test Protocol

For the testing protocol, the interaction with each athlete took approximately (~) 15 minutes. The test site was either the Canvas Stadium X-ray room (football) or CSU Clinical Biomechanics Laboratory in the Moby Arena Complex (all other sports). A pair of Hawkin Dynamics portable force platforms (Westbrook, ME, USA) set level on the ground (concrete) and ~1/4" apart were utilized for the assessments. The platforms are 2.75" tall, so they were surrounded by equally tall gymnastics mats for athlete safety. A webcam camera was set up as well, facing the athlete to capture a frontal plane view during the tests. The camera images were not assessed for this examination.

Workouts were not controlled in hours/days prior to testing. As such, some athletes were fresh, while others tired/sore/fatigued. Athletes warmed up on an exercise bike immediately prior for ~10 minutes. Upon arrival to the X-ray room/lab, each athlete was given an orientation followed by a verbal questionnaire about how they were feeling (sore, weak, fresh, tired, or other), whether they had past or current injuries, if they had worked out that day and what region of the body specifically, what shoe they were wearing, what their preferred kicking leg and throwing arms are (to determine dominant limbs), along with age and year in school. Athletes were shown proper technique for each movement, introduced to the chime sound that initiates each individual data collection trial, and told to perform movements with maximum effort while remaining on the plates for the duration of each trial. After determining if the athlete was properly warmed up, the testing protocol commenced, first with practice trials prior to each movement until both the athlete and investigator were satisfied with the movement technique. Athletes performed 3 acceptable trials of each movement in the following order: CMJR, DJ, and SLCMJ. If a jump was less than maximal, looked/felt off, it was discarded, and the jump repeated.

CMJR: Countermovement Jump Rebound

Athletes were instructed to place hands on hips for the entire movement, stand with one leg on each platform, perform a maximal effort CMJ descending to a comfortable depth before propelling themselves upward, and then perform a quick and explosive rebound jump (RBJ) upon landing, spending as little time on the ground as possible. After the final landing, the athlete was instructed to remain still for several seconds.

DJ: Drop Jump

Each athlete was asked to stand on a 30 cm wooden platform placed 15-30 cm behind the force platforms (edge-to-edge) with slight adjustments made to accommodate athlete size and technique. They stood with toes at the leading edge of the platform and hopped forward off the platform once hearing the tone. Athletes were instructed to minimize the height of the hop and leave the platform simultaneously with both feet. Upon landing on the force platforms (one foot on each) they performed a quick and explosive vertical jump, minimizing ground contact time. Arm placement and movement was not controlled for, and the athlete was instructed to remain on the platforms for several seconds upon final landing.

SLCMJ: Single-Leg Countermovement Jump

From static standing with one foot on each force platform, athletes were first instructed to lift their left foot up and stand motionless on their right foot. Then they were instructed to perform a maximal CMJ on this leg and then land in whatever configuration felt most comfortable (either landing with both feet or just one foot). Arms were held on the hips. The process was repeated for the left leg, with a total of 3 trials for each leg alternating back and forth.

The assessment concluded with a set of ten repetitions of the push-up exercise where forces were recorded under the hands. The push-ups were not part of this analysis. Data was processed and returned to the Athletic Trainers within several days of the athlete's visit. All visits occurred Summer/Fall 2019 and the start of Spring 2020.

Data Processing and Analyses

The Hawkin Dynamics dual force platform system was used to not only collect the vGRFs but also perform the initial processing of the data. The system samples 1 kHz with some unknown level of low-pass filtering to remove high-frequency noise. The Hawkin Dynamics software automatically calculated the vGRF force asymmetries for the DJ and CMJR (both CMJ and RBJ), but the SLCMJ asymmetries had to be calculated separately in Excel (Microsoft, Redmond, WA) using forces from individual limbs (as both limbs did not contact the plates during a single recording). The asymmetry equation ((Left limb force-Right Limb force)/((0.5)*(Right limb force+Left limb force)))*100=% asymmetry. The equation seems to match that used by the Hawkin Dynamics software. This method yields values that are positive when more force is generated by the Left limb and negative values when more force is generated by the Right limb. The variables calculated and assessed for the CMJR were: CMJ average propulsive force asymmetry, RBJ average braking force asymmetry, and RBJ average propulsive force asymmetry. For the DJ, the variables collected were average braking force asymmetry, average propulsive force asymmetry, peak propulsive force asymmetry, and peak braking force asymmetry. For the SLCMJ, only average propulsive force asymmetry and jump height asymmetry were calculated (using the asymmetry equation above). All calculated asymmetries were averaged from the 3 trials.

Statistical Analyses

Pearson's correlations (*r*) were performed to evaluate the associations between the average propulsive force and average braking force asymmetry variables of the DJ and those of the CMJR (both CMJ and RBJ) and SLCMJ. Based on variables able to be extracted from Hawkin Dynamic initially, the correlations assessed include DJ Average Propulsive Force (APF) vs. CMJ APF, DJ APF vs. RBJ APF, DJ APF vs. SL CMJ APF, CMJ APF vs. RBJ APF, CMJ APF vs. SL CMJ APF, RBJ APF vs. SL CMJ APF, DJ Average Braking Force (ABF) vs. RBJ ABF, DJ APF vs. DJ ABF, and RBJ APF vs. RBJ ABF. Statistical analyses were conducted in IBM SPSS Statistics version 19.0 (Chicago, IL, USA) with significance set to $p \leq 0.05$. Asymmetry values were removed from correlations if they were extreme outliers: data points that lie more than 3.0 times the interquartile range below the first quartile or above the third quartile.

RESULTS

Of the 104 participants included, 103 completed all of the movements. All nine asymmetry correlations were significant positive Pearson's correlations at the $p=0.01$ level. All correlations of average propulsive force asymmetries between the DJ, CMJ, RBJ, and SLCMJ had an *r* value of at least 0.25, but the three bilateral movements (DJ, CMJ, RBJ) had strong positive correlations with each other in asymmetry values ($0.5 < |r|$; Cohen 2013), but each of the three bilateral movements had weak to moderate positive correlations with the SLCMJ ($0.1 < |r| < 0.5$; Cohen 2013) (Table 1). The Pearson's correlation between the RBJ average propulsive force asymmetry and the RBJ average braking force asymmetry was r=.440 (n=102), while the Pearson's correlation between the DJ average propulsive force asymmetry and the DJ average braking force asymmetry was r=.485 (n=100). These are both moderate correlations ($0.3 < |r| < 0.5$; Cohen 2013). The Pearson's correlation between RBJ average braking force asymmetry and DJ average braking force asymmetry was r=.573 (n=103), a strong correlation ($0.5 < |r|$; Cohen 2013), but with a lower correlation coefficient value than these two movements compared in average propulsive force asymmetry. See Appendix 1 for a scatterplot representation of correlations.

Table 1. Average propulsive force asymmetries correlations (*r*) (*n*=x – 104).

	DJ_APF	SLCMJ_APF	RBJ_APF
CMJ_APF	.679**	.321**	.708**
RBJ_APF	.660**	.278**	
SLCMJ_APF	.350**		

DJ_APF=drop jump average propulsive force asymmetry; SLCMJ_APF=single leg countermovement jump average propulsive force asymmetry; CMJ_APF=CMJR countermovement jump asymmetry; RBJ_APF=CMJR rebound jump asymmetry

** correlation significant at the 0.01 level (2-tailed)

DISCUSSION

Our hypotheses were partially supported in regard to asymmetry correlations: the three individual bilateral movement assessment correlated strongly with each other, the SLCMJ had significantly weaker correlations to the bilateral movements, and the eccentric phases also correlated strongly. However, the eccentric and concentric phase data correlated more strongly than expected with a moderate correlation; we expected a poor correlation in asymmetry data between these two phases of the movement assessments.

The CMJ and RBJ both correlated strongly to the DJ and thus provided some of the same asymmetry information for the concentric propulsive phase of the jumps. However, because neither correlation was a near perfect linear relationship ($0.9 < |r|$), the DJ should not be considered as a replacement test for the CMJ and RBJ, as the latter two movements still potentially provided unique asymmetry information not provided by the DJ. Similarly, the DJ should not be considered a replacement functional movement assessment for the RBJ in the eccentric phase because the average braking force asymmetries correlated strongly (though less strongly than these movements correlated in average propulsive force asymmetry) but not in a nearly perfect linear relationship. Both concentric and eccentric phases of the RBJ and concentric phase of the CMJ may be providing asymmetry information not given by the DJ, and thus the CMJR may be a valuable addition to a functional movement assessment along with the DJ. The comparatively weak correlations observed between the SLCMJ and the three bilateral movements (DJ, CMJ, RBJ) suggests that the SL CMJ likely provided a higher degree of unique concentric asymmetry information than either of the bilateral movement assessments do with each other. Thus, neither of the bilateral movements (DJ, CMJ, or RBJ) should function as a replacement for the SLCMJ. Lastly, the moderate Pearson's correlations between concentric average propulsive force asymmetry values and eccentric average braking force asymmetry values within each the DJ and RBJ suggest that the concentric and eccentric phases of each of these movements are not similar enough to replace each other, as each provided slightly differing information.

Many movements in sport and daily activity occur in a predominantly unilateral fashion with most of the force applied by either the left or right leg, and it would appear that single leg movement assessments would be able to better, or at least differently, reproduce specific movement patterns than bilateral movement assessments (Meylan et al. 2010). Therefore, the weak correlation of asymmetry data between the SLCMJ and the other 3 individual bilateral movement assessments (DJ, CMJ, RBJ) could potentially be explained by differences in mechanics and physiology between unilateral (single leg) and bilateral movements. A study by DeForest et al. (2014) found in an analysis of electromyographic (EMG) data from various quadriceps and hamstring muscles squatting movements that muscle activity in the biceps femoris was significantly higher in the back squat (bilateral) than the split squat (unilateral) during the concentric phase. However, activity in other muscles were similar between unilateral and bilateral squats (DeForest et al. 2014). Furthermore, in a study design where subjects were loaded with the same external load per leg, Eliassen et al. (2018) found that there was greater activation in the rectus femoris, vastus medialis, vastus lateralis, biceps femoris, and erector spinae during a bilateral squat than in unilateral squats. Other studies found higher EMG activity in gluteus medius and hamstrings during the single-leg squat and higher quadriceps activity in the bilateral squat (McCurdy et al. 2010), and higher activation of both hamstring and quadriceps muscles in a single-leg squat exercise compared to a couple bilateral squat exercises (Monajati et al. 2019). Protocol differed slightly in each design above, which could partially explain the variability in results, and it is important to note that movements containing an eccentric countermovement phase followed by a jump (like the DJ, CMJR, and SLCMJ) have different muscle loading patterns and contractile/stimulation dynamics than squatting movements (Bobbert et al. 1996; Earp et al. 2010; Finni et al. 2000). However, different muscle activation patterns between unilateral and bilateral functional movement assessments in the studies above could explain the low correlation of asymmetry data between the SLCMJ and the DJ, CMJ, and RBJ.

The moderate correlation in asymmetry data between concentric and eccentric phases of the DJ and RBJ may be consistent with the limited, mixed nature of prior literature on concentric vs. eccentric asymmetry comparisons. A study by Paterno et al. (2007) on ACL-reconstructed vs. control female athletes found that significant left and right limb asymmetry of peak vGRF was observed in both landing (eccentric) and takeoff (concentric) phases of the drop vertical jump in ACL-reconstructed groups. However, other studies found differences in asymmetry data between concentric and eccentric phases of functional movement assessments. One study on male soccer players found no significant difference in peak vGRF between the dominant leg and non-dominant leg during the CMJ eccentric phase but did find a significant difference in concentric phase variables (which included flight time, flight height, and speed of takeoff) (Yanci and Camara, 2016). Furthermore, a study on ski racers with and without ACL reconstruction found left/right leg % impulse asymmetry (the integration of the force-time curve over the time of the jump) to be significant during the concentric phase of the CMJ and eccentric phase of the squat jump (SJ), but not significant for the eccentric CMJ or concentric SJ. As stated previously, differences in neuromuscular activation of concentric and eccentric muscles in the leg (Ghena et al. 1991; Westing et al. 1991) could have contributed to this moderate, rather than strong, correlation in asymmetry values. Conversely, the strong correlation in eccentric phase average braking force asymmetry between the DJ and RBJ has a lack of prior literature to give context and support to our observation. Most past studies on force platform asymmetries used peak vGRFs to measure functional asymmetry in the lower extremities for different movements rather than divide them intro average concentric and average eccentric measurements. More research is needed to evaluate the relative reliability of isolated concentric and eccentric phases between and within difference functional movement assessments.

Though prior injury history could have led to the development of functional asymmetry in the lower extremities, it is important to discuss non-pathologic factors that could have affected our data as well. One of these is the genetic development of left/right body asymmetry and limb dominance. Left/right asymmetry in body planning in humans (such as the heart, spleen and pancreas being on the left side and gall bladder and most of liver residing on the right) is based on well-documented developmental pathways. These include transforming growth factor-β molecules being expressed asymmetrically by *lefty*, *nodal*, and *Pitx2* genes during early embryonic development (Hamada et al. 2002; Meno et al. 1998) and Nodal flow: the leftward movement of fluid at the ventral node (a transient midline structure during gastrulation) by cilia which can cause activation of a signaling pathway for asymmetry gene expression in the left and right in the embryo (Hamada et al. 2002; Hirokawa et al. 2006). Limb dominance or "handedness" could be a polygenic trait controlled by the aforementioned molecular mechanisms that establish left/right asymmetry early in embryonic development (Brandler et al. 2013). Recently, handedness was found to be significantly associated with 4 loci in the human genome (Wiberg et al. 2019). Handedness, or limb dominance, could be associated with a bilateral asymmetry in muscular strength. A metanalysis of 11 different studies by McGrath et al. (2015) found no statistical effect of lower extremity limb dominance on functional tests of asymmetry, including single-leg vertical jump vGRF tests, however, there is some evidence that there is a difference in muscle strength between dominant and non-dominant limbs on non-elite athletes (Lanshammar and Ribom, 2011; Balogun and Onigbinde, 2009; Ditroilo et al. 2010). Genetic processes during development, which could have led to bilateral limb dominance and strength asymmetry, could have affected functional asymmetry measurements and perhaps explain why asymmetry is observed in those who never trained. In addition, differences in neurological and motor control between non-dominant and dominant limbs could have also affected concentric and eccentric vGRF bilateral asymmetry values. Past research designs that studied this have focused on gait analysis and bilateral limb behavior tasks (which measure the motor control abilities of each leg), finding that participants tend to use the dominant leg for mobilization (such as kicking a ball) and non-dominant leg for postural stability and weight-bearing (Hirokawa 1989; Sadeghi et al. 1997; Sadeghi et al. 2000; Spry et al. 1993; Velotta et al. 2011). Bilateral differences in neurological control may have contributed to asymmetries in the SLCMJ more than the bilateral movements due to the increased balance and stability requirements associated with single-leg movements. It is less certain how bilateral asymmetries in strength due to limb dominance contributed to different movements in this study. As described above, there is limited research to suggest limb dominance is a variable that could affect functional tests of asymmetry in the lower extremities.

Functional asymmetry can also vary by sport. Analysis of cross-sectional areas (CSAs) of various muscles in elite cycling, running, heptathlon, and skeleton racing athletes found that muscle imbalances occur in a wide range of athletes and may be related to injury occurrence (Franettovich et al. 2011). However, muscular asymmetries may be adaptive in some cases and not necessarily pathologic. In elite Australian football players, CSA analyses of various muscles indicated bilateral imbalances in lumbopelvic stability muscles (Hides and Stanton, 2012) and hip flexor muscles with more mass ipsilateral to the kicking leg (Hides et al. 2008; Stewart et al. 2009), the latter of which was not related to injury occurrence. Furthermore, there is evidence to suggest that pelvic asymmetry may be linked to participation in sports with asymmetric lower body movement patterns (with a predominantly laterally dominant component) such as field hockey, ice hockey, and speed skating, and this may be adaptive (Bussey, 2010). Asymmetry of lower back muscles and shoulder muscles in cricket fast bowlers and baseball pitchers (vs. non-pitchers), respectively, was observed and suggested to be adaptive to asymmetrical stresses put on the left and right limbs (Gray et al. 2016; Cook et al. 1987). With the variety of sports represented in this study, some asymmetries observed may be adaptive for certain athletes and may not be related to injury history. It is possible that athletes representing sports with a higher prevalence of pivoting motions and forces on a single leg (such as soccer or football) may contribute to asymmetry measurements more in single-leg assessments like the SLCMJ, but more research is needed to make this determination.

Another confounding variable that could have affected our results is leg length asymmetry. Unequal leg lengths have been found to result in asymmetric vGRF limb loading, though the magnitude of leg length discrepancy required to generate musculoskeletal disorders such a low back pain, stress fractures, and scoliosis or risky gait and running mechanics was a source of controversy (Gurney, 2002, McCaw and Bates, 1991). A later study by White et al. (2004) performed walking vGRF tests on leg-length asymmetric college students and found significantly higher eccentric vGRF forces on the shorter limbs than the longer limbs, with concentric values being higher but not significant. The authors concluded that the shorter limb sustains a greater proportion of load and loading rate than the longer limbs, even if the leg-length discrepancy was less than 3 cm, and orthotics or other corrective strategies should be considered with even a leg-length discrepancy of less than 3 cm (White et al. 2004). In this study, leg-length discrepancy may have contributed more to bilateral movement asymmetries than single-leg assessments due to the potential for a participant to shift their weight to either limb. Again, more research is needed to make this determination.

Some limitations exist within the research design of this study. Because of the limited availability of the participants, the length and type of warmup was not able to be controlled. Furthermore, the type, duration, and region of body worked out prior in the day was unable to be controlled, which could have affected functional asymmetry data for each movement particularly if an athlete's lower extremities were fatigued at the time of testing. Additionally, no sex-specific or sport-specific analyses were performed. As stated previously, there may be some rationale in performing sport-specific analyses as athletes from different sports may have unique trends in functional asymmetry.

Future research designs to compare vGRF asymmetry data between functional movement assessments should address the limitations of this study by controlling for warmup type and duration and controlling for workout length prior to the functional movement assessment on the day of testing (perhaps having athletes rest that day). Though it may be more challenging to find a large sample size for each comparison, sport-specific and sex-specific analyses of functional asymmetries across different movement types could help determine how these factors contribute to functional asymmetry data. Another interesting analysis would be to divide the participant population into leg-length discrepancy classes (those with none, mild (<1 cm), and large (>1 cm)—loosely based on a study of military recruits by Hellsing (1988)) and perform Pearson's correlations between movements within each leg-length category. This would control for the variable of vGRF asymmetry caused by leg-length asymmetry. Though testing these variables would add complexity and time to a study design, muscle strength and neurological control could be measured individually in each limb through dynamometers and balance/motor control tests respectively to determine how each of these factors may contribute to vGRF asymmetries in different movement assessments. Many prior studies have analyzed DJ, BW squat, or SL Squat movements using frontal plane kinematic variables, thus another future design may elucidate more information on how DJ, CMJR, and SL CMJ movements correlate in the information they give us by using a 3-dimensional motion capture system to analyze correlations in kinematic variables between the 3 movements.

CONCLUSIONS

Asymmetry data between the single-leg countermovement jump, countermovement jump w/ rebound, and drop jump was not strongly correlated enough to replace any movement with each other. However, concentric and eccentric asymmetries between bilateral movements were stronger than those between single-leg and bilateral movements, and concentric and eccentric values with the same movements. Anthropometric, neurological, sport-specific, and other individual non-pathologic variables between each participant may explain the lack of correlation in asymmetry between each movement.

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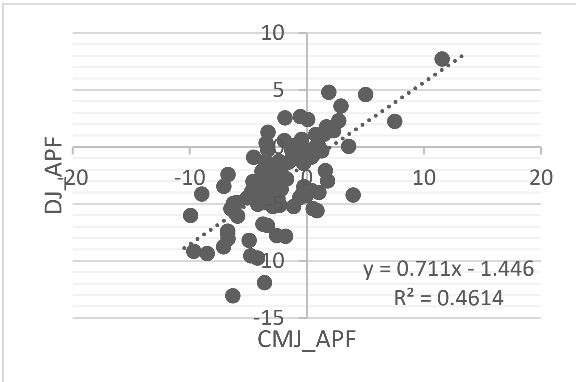
Appendix 1

A



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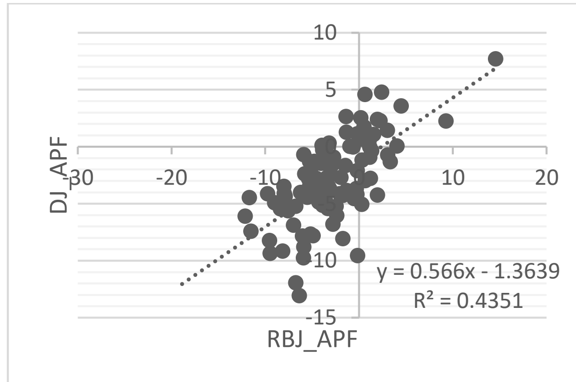

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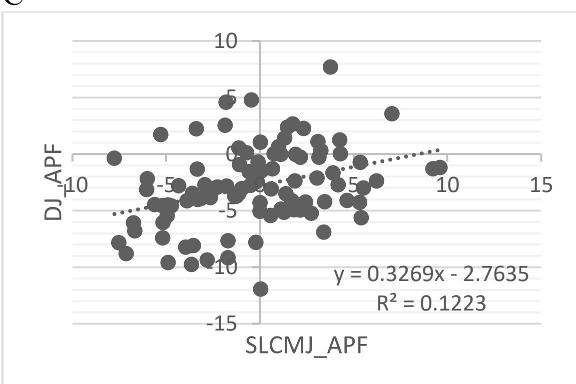

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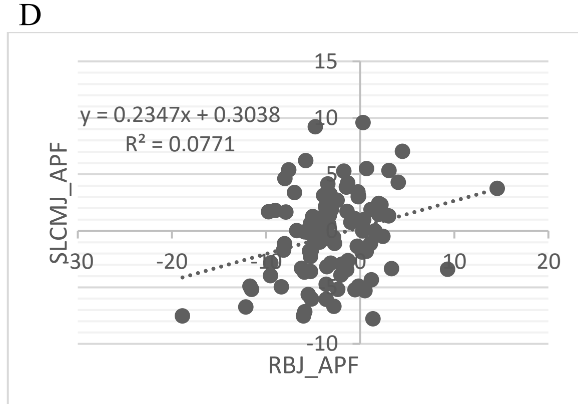

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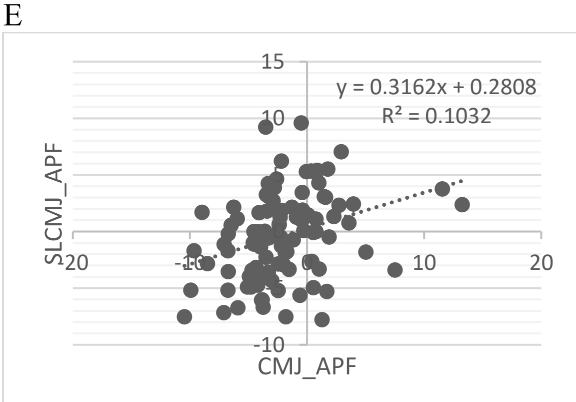

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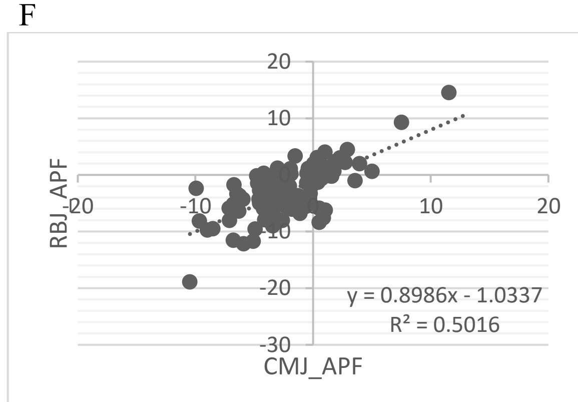

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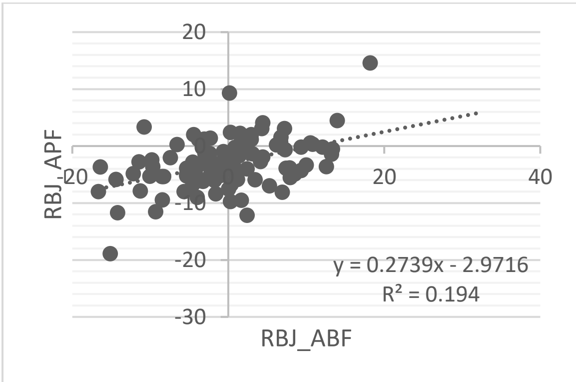

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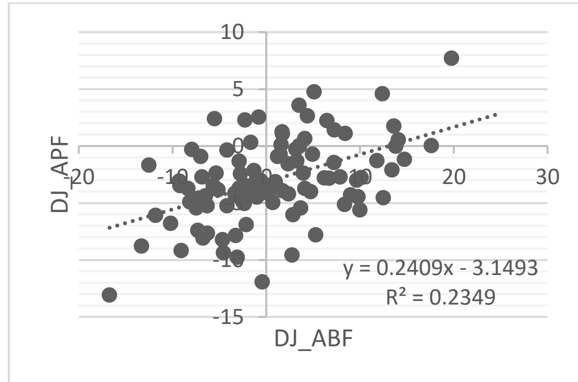

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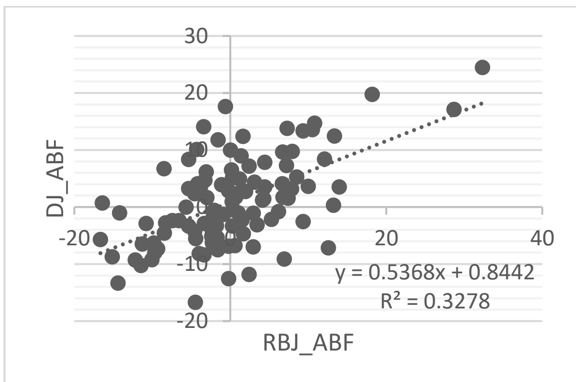

Figure 1. Correlations represented as scatterplots with lines of best fit and R^2 values included. Figures 1A-1F represent six possible average propulsive force correlations between drop jump average propulsive force asymmetry (DJ_APF), single-leg countermovement jump average propulsive force asymmetry (SLCMJ_APF), countermovement jump average propulsive force asymmetry (CMJ_APF), and rebound jump average propulsive force asymmetry (RBJ_APF). Figure 1G is the correlation between rebound jump average braking force asymmetry (RBJ_ABF) and rebound jump average propulsive force asymmetry (RBJ_APF), while 1H is the correlation between drop jump average braking force asymmetry (DJ_ABF) and drop jump average propulsive force asymmetry (DJ_APF). Figure 1I displays the correlation between rebound average braking force asymmetry (RBJ_ABF) and drop jump average braking force asymmetry (DJ_ABF).