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Bilateral Ground Reaction Force Jumping Asymmetry and Performance

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Bilateral Ground Reaction Force Jumping Asymmetry and Performance

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by

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ABSTRACT

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The prevalence of asymmetry in performance research has increased in recent years with mixed results. Much of the performance research has focused on unilateral jumping activities attempting to show relationships to other performance variables. However, bilateral ground reaction forces (bGRF) from jumps are more frequently assessed in athlete monitoring programs and the asymmetry from those jumps could be a simple addition to data already being collected. Research into bGRF asymmetries is lacking and no studies have addressed longitudinal changes. Additionally, research into the relationship of asymmetries to performance have infrequently used athletes. For these reasons, this dissertation will focus on bGRFs by assessing reliability, determining the relationship to performance, and tracking longitudinal changes among collegiate athletes. These data indicate that impulse has high absolute (ICC > 0.87) and relative (CV < 3.22) reliability values and should be the preferred metric for assessing jumping asymmetry. As well, a combination of the braking and propulsive phase above body mass has higher correlations ($r = -0.25$ to -0.49) to jumping performance compared to the propulsive phase alone ($r = -0.09$ to 0.26). Males and female soccer players have differing relationships with asymmetry as males had the greatest correlations between weighted countermovement jump (CMJ) asymmetry and weighted CMJ performance ($r = -0.49$), whereas females produced their greatest correlations with unweighted CMJs ($r = -0.43$). Additionally, all statistically significant correlations between asymmetry and performance were negative. Athletes with higher asymmetry values typically realize improvements over time without specific interventions, whereas athletes with lower values may not experience many fluctuations. Overall, asymmetry has negligible relationships to

strength levels (r = -0.30 to 0.22) but seems to be associated with the improved motor coordination involved with strength training. Indeed, athletes with higher asymmetry values even displayed trends of greater performance gains over time.

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Chapter 1. Introduction

Asymmetry and symmetry are often used synonymously in the literature with both relating to the performance of one limb compared to the contralateral limb. With true symmetry being rare in biological development, asymmetry appears to be the more appropriate term and will be used henceforth. The importance of asymmetry in athlete performance has been debated in the literature with mixed outcomes. The results of several studies have linked asymmetries to an imbalance of muscle development (Bell et al., 2014), suboptimal performances (Bailey et al., 2015b; Bell et al., 2014; Bishop et al., 2018; Maloney et al., 2017; Owens et al., 2011), and a potential risk of injury (De la Motte et al., 2017; Knapik et al., 1991; Stiffler et al., 2017; Zouita et al., 2016). Countermovement jump (CMJ) asymmetries of >5% may be associated with reduced sprinting and change of direction performance (Bishop et al., 2019); asymmetries of approximately 10% have been associated with reduced jump heights (Bell et al., 2014); and asymmetries of >12.5% are associated with slower sprint accelerations (Bishop et al., 2018a). Conversely, other studies have not found statistically significant evidence that jumping asymmetries correlate with sprinting or change of direction tasks (Exell et al., 2017; Hoffman et al., 2007; Lockie et al., 2014). Indeed, there is evidence that asymmetry in most athletes is likely related to their sport (Hart et al., 2017; Read et al., 2018; Sannicandro et al., 2011). Some degree of asymmetry may be an adaptation which might result in a superior performance, such as track athletes running around the track in the same direction. Many of these types of asymmetries are likely to be partially a function of limb dominance and are probably magnified by long-standing participation within a specific sport. However, sporting asymmetries do not seem to carry a clear influence on athletic performance measures (Maloney, 2019).

Differing assessments have been used to investigate asymmetries (Bishop et al., 2018a; Jones & Bampouras, 2010; Stiffler et al., 2017) leading to some of the conflicting information. Nevertheless, evaluating bilateral jump performance from force plate platforms is common (Bailey et al., 2015a; Bailey et al., 2015b; Impellizzeri et al., 2007; Menzel et al., 2013; Sannicandro et al., 2012; Whyte et al., 2017). Countermovement jumps (CMJ) and static jumps (SJ) have been used as a simple non-fatiguing, non-invasive, reliable assessment for athlete monitoring (Balloch, 2018; Carroll et al., 2019; Gathercole et al., 2015; Kraska et al., 2009; Sole et al., 2018) and in the determination of asymmetries (Bailey et al., 2015a; Bailey et al., 2015b; Owens et al., 2011). Additionally, instantaneous variables derived from the CMJ alone may reveal improvements in strength and power (Balloch, 2018). However, analyzing the characteristics and shape of the force-time curve can provide more precise information about neuromuscular function and stretch shortening cycle (SSC) usage (Balloch, 2018; Gathercole et al., 2015; Sole et al., 2018). A better understanding of these bilateral variables may prove useful for practitioners when interpreting jump asymmetries and possible effects on performance.

Chapter 2. Review of the Literature

A level of asymmetry is expected in all human development and there is likely a threshold for meaningful asymmetry in all athletic movements (Guiard, 1987). Some underlying causes are yet to be completely understood, but bilateral asymmetries may be attributed to imbalances from training including metabolic disturbances, impaired excitation-contraction coupling, reduced muscle stiffness, and delayed inflammatory responses of the damaged muscle (Balloch, 2018). Altered movement strategies compensate for changes in the SSC and may be indicative of the neuromuscular status of an athlete (Gathercole et al., 2015; Nicol et al., 2006). Asymmetry research has produced confounding results, but some of that may be attributed to the varying methods of assessing asymmetry.

Investigations into asymmetry have been a long-standing topic in the literature with much of the early research focused on rehabilitation. Researchers have investigated the asymmetries of anthropometrics (Bell et al., 2014) compared to performance measures (Bailey et al., 2015a; Bailey et al., 2015b; Bishop et al., 2019). Within the asymmetry research articles, there are many discrepancies which can confound results when comparing the outcomes. Even when narrowing the focus to research that involves jumping asymmetry, there are several issues that need to be clarified: 1.) equations used to determine asymmetry; 2.) administered performance tests; and 3.) which variables to assess.

Equations from the Literature

Throughout the literature there have been several equations proposed to calculate asymmetry. When assessing each equation, it is important to understand that while symmetry and asymmetry are essentially synonymous, they can produce opposite results if an equation is geared to finding one versus the other. An example of this would be similar to suggesting an athlete is 90% symmetrical versus 10% asymmetrical. Each result would be proportional to the desired outcome. Bishop and colleagues (2016) pulled together a concise list of equations discussing their individual differences. Considering this background information, this dissertation will focus of the general nature of equation differences and not delve into the individual nuances of each. Nonetheless, equations can be classified into one of two categories: dominant limb dependent and side dependent.

Dominant Limb Dependent Equations

Dominant limb dependent equations require knowing which limb is dominant in order to proceed. While methods of dominance determination can be argued (Schorderet et al., 2020), much of the research using the dominant limb dependent equations asked each participant to self-determine dominance (Kozinc & Šarabon, 2020; Maulder & Cronin, 2005). However, also included in this category of equations would be injured/involved versus uninjured/uninvolved limb (Barber et al., 1990; Knezevic et al., 2014). Typically, the uninjured/uninvolved limb would be designated as the dominant limb and the injured/involved limb would be the non-dominant limb.

Side Dependent Equations

Equations falling into the side dependent category typically select one side to be subtracted from the other regardless of limb performance or preference (Bell et al., 2014; Menzel et al., 2013). This does negate the self-selection issue presented by the dominant limb dependent equations. Included in this category are strength dependent equations which can be similar to the dominant limb equations, but the determination is conducted based on the results of the test for each limb (Bailey et al., 2015a; Bailey et al., 2015b; Bazyler et al., 2014; Bishop et al., 2021;

Bishop et al., 2018a; Lockie et al., 2014; Madruga-Parera et al., 2020; Shorter et al., 2008). This method is often conducted to assess the overall magnitude of asymmetry instead of being concerned with the direction.

Equation Limitations and Confounding Factors

Limitations do exist for each category of equation determination. The determination of limb dominance may change depending whether it is force or skill dominant (Lake et al., 2011) and may even fluctuate based on the task (Maloney, 2019) or perceived effort (Simon & Ferris, 2008). Side dependent equations often lack the direction of asymmetry thus having the potential to miss side-to-side fluctuations.

Of the two presented categories, numerous mathematical variations have occurred. Varying combinations in the numerator and denominator in the equations make it nearly impossible to determine a standard level of asymmetry as some equations can produce up to twice the value of asymmetry compared to other equations (Bishop et al., 2016). While suggestions have been made for asymmetry threshold values acceptable to reduce injury risk (Barber et al., 1990; Impellizzeri et al., 2007; Knapik et al., 1991) and improve performance (Bell et al., 2014; Hoffman et al., 2007), close attention must be paid to the equation used for assessing asymmetry. As well, the suggested thresholds have been disputed since asymmetry magnitudes vary depending on the task (Exell et al., 2014).

Methods of Assessing Asymmetry

Performance Measurements

Isokinetic, isometric, and isoinertial tests have all been employed to determine asymmetry with all producing differing results (Bailey et al., 2015a; Balloch, 2018; Bazyler et al., 2014; Dos'Santos et al., 2017; Furlong & Harrison, 2014; Hoffman et al., 2007; Kaçoğlu, 2019; Kozinc & Šarabon, 2020; Lockie et al., 2014; Menzel et al., 2013). Theoretically, isokinetic tests can be used to investigate biomechanics during a set speed of motion, though there is still some changes in speed at the ends of the exercise range of motion. This method can be used to assess eccentric or concentric muscle activation but does not typically reflect the carry-over from eccentric to concentric activation. Benefits of isokinetic testing include the ability to measure differing resistances that can be produced for the eccentric and concentric contractions. However, access to isokinetic testing equipment can be limited, as typically only isolated single joint movements are assessed, and it is impractical for measurement in athletic settings (Jones & Bampouras, 2010; Stone et al., 2002). Another performance measure often assessed are isometric tests, which can have a high correlation to dynamic exercise including actions more plyometric in nature (Cronin et al., 2000; Stone et al., 2003). Most dynamic tests often include an SSC component, though some tests attempt to remove the SSC influence by starting from a set position (i.e. static jumps). The difference in neural activation may explain a portion of the variance between these activities indicating that specificity is a necessary component even when assessing asymmetry (Furlong & Harrison, 2014; Maloney, 2019).

Testing Metrics

Among the various methods used for assessing asymmetry, multiple variables have also been used in the calculation of asymmetry which can further confound continued research. In jumping performance research, the metrics used for assessing asymmetry can be divided into two main categories: performance differences and ground reaction force variables.

Performance Differences

The difference in the performance of one limb versus the other can be a simple procedure involving little technology. This is often employed when analyzing single limb performance. An example of this is comparing single leg horizontal jump distances to obtain an asymmetry measure. While some argue that single limb performance asymmetries have a stronger relationship to other performance tests such as, change of direction (Bishop et al., 2018a; Madruga-Parera et al., 2020), these tests may not reach a high level of specificity for many sports. A limiting factor for using single limb performance differences is the lack of representation of limb coordination in movements, or the contralateral neurological contributions (Hortobágyi et al., 2003). Bilateral movements are common in many sporting activities and should not be overlooked, but it should be noted that bilateral and unilateral jumps have not produce related results in asymmetry (Benjanuvatra et al., 2010).

Ground Reaction Force Variables

The collection of ground reaction force (GRF) variables from force plates is becoming more common in sport science research and athlete monitoring programs. Investigations using GRF have covered both unilateral and bilateral movements. Dual ground reaction force (dGRF) asymmetries have also been researched and require two adjacent force plates. However, a consensus has not been reached on the most appropriate metric to represent asymmetry. Studies assessing jumping asymmetry have used force, power, net impulse, impulse, or a combination of those (Bailey et al., 2015a; Bailey et al., 2015b; Bell, Sanfilippo et al., 2014; Impellizzeri et al., 2007; Menzel et al., 2013) with varying results. According to Menzel et al. (2013) dGFR impulse and maximal power during CMJ on a double force platform appear to be the optimal approach for assessing GRF asymmetries. No matter the variable used, asymmetry research has primarily focused on only the propulsive phase of jumps.

Asymmetry and Performance

Higher strength levels have accounted for decreased asymmetry in some metrics, suggesting that weaker athletes have greater asymmetry than stronger athletes, and this strength gap may explain the disparity in female compared to male athletes (Bailey et al., 2015b; Bazyler, Bailey et al., 2014). Additionally, stronger athletes tend to have higher jump heights than weaker athletes (Sole et al., 2018). As well, strength training has shown to increase motor competency (Behringer et al., 2011) which may be more indicative of reduced asymmetry than increased strength alone since strong individuals may also produce high asymmetry values (Bell et al., 2014). Nevertheless, development of functional asymmetries (Hart et al., 2017; Read et al., 2018; Sannicandro et al., 2011) resulting from certain sports (e.g. soccer) may further confound bilateral interpretations of jumping asymmetries.

Seemingly, no published study has explored phase-by-phase asymmetry by employing a longitudinal method nor have CMJ asymmetries been compared to SJ asymmetries by phases. Thus, the purpose of this dissertation is to 1.) Examine the variability of bilateral F-Tc phase characteristics of the CMJ and SJ; 2.) Examine the relationship of asymmetry to performance; 3.) Explore the bilateral F-Tc changes in jumping phases over time in collegiate athletes.

Chapter 3. Reliability of Bilateral Ground Reaction Force Asymmetry Measures

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Abstract

Multiple methods have been deployed to investigate the relationship between asymmetry and performance. Dual ground reaction forces (dGRF) have become more commonly used, but the metrics used in the literature have not been consistent. To alleviate some of the confusion, the purpose of this study is to provide evidence of the absolute and relative intra-session reliability of dGRF asymmetry values throughout the force -time curve of various vertical jumps. A total of 98 male (n = 49) and female (n = 49) athletes from Division I collegiate soccer and tennis programs. The data was selected from an ongoing athlete research repository database. Each athlete produced two maximal effort jumps in the following categories: unweighted static jump (SJ0), weighted static jump (SJ20), unweighted countermovement jump (CMJ0), weighted countermovement jump (CMJ20). Metrics selected for analysis included force, impulse, power, and modified shape factor. Countermovement jumps were split into three phases (unweighting, braking, and propulsive) whereas static jumps only included a propulsive phase. Results showed impulse and modified shape factor produced the best overall absolute (ICC > 0.87, 0.90; respectively) and relative (CV < 3.83, 1.85; respectively) reliability values. The unweighting phases of CMJ0 and CMJ20 produced the least reliable values (ICC > 0.86; CV < 3.23) while the braking and propulsive produced the most reliable values (ICC > .90; CV < 1.65). Both SJ0 and SJ20 produced higher overall reliability (ICC > 0.94; CV < 1.14) compared to CMJ0 and CMJ20 (ICC > 0.87; CV < 3.83). As well, weighted jumps were more reliable than their unweighted counterpart. It is recommended that researchers using dGRF moving forward with asymmetry studies should focus on impulse or modified shape factor during the braking and propulsive phases while including both unweighted and weighted jumps.

Introduction

Sporting asymmetry has been associated, as a function, with an athlete's long-standing participation in their sport (Maloney, 2019). The effect of asymmetries on performance have been assessed using a variety of methods and mathematical techniques (Bailey et al., 2015a; Bailey et al., 2015b; Bell et al., 2014; Bishop et al., 2018b; Impellizzeri et al., 2007; Kaçoğlu, 2019; Menzel et al., 2013). A large share of the research on asymmetry has been focused on jumping. However, differing tactics to assess jumping asymmetry have led to confounding results.

Researchers have used both unilateral (Bishop et al., 2018a; Exell et al., 2012; Kozinc & Šarabon, 2020; Madruga-Parera et al., 2020; Pérez-Castilla et al., 2021) and bilateral (Bailey et al., 2015a; Bailey et al., 2015b; Bishop et al., 2019; Menzel et al., 2013) jumps in a variety of ways to assess the relationship of asymmetry with performance. Additionally, researchers have used a variety of metrics to determine asymmetry such as: Peak force, impulse, peak power, and jump height (Bailey et al., 2015a; Bishop et al., 2018b; Impellizzeri et al., 2007; Kozinc & Šarabon, 2020; Madruga-Parera et al., 2020; Maloney, 2019; Menzel et al., 2013). While impulse has been suggested to be a more sensitive measure of asymmetry (Menzel et al., 2013). When analyzing the ground reaction forces (GRF) of a jump, the propulsive phase has been the primary focus in research (Benjanuvatra et al., 2010; Impellizzeri et al., 2007; Menzel et al., 2013). However, using only the propulsive phase negates the majority of the force-time curve (F-Tc) for countermovement jumps (CMJ).

The results from asymmetry studies have been mixed. Data from some studies indicate that there are relationships between jumping asymmetries and change of direction (Madruga-Parera et al., 2020; Maloney et al., 2017), sprint times (Maulder & Cronin, 2005), and jump performance (Bishop et al., 2018a). Conversely, other studies have not confirmed these results showing little to no relationships between jumping asymmetry and performance (Dos'Santos et al., 2017; Hoffman et al., 2007). Confounding the results of these studies, some evidence suggests that GRF asymmetries derived from bilateral CMJs are not related to asymmetry results derived from unilateral CMJs (Benjanuvatra et al., 2010). However, researchers have suggested that asymmetry derived from bilateral activities produce higher overall absolute and relative reliability than the unilateral counterpart (Pérez-Castilla et al., 2021).

With all the differing methods, it is imperative to establish test-retest reliability of any measure to validate continued usage. Recommendations for measurement reliability include a heterogeneous sample of ≥ 30 and at least 3 raters if multiple raters are needed (Koo & Li, 2016). Intraclass correlation coefficient (ICC) and the coefficient of variation (CV) are common statistical procedures to assess measurement reliability, but confidence intervals (CI), standard error of the measurement (SEM), and minimal detectable change (MDC) are often not calculated. With many studies using small sample sizes ($n < 30$), homoscedasticity can be problematic, indicating a need for the use of SEM (Atkinson & Nevill, 1998). For these reasons, the purpose of this study is to provide a more definitive description of GRF reliability for all phases of bilateral vertical jumping asymmetry assessments.

Methods

Athletes

All data was selected from an ongoing athlete research repository database of NCAA D-I soccer and tennis teams including both male and female athletes. This research was approved by the University Institutional Review Board. The inclusion criteria for each athlete were as follows; 1) all jump testing was conducted on dual force plates; 2.) participated in all performance tests during the testing session (indicating fully cleared to play by athletic training staff) with a minimum of two maximum effort trials for each jump test. A total of 98 athletes were selected from soccer (male n = 35, female n = 35) and tennis (male n = 14, female n = 14) after implementing the inclusion criteria. Table 3.1 shows the athletes' body mass and flight times for unweighted and weighted jumps.

Table 3.1 Descriptive Data for Reliability

	Body Mass (kg)	CMJ_0 Flight time (s)	CMJ_{20} Flight time (s)	SJ_0 Flight time (s)	SJ_{20} Flight time (s)
Female (n = 49)	67.73 ± 10.52	0.41 ± 0.04	0.33 ± 0.03	0.39 ± 0.04	0.33 ± 0.16
Male (n=49)	76.33 ± 8.68	0.50 ± 0.04	0.43 ± 0.05	0.48 ± 0.05	0.41 ± 0.05

Note: Reported in mean ± standard deviation (M ± SD); CMJ_0 = Unweighted countermovement jump; CMJ_{20} = Weighted (20 kg) countermovement jump; SJ_0 = Unweighted static jump; SJ_{20} = Weighted (20 kg) static jump

Testing Sessions

Each testing session included a standardized warm-up (Sole et al., 2018), unweighted static jumps (SJ_0), weighted static jumps (SJ_{20}), unweighted countermovement jumps (CMJ_0), and weighted countermovement jumps (CMJ_{20}), in that order. All weighted jumps were performed with a 20 kg barbell and all unweighted jumps were performed with a PVC pipe (essentially 0 kg) in place of the barbell (behind neck across shoulders) to prevent arm swing. Practice jumps of 50% and 75% perceived maximum effort were given before recording the two maximal effort jumps for each trial. If a jump was deemed less than maximum a third trial was allowed. Before the start of each jump type, a standing system mass value was obtained for a minimum of 1.0 s. All CMJ had a self-selected unweighting depth, whereas all SJ had a start depth at a 90° knee angle as measured using a goniometer.

All jumps were performed on dual force plates (91.0 cm 3 91.0 cm; Rice Lake Weighing Systems, Rice Lake, WI, USA) with the analog signal from the force platform collected using a customized LabView (National Instruments, Austin, TX, USA) program at 1000 Hz. The vertical GRF data were exported as text files and analyzed using a customized 2019 Microsoft Excel® spreadsheet and VBA coding (Microsoft Corporations, Redmond, Washington, USA). Raw voltage data from force plates were smoothed using a 50-point FIR filter and then converted into Newtons (N) to develop the F-Tc for each jump. The F-Tc for CMJ_0 and CMJ_{20} were divided into an unweighting phase, a braking phase, and a propulsive phase. The propulsive phase included everything after the braking phase to the start of flight time. Each phase in the CMJ was designated by a mathematical technique from the summation of the dual F-Tc based on previous research (Sole et al., 2018; Chavda et al., 2018). The concepts of analyzing CMJs were also used with SJ were applicable. To remain consistent between SJ and CMJ the detection of the start of the SJ was determined to be 5 standard deviations above the standing system mass value instead of below the system mass value as used in CMJs. This was necessary as the CMJ begins with an unweighting phase which drops the F-Tc under the system mass, whereas the initiation of the SJ should begin with increased forces above system mass.

Data Analysis

A modified symmetry index score (SI_m) (Sato & Heise, 2012) (see Equation 3.1) was calculated for each phase of SJ_0, SJ_{20}, CMJ_0, and CMJ_{20}. This method produced scores of 100 for complete symmetry, scores below 100 for skewed right indications, and scores above 100 for skewed left indications. This method was used to avoid the possibility of a zero denominator in some statistical calculations.

Equation 3.1 - Modified Symmetry Index Score

$$SI_m = \left(\frac{(Left\ Force\ Plate\ value - \ Right\ Force\ Plate\ value)}{(Left\ Force\ Plate\ value + \ Right\ Force\ Plate\ value)}\ x\ 100 \right) + 100$$

Force, impulse, power, and modified shape factor (mSHP) were analyzed for each phase of the F-Tc with an SI_m being equated for each. Power for each leg was determined through velocity by using 50% of the system mass (Pérez-Castilla et al., 2021). Table 3.2 displays the calculation methods for each variable.

Table 3.2 Variable Determination for Modified Symmetry Index

Variable for SI_m Calculation	**Phase**		
	Unweighting	**Braking**	**Propulsive**
Force	$Force\ at\ return\ to\ BM$	$Max\ Phase\ Force$	
Impulse	$Phase\ force\ \times\ Phase\ time$		
Power	$Peak\ Phase\ Power$		
Modified Shape Factor	$(Phase\ Impulse)\ /\ (Max\ Dual\ Phase\ Force\ \times Phase\ Duration)$		

Note: Refers to each individual force plate unless noted by "Dual"; BM = Body mass.

Statistics

All statistical calculations were conducted using Rstudio (R version 3.6.1, 07/05/2019). Variables were screened for normality of distribution with a combination of histograms and Shapiro-Wilks's calculations. Independent t-tests were used to distinguish statistically significant differences between male and female athletes.

Relative reliability of measures was assessed with intraclass correlation coefficient (ICC) calculations and 95% confidence intervals (CI), based on the mean of measurements ($k = 2$), absolute agreement, 2-way mixed-effects model (Koo & Li, 2016). All ICC and corresponding CI values were rated using the following scale: < 0.5 were poor, between 0.5 and 0.8 were moderate, between 0.8 and 0.9 were good, and values > 0.90 were excellent. Coefficients of variation (CV) with CI, standard error of the measurement (SEM), and minimal detectable change (MDC) were also calculated for each variable to determine absolute reliability (See Table 3.3 for equations).

Table 3.3 Reliability Calculations

Calculation	Equation
Coefficient of variation (CV)	$\frac{SD_{t1-t2}}{M} \times 100$
Standard error of the measurement (SEM)	$SD \times \sqrt{1 - ICC}$
Minimal detectable change (MDC)	$SEM \times 1.96 \times \sqrt{2}$

Note: ICC = Intraclass correlation coefficient; $SD_{t1\text{-}t2}$ = Standard deviation for trial 1 to trial 2; SD = Sample standard deviation; M = Mean from trial 1 and trial 2.

Results

Normal distributions ($p < 0.05$) were found in 29 of the 32 SI variables. The abnormally distributed variables were force during the second SJ_0 ($p = 0.01$), the CMJ_0 force during the unweighting phase during in the first trial ($p = 0.03$), and the CMJ_{20} force during the propulsive phase of the first trial ($p < 0.01$). No statistical differences were found between male and female SI_m for all variables ($p > 0.05$). Descriptive statistics for each variable can be found in Table 3.4

Table 3.4 Descriptive Statistics for Modified Symmetry Index Scores

	Descriptive Statistics				
	Phase	Force	Impulse	Power	Shape Factor
CMJ0	Unweighting Phase SI_m	98.17 ± 10.49	98.56 ± 9.69	96.28 ± 349.76	99.87 ± 5.99
	Braking Phase SI_m	101.01 ± 5.18	101.18 ± 4.80	102.83 ± 16.09	101.21 ± 4.80
	Propulsive Phase SI_m	101.36 ± 4.84	100.45 ± 5.68	109.24 ± 495.61	100.45 ± 5.68
CMJ20	Unweighting Phase SI_m	97.62 ± 9.51	98.26 ± 10.02	101.87 ± 50.21	99.56 ± 5.97
	Braking Phase SI_m	100.73 ± 5.37	100.97 ± 4.83	101.39 ± 12.41	100.96 ± 4.83
	Propulsive Phase SI_m	101.00 ± 5.11	100.22 ± 5.55	98.88 ± 24.79	100.29 ± 5.68
SJ0	Propulsive Phase SI_m	101.07 ± 4.54	100.90 ± 4.58	103.12 ± 10.03	100.90 ± 4.58
SJ20	Propulsive Phase SI_m	100.99 ± 4.75	100.58 ± 4.46	102.13 ± 9.92	100.58 ± 4.46

Note: Reported in M ± SD; SI_m = Modified Symmetry Index Score; CV = Coefficient of variation; SEM = Standard error of the measurement; MDC = Minimal detectable change; CMJ0 = unweighted countermovement jump; CMJ20 = weighted (20 kg)countermovement jump; SJ0 = unweighted static jump; SJ20 = weighted (20 kg)static jump.

Force reliability calculations, with confidence intervals, revealed that variables for the CMJ_0 and CMJ_{20} ranged from 0.70 to 0.95 with the most reliable values produced in the propulsive phase (see Table 3.5). Force reliability values for both SJ_0 and SJ_{20} displayed higher

Table 3.5 Force Test-Retest Reliability Statistics

	Force Test-retest Reliability Statistics				
	Phase	ICC (CI)	CV (CI)	SEM	MDC
CMJ0	Unweighting Phase SI_m	0.80 (0.70, 0.87)	4.90 (4.06, 5.74)	4.67	12.95
	Braking Phase SI_m	0.86 (0.79, 0.91)	1.95 (1.61, 2.28)	1.93	5.34
	Propulsive Phase SI_m	0.92 (0.88, 0.95)	1.40 (1.18, 1.63)	1.36	3.76
CMJ20	Unweighting Phase SI_m	0.80 (0.70, 0.87)	3.51 (2.80, 4.21)	4.24	11.75
	Braking Phase SI_m	0.84 (0.76, 0.89)	1.91 (1.48, 2.35)	2.17	6.02
	Propulsive Phase SI_m	0.92 (0.88, 0.95)	1.61 (1.19, 2.04)	1.43	3.97
SJ0	Propulsive Phase SI_m	0.96 (0.94, 0.97)	0.96 (0.79, 1.13)	0.95	2.62
SJ20	Propulsive Phase SI_m	0.96 (0.94, 0.97)	1.04 (0.87, 1.22)	0.99	2.63

Note: ICC = Intra-class correlation coefficient, CI = 95% confidence interval, SI_m = Modified Symmetry Index Score, CV = Coefficient of variation, SEM = Standard error of the measurement, MDC = Minimal detectable change; CMJ0 = unweighted countermovement jump; CMJ20 = weighted (20 kg)countermovement jump; SJ0 = unweighted static jump; SJ20 = weighted (20 kg)static jump.

reliabilities (ICC of 0.94-0.97) than each comparable CMJ. Force SI_m variables for CMJ reached good reliability levels (mean ICC of 0.86 ± 0.05; mean CV of 2.55 ± 1.37) and excellent reliability levels in the SJ (mean ICC of 0.96 ± 0.00; mean CV of 1.00 ± 0.06).

Calculations for IMP displayed higher reliabilities for the unweighting and braking phases in both the CMJ_0 and CMJ_{20} (see Table 3.6) when compared to force. Reliability of the

Table 3.6 Impulse Test-Retest Reliability Statistics

Impulse Test-retest Reliability Statistics					
	Phase	ICC (CI)	CV	SEM	MDC
CMJ0	Unweighting Phase SI_m	0.89 (0.84, 0.93)	3.28 (2.66, 3.90)	3.22	8.93
	Braking Phase SI_m	0.92 (0.88, 0.94)	1.83 (1.57, 2.09)	1.64	4.55
	Propulsive Phase SI_m	0.90 (0.86, 0.94)	1.83 (1.57, 2.09)	1.64	4.55
CMJ20	Unweighting Phase SI_m	0.87 (0.81, 0.92)	3.82 (3.21, 4.44)	1.81	5.02
	Braking Phase SI_m	0.89 (0.83, 0.92)	1.86 (1.52, 2.20)	1.86	5.17
	Propulsive Phase SI_m	0.91 (0.86, 0.94)	1.46 (1.19, 1.73)	1.54	4.28
SJ0	Propulsive Phase SI_m	0.94 (0.92, 0.96)	1.14 (0.96, 1.32)	1.08	2.99
SJ20	Propulsive Phase SI_m	0.96 (0.94, 0.97)	0.99 (0.84, 1.14)	0.95	2.63

Note: ICC = Intra-class correlation coefficient, CI = 95% confidence interval, SI_m = Modified Symmetry Index Score, CV = Coefficient of variation, SEM = Standard error of the measurement, MDC = Minimal detectable change; CMJ0 = unweighted countermovement jump; CMJ20 = weighted (20 kg)countermovement jump; SJ0 = unweighted static jump; SJ20 = weighted (20 kg)static jump.

SJ_0 were slightly lower than the force (ICC of 0.92-0.96), but the same for the SJ_{20}. Overall, IMP values outperformed force in CMJ (mean ICC of 0.90 ± 0.02; mean CV of 2.31 ± 0.99) and had similar results for the SJ (mean ICC of 0.95 ± 0.01; mean CV of 1.07 ± 0.11).

Power reliabilities were found to be relatively low in the unweighting and braking phases of the CMJ_{20} (ICC = 0.72, 0.81; respectively) with the most volatile reliabilities in the CMJ_0 (ICC = 0.20, 0.03; respectively) during the same phases (see Table 3.7). While adding weight to jumps improved reliability values for power, only the propulsive phase of CMJ_{20}, SJ_0, and SJ_{20} displayed acceptable results when considering the CI. Overall, power displayed the poorest CMJ reliability values (mean ICC = 0.60 ± 0.39; mean CV = -193.72 ± 537.88) but excellent reliability for SJ (mean ICC = 0.92 ± 0.04; mean CV = 2.94 ± 0.47).

Table 3.7 Power Test-Retest Reliability Statistics

Power Test-retest Reliability Statistics					
	Phase	ICC (CI)	CV (CI)	SEM	MDC
CMJ0	Unweighting Phase SI_m	0.20 (-0.19, 0.46)	76.61 (-66.5, 219.73)	312.40	865.92
	Braking Phase SI_m	0.03 (-0.45, 0.35)	-1290.22 (-3959.62, 1379.17)	488.99	1355.42
	Propulsive Phase SI_m	0.91 (0.87, 0.94)	4.94 (4.08, 5.80)	4.77	13.23
CMJ20	Unweighting Phase SI_m	0.72 (0.59, 0.82)	32.05 (25.78, 38.33)	2.68	7.44
	Braking Phase SI_m	0.81 (0.72, 0.87)	10.68 (8.78, 12.59)	10.81	29.98
	Propulsive Phase SI_m	0.92 (0.87, 0.94)	3.63 (3.01, 4.26)	1.49	4.13
SJ0	Propulsive Phase SI_m	0.89 (0.84, 0.93)	3.28 (2.74, 3.81)	3.29	9.11
SJ20	Propulsive Phase SI_m	0.94 (0.91, 0.96)	2.61 (2.22, 3.00)	1.15	3.18

Note: ICC = Intra-class correlation coefficient, CI = 95% confidence interval, SI_m = Modified Symmetry Index Score, CV = Coefficient of variation, SEM = Standard error of the measurement, MDC = Minimal detectable change; CMJ0 = unweighted countermovement jump; CMJ20 = weighted (20 kg)countermovement jump; SJ0 = unweighted static jump; SJ20 = weighted (20 kg)static jump.

Modified shape factor (mSHP) displayed the highest relative and absolute reliability in CMJ (mean ICC of 0.93 ± 0.04; mean CV of 1.29 ± 0.50) with a strong reliability for SJ (mean ICC of 0.94 ± 0.00; mean CV of 1.07 ± 0.11) as well (see Table 3.8). Interestingly, results for the

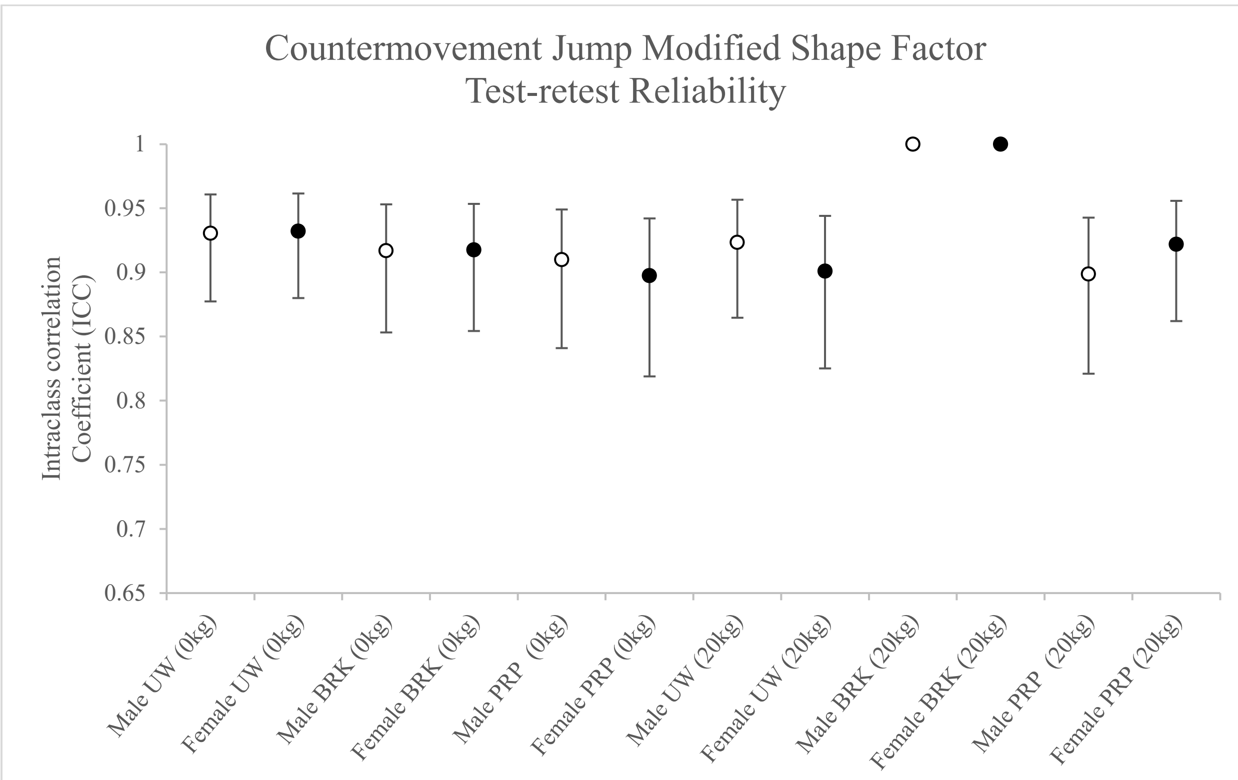
Table 3.8 Modified Shape Factor Test-Retest Reliability Statistics

Modified Shape Factor Test-retest Reliability Statistics					
	Phase	ICC (CI)	CV	SEM	MDC
CMJ0	Unweighting Phase SI_m	0.93 (0.90, 0.95)	1.71 (1.44, 1.99)	1.58	4.38
	Braking Phase SI_m	0.92 (0.88, 0.94)	1.83 (1.57, 2.09)	1.64	4.55
	Propulsive Phase SI_m	0.90 (0.86, 0.94)	1.59 (1.35, 1.83)	1.49	4.14
CMJ20	Unweighting Phase SI_m	0.91 (0.87, 0.94)	1.84 (1.53, 2.16)	1.77	4.90
	Braking Phase SI_m	1.00 (1.00, 1.00)	0.00 (0.00, 0.00)	0.00	0.00
	Propulsive Phase SI_m	0.91 (0.86, 0.94)	1.47 (1.20, 1.47)	1.46	4.05
SJ0	Propulsive Phase SI_m	0.94 (0.92, 0.96)	1.14 (0.96, 1.32)	1.08	2.99
SJ20	Propulsive Phase SI_m	0.94 (0.92, 0.96)	0.99 (0.84, 1.14)	1.05	2.91

Note: ICC = Intra-class correlation coefficient, CI = 95% confidence interval, SI_m = Modified Symmetry Index Score, CV = Coefficient of variation, SEM = Standard error of the measurement, MDC = Minimal detectable change; CMJ0 = unweighted countermovement jump; CMJ20 = weighted (20 kg)countermovement jump; SJ0 = unweighted static jump; SJ20 = weighted (20 kg)static jump.

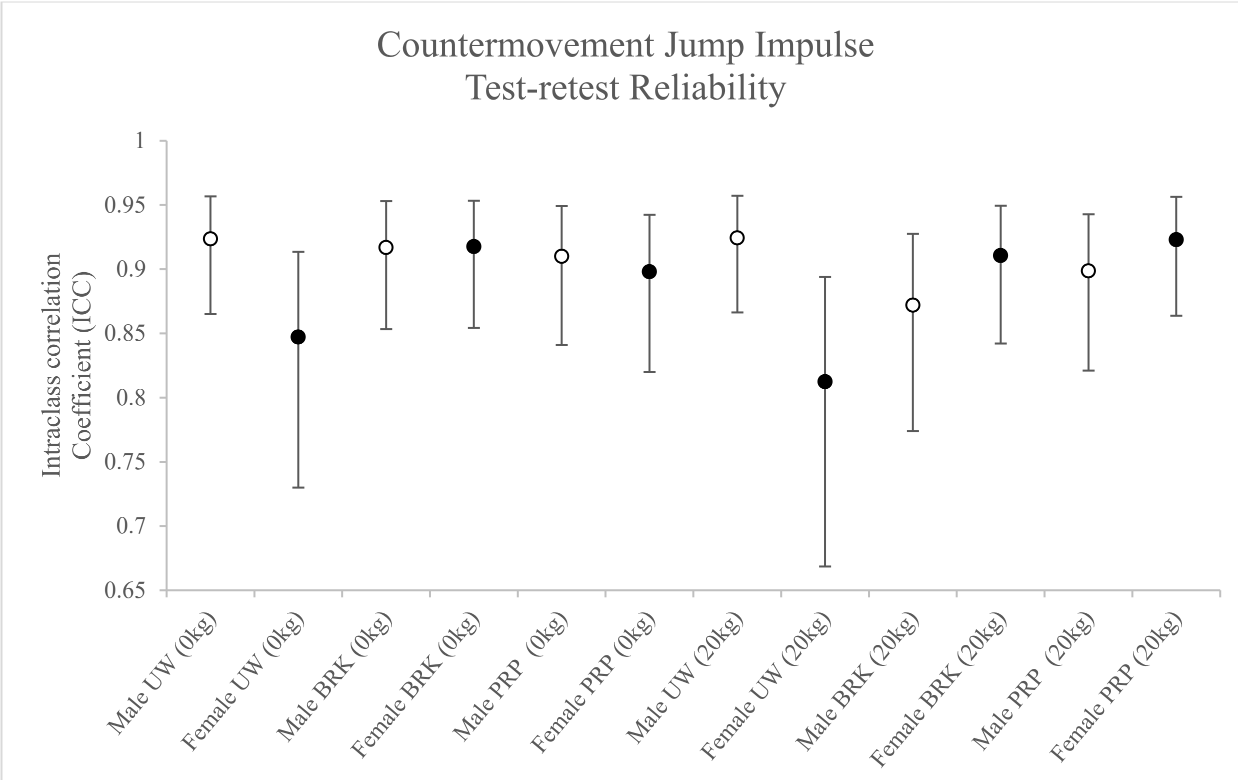
CMJ20 braking phase showed near perfect reliability. Males and females displayed little difference in mSHP reliability with < 0.03 difference in ICC values and < 0.18 difference in CV values (see Figure 3.1 and Figure 3.2). The greatest differences were found during the

Figure 3.1 Countermovement Jump Modified Shape Factor Test-Retest Reliability



Note: Displayed as values with 95% confidence intervals; UW = unweighting phase; BRK = breaking phase; PRP = propulsive phase; (0kg) = unweighted jumps; (20kg) = weighted jumps.

Figure 3.2 Countermovement Jump Impulse Test-Retest Reliability



Note: Displayed as values with 95% confidence intervals; UW = unweighting phase; BRK = breaking phase; PRP = propulsive phase; (0kg) = unweighted jumps; (20kg) = weighted jumps.

propulsive phase of both CMJs. All SJ reliability variables were identical between males and females. Females displayed lower reliability for impulse values with the CI of ICC dropping below 0.80 for CMJ_0 and CMJ_{20} unweighting phases. In addition, CV values with CI for females in the unweighting phase produced higher variability which was also reflected in a higher SEM and MDC.

Discussion

The purpose of this study was to provide intra-session reliability values for the entire F-Tc duration of vertical jumps both static and countermovement. The key findings from this study are 1.) impulse and shape factor display the best overall absolute and relative reliability values;

2.) the addition of weight (20 kg) improves reliability for all variables; 3.) both the braking and propulsive phases of the CMJ are highly reliable; 4.) males and females produced similar SI scores despite statistically significant differences in jump flight times; 5.) both unweighted and weighted SJs produce superior reliability in most comparable instances.

Researchers and practitioners should use caution when assessing asymmetry with force and particularly power outputs as reliability was somewhat questionable, however, impulse and shape factor SI scores were more reliable overall. While force and power outputs are reliable during the propulsive phase, this only accounts for a minimal portion of a countermovement jump. While force SI_m provides the most reliable measure for SJ_0 and SJ_{20}, it may violate distribution normality indicating additional caution should be used. More research is needed to ascertain the relationship of each variable to performance measures.

In contrast to unilateral jumping asymmetry, weighted jumps may be familiar enough to many athletes to produce more reliable values. The addition of weight to each jump type does increase the absolute and relative reliability of most metrics of asymmetry. Weighted jumps, at least at the loads used in this study, may challenge the neuromotor patterns of the movement enough to require more coordinated muscle activation. While asymmetry research involving weighted jumps is lacking, these data will provide efficacy for continued research in this area.

Using self-select depths in the unweighting phase have been shown to be a less reliable measure for jumping (Carroll et al., 2019), however both the braking and propulsive phase are highly reliable. This observation provides evidence that interactions during the braking phase should be evaluated along with the propulsive phase. This interaction may illuminate the relationship between asymmetry and performance.

In essence, SJs are comprised of only a propulsive phase and, as such, are expected to mimic the asymmetry during the CMJ propulsive phase. With SJ asymmetry being more reliable than the propulsive phase of the CMJ, it may be a truer representation of concentric asymmetries. The eccentric phase of the CMJ influences the CMJ propulsive phase which may be a more representative measure of stretch-shortening cycle usage and overall coordination.

Males and females produced similar SI_m scores in most asymmetry metrics while producing statistically different flight times, and therefore jump heights. When assessing the relationship of asymmetry to performance, researchers should separate the sexes or mathematically account for these differences. As such, developed sporting asymmetries may be consistent between sexes and sports. However, while all athletes that participated were cleared by the athletic training staff, no past or present injury data were obtained in the current study which may have influenced these relationships (Hart et al., 2019).

This evidence dealing with reliability can alleviate the calculation confusion for future asymmetry studies. Power is a less reliable measure for jumping (Carroll et al., 2019) and may not be a viable avenue to discern asymmetry in bilateral CMJ. While power, in the propulsive phase of SJs and CMJs, showed good to excellent relative reliability, absolute reliability was worse than all other variables in the same phase. This may partially be explained by a shifting of body weight from one side to the other which may confound the power calculation method of using 50% system mass. However, more research is needed in this area.

Conclusion

Practitioners and researchers interested in pursuing asymmetry from dual GRF should focus on impulse or mSHP moving forward. Adding weight to jumps will provide a new avenue for asymmetry research, however an appropriate amount of weight is yet to be determined. Asymmetries in bilateral GRF from vertical style jumps are reliable and can be a simple addition to jumps already being monitored.

References

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports medicine, 26(4), 217-238.

Bailey, C., Sato, K., Burnett, A., & Stone, M. (2015a). Carry-over of force production symmetry in athletes of differing strength levels. journal of strength and conditioning research, 29(11), 3188-3196.

Bailey, C., Sato, K., Burnett, A., & Stone, M. (2015b). Force-production asymmetry in male and female athletes of differing strength levels. International Journal of Sports Physiology and Performance, 10(4), 504-508.

Bazyler, Bailey, Chiang, Sato, & Stone. (2014). The effects of strength training on isometric force production symmetry in recreationally trained males. Journal of Trainology, 6-10.

Bell, D. R., Sanfilippo, J. L., Binkley, N., & Heiderscheit, B. C. (2014). Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. Journal of strength and conditioning research, 28(4), 884.

Benjanuvatra, N., Lay, B., Alderson, J., & Blanksby, B. (2010). Comparison of ground reaction force asymmetry in one-and two-legged countermovement jumps. The Journal of Strength & Conditioning Research, 27(10), 2700-2707.

Bishop, C., Brashill, C., Abbott, W., Read, P., Lake, J., & Turner, A. (2019). Jumping asymmetries are associated with speed, change of direction speed, and jump performace in elite academy soccer players. Journal of Strength and Conditioning Research.

Bishop, C., Read, P., McCubbine, J., & Turner, A. N. (2018a). Vertical and horizontal asymmetries are related to slower sprinting and jump performance in elite youth female soccer players. Journal of strength and conditioning research.

Bishop, C., Turner, A., & Read, P. (2018b). Effects of inter-limb asymmetries on physical and sports performance: a systematic review. Journal of Sports Sciences, 36(10), 1135-1144.

Carroll, K. M., Wagle, J. P., Sole, C. J., & Stone, M. H. (2019). Intrasession and intersession reliability of countermovement jump testing in division-I volleyball athletes. The Journal of Strength & Conditioning Research, 33(11), 2932-2935.

Chavda, S., Bromley, T., Jarvis, P., Williams, S., Bishop, C., Turner, A., Lake, J., & Mundy, P. (2018). Force-time characteristics of the countermovement jump: Analyzing the curve in Excel. Strength & Conditioning Journal, 40(2), 67-77.

Dos'Santos, T., Thomas, C., Jones, P., & Comfort, P. (2017). Asymmetries in single and triple hop are not detrimental to change of direction speed. Journal of Trainology, 6(2), 35-41.

Exell, T. A., Irwin, G., Gittoes, M., & Kerwin, D. (2012). Implications of intra-limb variability on asymmetry analyses. Journal of Sports Sciences, 30(4), 403-409.

Gathercole, R., Sporer, B., Stellingwerff, T., & Sleivert, G. (2015). Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. International Journal of Sports Physiology and Performance, 10: 84-92.

Hart, N., Nimphius, S., Weber, J., Spiteri, T., Rantalainen, T., Dobbin, M., & Newton, R. (2017). Musculoskeletal asymmetry in football athletes: a product of limb function over time. Medicine and science in sports and exercise, 48(7), 1379-1387.

Hart, L. M., Cohen, D. D., Patterson, S. D., Springham, M., Reynolds, J., & Read, P. (2019). Previous injury is associated with heightened countermovement jump force-time asymmetries in professional soccer players. *Translational Sports Medicine*, *2*(5), 256-262.

Hoffman, J. R., Ratamess, N. A., Klatt, M., Faigenbaum, A., & Kang, J. (2007). Do bilateral power deficits influence direction-specific movement patterns? Research in Sports Medicine, 15(2), 125-132.

Impellizzeri, F., Rampinini, E., Maffiuletti, N., & Marcora, S. (2007). A vertical jump force test for assessing bilateral strength asymmetry in athletes. Medicine and Science in Sports and Exercise, 39(11), 2044-2050.

Jones, P., & Bampouras, T. (2010). A comparison of isokinetic and functional methods of assessing bilateral strength imbalance. Journal of Strength and Conditioning Research, 24(6), 1553-1558.

Kaçoğlu , C. (2019). Relationship between lower extremity strength asymmetry and jump and sprint performance. Türk Spor ve Egzersiz Dergisi, 21(2), 204-210.

Knapik, J., Bauman, C., Jones, B., Harris, J., & Vaughn, L. (1991). Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. The American Journal of Sports Medicine, 19(1): 76-81.

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. Journal of chiropractic medicine, 15(2), 155-163.

Lockie, R. G., Callaghan, S., Berry, S., Cooke, E., Jordan, C., Luczo, T., & Jeffriess, M. (2014). Relationship between unilateral jumping ability and asymmetry on multidirectional speed in team-sport athletes. The Journal of Strength & Conditioning Research, 28(12), 3557-3566.

Madruga-Parera, M., Bishop, C., Fort-Vanmeerhaeghe, A., Beltran-Valls, M., Skok, O., & Romero-Rodríguez, D. (2020). Interlimb asymmetries in youth tennis players: Relationships with performance. The Journal of Strength & Conditioning Research, 34(10), 2815-2823.

Maloney, S. J. (2019). The relationship between asymmetry and athletic performance: A critical review. The Journal of Strength & Conditioning Research, 33(9), 2579-2593.

Maloney, S., Richards, J., Nixon, D., Harvey, L., & Fletcher, I. (2017). Do stiffness and asymmetries predict change of direction performance? Journal of sports sciences, 35(6), 547-556.

Maulder, P., & Cronin, J. (2005). Horizontal and vertical jump assessment: reliability, symmetry, discriminative and predictive ability. Physical therapy in Sport, 6(2), 74-82.

Menzel, H., Chagas, M., Szmuchrowski, L., Araujo, S., Andrade, A., & Jesus-Moraleida, F. (2013). Analysis of lower limb asymmetries by isokinetic and vertical jump tests in soccer players. Journal of Strength and Conditioning Research, 27(5), 1370-1377.

Owens, E., Serrano, A., Ramsey, M., Mizuguchi, S., Johnston, B., & Stone, M. H. (2011). Comparing lower-limb asymmetries in NCAA DI male and female athletes. The Journal of Strength & Conditioning Research, 25, S44-S45.

Pérez-Castilla, A., García-Ramos, A., Janicijevic, D., Miras-Moreno, S., De la Cruz, J., Rojas, F., & Cepero, M. (2021). Unilateral or bilateral standing broad jumps: which jump type provides inter-limb asymmetries with a higher reliability? Journal of Sports Science and Medicine, 20(2), 317-327.

Sannicandro, I., Piccinno, A., Rosa, R., & Pascalis, S. (2011). Functional asymmetry in the lower limb professional soccer players. British Journal of Sports Medicine, 45(4), 370-370.

Sannicandro, I., Rosa, R., Pascalis, S., & Piccinno, A. (2012). The determination of functional asymmetries in the lower limbs of young soccer players using the countermovement jump. The lower limbs asymmetry of young soccer players. Science & Sports, 27(6), 375-377.

Schiltz, M., Lehance, C., Maquet, D., Bury, T., Crielaard, J. M., & Croisier, J. (2009). Explosive strength imbalances in professional basketball players. Journal of Athletic Training., 44, 39-47.

Sole, C., Mizuguchi, S., Sato, K., Moir, G., & Stone, M. (2018). Phase characteristics of the countermovement jump force-time curve: a comparison of athletes by jumping ability. Journal of Strength of Conditioning Research, 32(4): 1155-1165.

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. 46(10), 1419-1449.

Zifchock, R. A., Davis, I., Higginson, J., & Royer, T. (2008). The symmetry angle: a novel, robust method of quantifying asymmetry. Gait & posture, 27(4), 622-627.

Chapter 4. Relationships of Bilateral Ground Reaction Force Asymmetry and Countermovement Jumping Performance in Collegiate Soccer Players

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Abstract

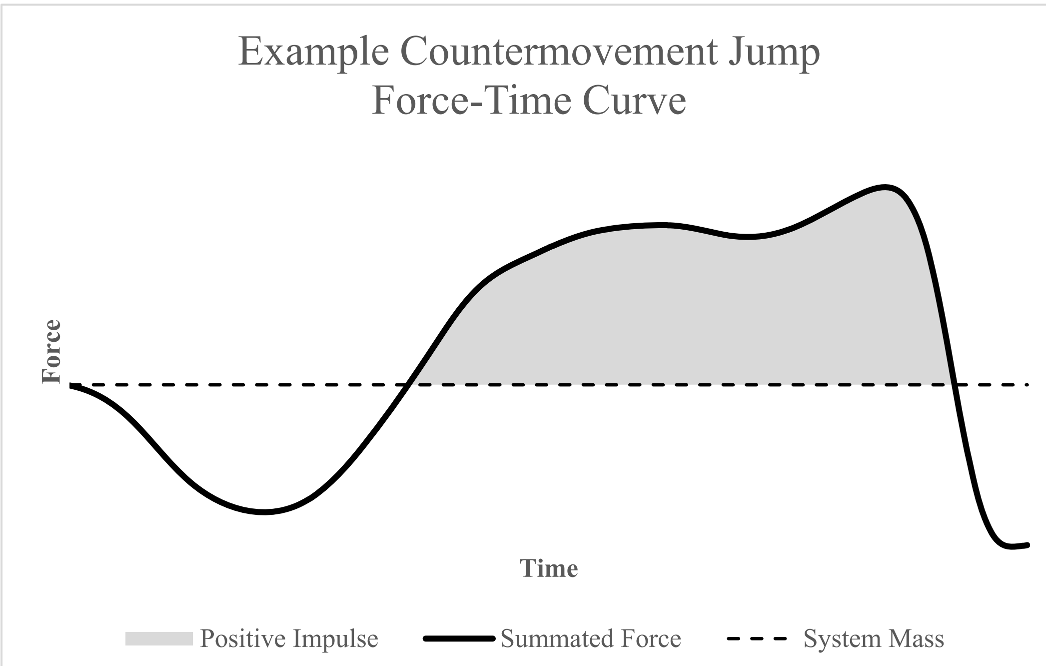
The relationship between asymmetry and performance is still being scrutinized in the literature with varying results. While methods of assessing asymmetry have been inconsistent, much of the research has focused on the analysis of jumping asymmetry. Dual ground reaction forces (dGRF) are becoming more prevalent in athlete monitoring programs, though underutilized in asymmetry research. The purpose of this retrospective study is to assess the relationship of countermovement jump impulse asymmetry to performance from dGRF in collegiate soccer athletes. A total of 59 athletes male and female athletes were selected from an ongoing athlete research repository database of NCAA D-I soccer athletes. All athletes contributed two maximal effort unweighted countermovement jumps (CMJ0) and weighted countermovement jumps (CMJ20) using the mean for calculations. Propulsive phase asymmetry scores (PrPAS) and positive impulse asymmetry scores (PIAS) were calculated to determine the magnitude of asymmetry for each prospective phase. Statistically significant ($p > 0.05$) correlations were found between CMJ0 jump height and unweighted PIAS ($r = -0.43$) in females. Males produced statistically significant correlations between CMJ20 jump height and weighted PIAS ($r = -0.49$). Neither unweighted PrPAS nor weighted PrPAS produced statistically significant correlations ($r < 0.26$) to their prospective jump heights. When assessing CMJ asymmetry, it is recommended to conduct both weighted and unweighted CMJ testing utilizing PIAS as the metric to be assessed.

Introduction

Asymmetry can be defined as the unequal split of two halves whether that be side-to-side, front-to-back or some other combination. Some level of asymmetry is expected in all human movements and there is likely a threshold for meaningful asymmetry (Guiard, 1987). As such, sporting asymmetry refers to developed asymmetries to match the demands of a particular sport (Maloney S. J., 2019; Rouissi, et al., 2016; Bishop, Turner, & Read, 2018), indicating that athletes likely learn to adapt to asymmetrical developments and use it to their advantage. This may account for the task dependent nature of asymmetry (Bailey et al., 2015a; Bussey, 2010; Maloney, 2019) which should be considered when investigating asymmetry with performance, as motor coordination may be more indicative of poor performance than strength asymmetry (Bell et al., 2014).

Asymmetry and performance have shown mixed results in the literature and there has not been a consensus on their relationship (Maloney, 2019). Some studies have provided evidence that various jumping asymmetries do relate to performance measures (Bishop, Turner, & Read, 2018; Madruga-Parera, et al., 2020; Maloney, Richards, Nixon, Harvey, & Fletcher, 2017; Maulder & Cronin, 2005), others refute those claims (Dos'Santos et al., 2017; Hoffman et al., 2007). Most studies of ground reaction force asymmetry have focused on the peaks associated with the propulsive phase of the CMJ (Benjanuvatra et al., 2010; Impellizzeri et al., 2007) which leaves out the unweighting and breaking phases that account for over half of the jump. These phases are likely more malleable when encountering asymmetry (Bailey et al., 2015a). While the unweighting phase has been shown to be less reliable with self-selected depths (Carroll et al., 2019), the breaking phase has been shown to produce good to excellent reliability (Sole et al., 2018). As well, the breaking phase asymmetry could be an indicator of how an athlete recovers and reacts to the unweighting phase. For these reasons, this correlational study will deal with an assessment of the propulsive phase and the positive impulse phase which is comprised of the breaking phase to the point of return to system mass just before take-off (see Figure 4.3) which is also the impulse due to the GRF (Linthorne, 2001).

Figure 4.3 Positive Impulse Example Illustration



Additionally, very few researchers have included weighted jumps during asymmetry investigations, and this may be a crucial but overlooked component. Bilateral weighted CMJs may illicit a similar asymmetry response compared to previously investigated unilateral drop jumps (Maloney et al., 2017) and they have been found to exacerbate unloaded jump asymmetry values (Bailey et al., 2015a). Assessing loaded CMJs may be more representative of loads experienced in practice and game situations, as well as a method of increasing the difficultly of a learned task (Kraska et al., 2009). Adding a load should either cause athletes to become more or less asymmetrical in the time it takes to achieve PF. Thus, the inclusion of weighted CMJ asymmetry was also assessed. Overall, the goal of this study is to assess the relationship of CMJ asymmetry to CMJ performance using two alternative methods: propulsive phase asymmetry only and positive impulse phase asymmetry.

Methods

This was a retrospective study examining the relationships of jumping asymmetry to performance. All data were selected from the ongoing athlete research repository database of NCAA D-I male and female soccer teams. The inclusion criteria for each athlete were as follows; 1) all jump testing was conducted on dual force plates; 2.) participated in all performance tests during the testing session with a minimum of two maximum effort trials for each jump test; 3.) tests were conducted during the pre-season phase during the same month. A total of 59 athletes were selected (male n = 35, female n = 24) after implementing the inclusion criteria. This research was approved by the University Institutional Review Board.

Testing protocols

All athletes were cleared to participate by the athletic training staff. Testing consisted of a hydration test, anthropometrics, standard warm up, unweighted jumps, weighted jumps, and isometric mid-thigh pulls. Athletes were given a 50% and a 75% of perceived maximum effort warm up before each test. The average of the best two trials were used for data analysis. Weighted CMJs were performed with a 20 kg barbell (behind neck, across shoulders) and unweighted jumps were performed with a PVC pipe in place of the barbell to prevent arm swing. Before the start of each jump type, a standing system mass value was obtained for a minimum of 1.0 s. All jumps had an athlete self-selected unweighting depth. Isometric mid-thigh pulls (IMTP) were conducted after jump testing was complete. Athletes were positioned in a customized stationary rack at 125 ± 5° knee angle with an upright trunk position (Comfort et al., 2019; Kraska et al., 2009; Stone et al., 2019). All jumps and IMTPs were performed on dual force plates (91.0 cm 3 91.0 cm; Rice Lake Weighing Systems, Rice Lake, WI, USA) with the analog signal from the force platform collected using a customized LabView (National Instruments, Austin, TX, USA) program at 1000 Hz.

Data analysis

The vertical dual ground reaction force (dGRF) data from jumps were exported as text files and analyzed using a customized 2019 Microsoft Excel® spreadsheet and VBA coding (Microsoft Corporations, Redmond, Washington, USA) adopting previously established methods of analyzing CMJs (Chavda et al., 2018; Sole et al., 2018). Raw voltage data from force plates were smoothed using a 50-point FIR filter and then converted into Newtons (N) to develop the force-time curve (F-Tc) for each jump.

The propulsive phase of the CMJ is defined as the end of the eccentric phase to the start of flight time (Sole et al., 2018). Using impulse, a propulsive phase asymmetry score (PrPAS) and a positive impulse asymmetry score (PIAS) was calculated for each jump using an absolute asymmetry equation (see Equation 4.2) (Bazyler et al., 2014; Sato & Heise, 2012) to assess the overall magnitude of asymmetry.

Equation 4.2 Symmetry Index Equation

$$\frac{(Maximum\ value - Minimum\ value)}{(Maximum\ value + Minimumu\ value)} \times 100$$

This allowed for a true assessment of asymmetry rather than focusing on which side was dominant since previous research has shown asymmetry may shift sides depending on the task (Maloney, 2019).

Statistics

Means and standard deviations are presented as M ± SD. Normality of distribution was checked using the Shapiro-Wilks tests. Welch's T-tests were calculated to assess group differences. A Pearson's product correlation (r) with 95% confidence intervals (CI) were computed between all tests and asymmetry and are reported as r [CI]. Critical r values were calculated for both males and females. An alpha of 0.05 was set for all applicable statistical analyses. Data were analyzed using customized 2019 Microsoft Excel® spreadsheet (Microsoft Corporations, Redmond, Washington, USA).

Results

Descriptive statistics can be found in Table 4.9. All performance variables were normally distributed; however, asymmetry scores were not. Due to the overall curvilinear nature of the scatter plots from the concentration of asymmetry values at the lower end of the spectrum, a natural log transformation was used. After applying a natural log transformation to asymmetry scores, they were found to be normally distributed. Additionally, no outliers or influential cases were identified.

Statistically significant correlations were found between unweighted positive impulse asymmetry score (PIAS0) and weighted positive impulse asymmetry score (PIAS20) for males and females (r = 0.84, 0.87; respectively). While unweighted propulsive phase asymmetry score (PrPAS0) to weighted propulsive phase asymmetry score (PrPAS20) were also statistically significant, the correlation was not as strong for males (r = 0.51) nor for females (r = 0.57).

Table 4.9 Descriptive Data for Correlations

	Males	Females
Body Mass (kg)	76.3 ± 7.8	68.8 ± 12.0
Height (cm)	178.3 ± 5.9	165.3 ± 19.5
Age	19.7 ± 1.5	19.5 ± 0.8
IPFa	189.6 ± 27.2	153.4 ± 25.4
JH0 (cm)	30.82 ± 4.25	21.44 ± 4.72
JH20 (cm)	22.19 ± 3.67	14.42 ± 3.19
PIAS0	7.10 ± 5.45	5.96 ± 5.55
PIAS20	7.06 ± 4.59	5.53 ± 4.25

Notes: Data presented as Mean ± SD; PIAS0 = Positive impulse asymmetry score for unweighted countermovement jumps; PIAS20 = Positive impulse asymmetry score for weighted (20 kg) countermovement jumps; IPFa = allometrically scaled isometric peak force; JH0 = unweighted jump height; JH20 = weighted (20 kg) jump height.

Males and females produced statistically significant differences ($p < 0.05$) between unweighted jump heights (JH0), weighted jump heights (JH20), body mass (BM), and allometrically scaled isometric peak force (IPFa). No statistically significant differences were found between the sexes for PrPAS0 ($p = 0.97$), PrRAS20 ($p = 0.67$), PIAS0 ($p = 0.44$), nor PIAS20 ($p = 0.20$). Critical r values were determined to be ± 0.33 for males and ± 0.40 for females.

Unweighted jump heights for males (see Figure 4.4) fell just short of statistical significance with PIAS0. However, females (see Figure 4.5) did have statistically significant correlations with PIAS0 (see Table 4.10). Conversely, males presented statistically significant correlations between weighted jump heights and PIAS20 (see Table 4.10 and Figure 4.6), but females did not reach statistical significance in the same (Figure 4.7).

Table 4.10 Positive Impulse Asymmetry Score Correlations

	Description	Pearson Correlation (r) with [CI]	R^2	p value
Females (n = 24)	Jump Height 0kg : PIAS0	-0.43 [-0.71, -0.03]	0.19	0.03*
	Jump Height 20kg : PIAS20	-0.25 [-0.59, 0.17]	0.06	0.23
Males (n = 35)	Jump Height 0kg : PIAS0	-0.32 [-0.59, 0.01]	0.10	0.06
	Jump Height 20kg : PIAS20	-0.49 [-0.71, -0.19]	0.24	< 0.01*

*Note: CI = 95% confidence interval; JH0 = unweighted jump height; JH20 = weighted (20 kg) jump height; PIAS0 = Positive impulse asymmetry score for unweighted countermovement jumps; PIAS20 = Positive impulse asymmetry score for weighted (20 kg) countermovement jumps; * = Statistically significant with alpha of 0.05; All values based on LN transformation of PIAS0 and PIAS20.*

Figure 4.4 Plotted Male Unweighted Countermovement Jumps

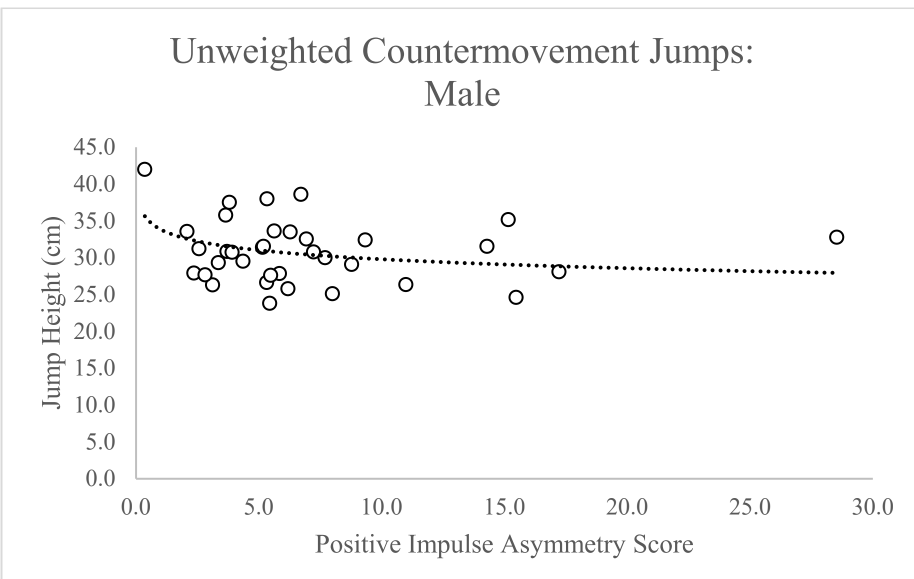


Figure 4.5 Plotted Female Unweighted Countermovement Jumps

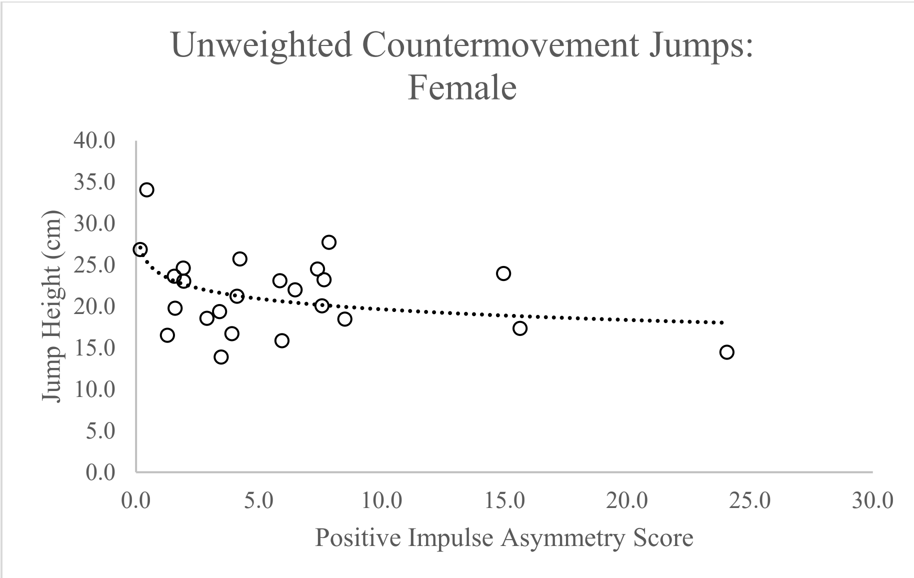


Figure 4.6 Plotted Male Weighted Countermovement Jumps

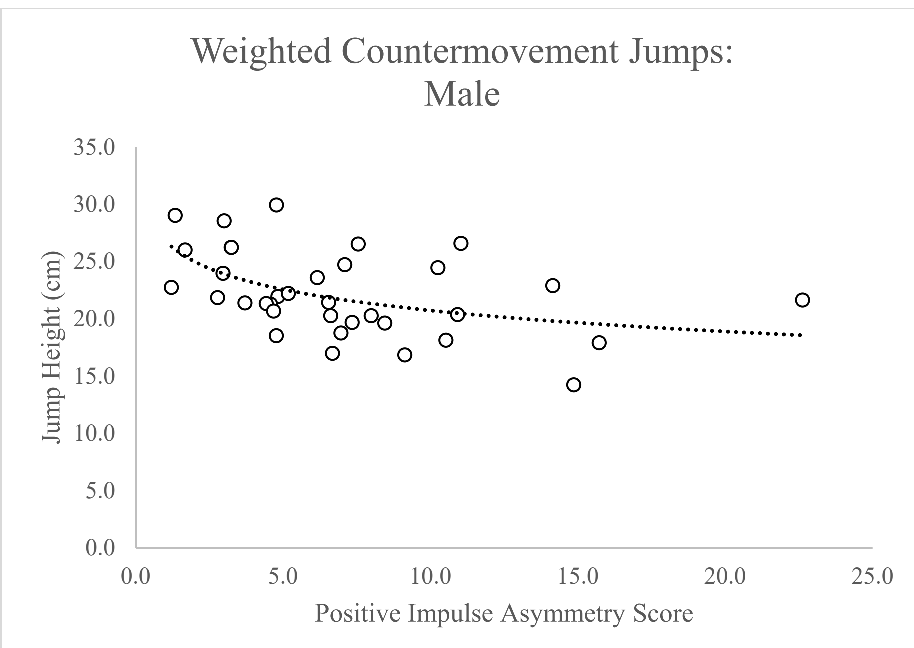
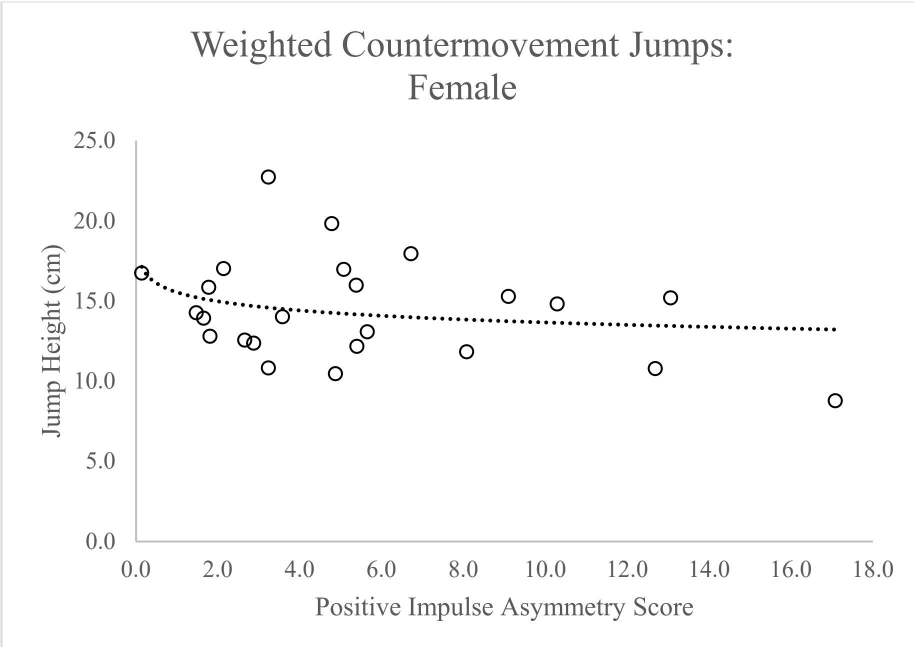


Figure 4.7 Plotted Female Weighted Countermovement Jumps



No statistically significant correlations were found for males or females between PrPAS0 and PrPAS20 with their respective jump heights (see Table 4.11). Interestingly, three of the four correlations became positive.

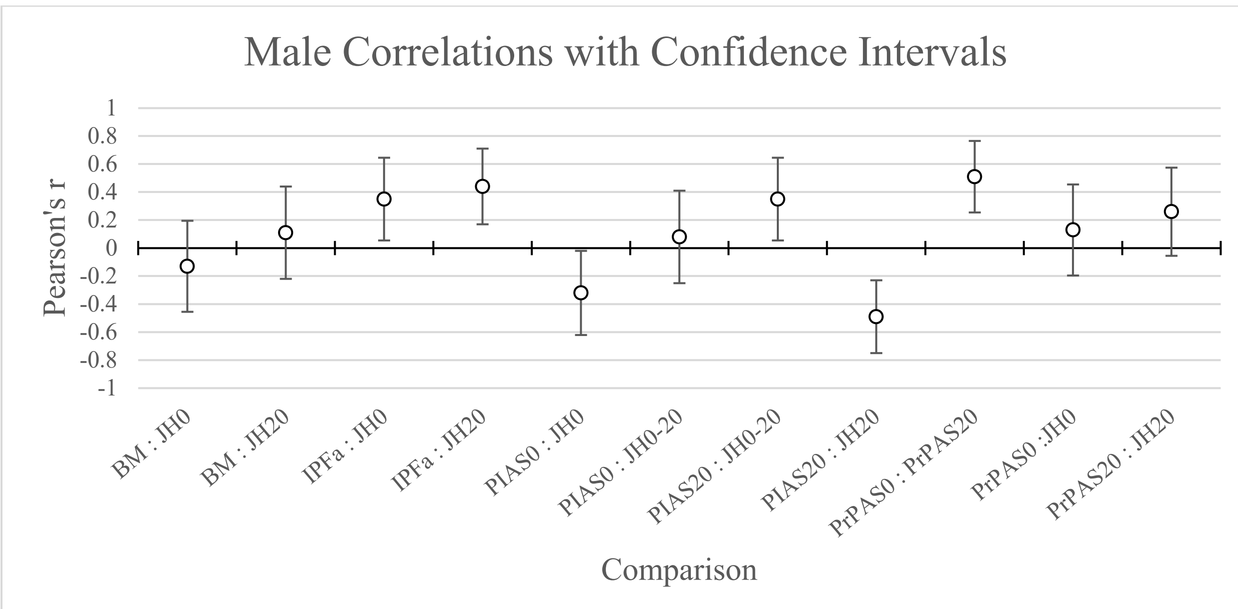
Table 4.11 Propulsive Phase Asymmetry Score Correlations

	Description	Pearson Correlation (r) with [CI]	R^2	p value
Females (n = 24)	Jump Height 0 kg : PrPAS0	-0.09 [-0.48, 0.33]	0.01	0.66
	Jump Height 20 kg : PrPAS20	0.11 [-0.31, 0.49]	0.01	0.60
Males (n = 35)	Jump Height 0 kg : PrPAS0	0.13 [-0.21, 0.44]	0.02	0.46
	Jump Height 20 kg : PrPAS20	0.26 [-0.08, 0.55]	0.07	0.13

*Note: CI = 95% confidence interval; JH0 = unweighted jump height; JH20 = weighted (20 kg) jump height; PrPAS0 = Positive impulse asymmetry score for unweighted countermovement jumps; PrPAS20 = Positive impulse asymmetry score for weighted (20) countermovement jumps; * = Statistically significant correlations with alpha level of 0.1; Based on LN transformation of PrPAS0 and PrPAS20.*

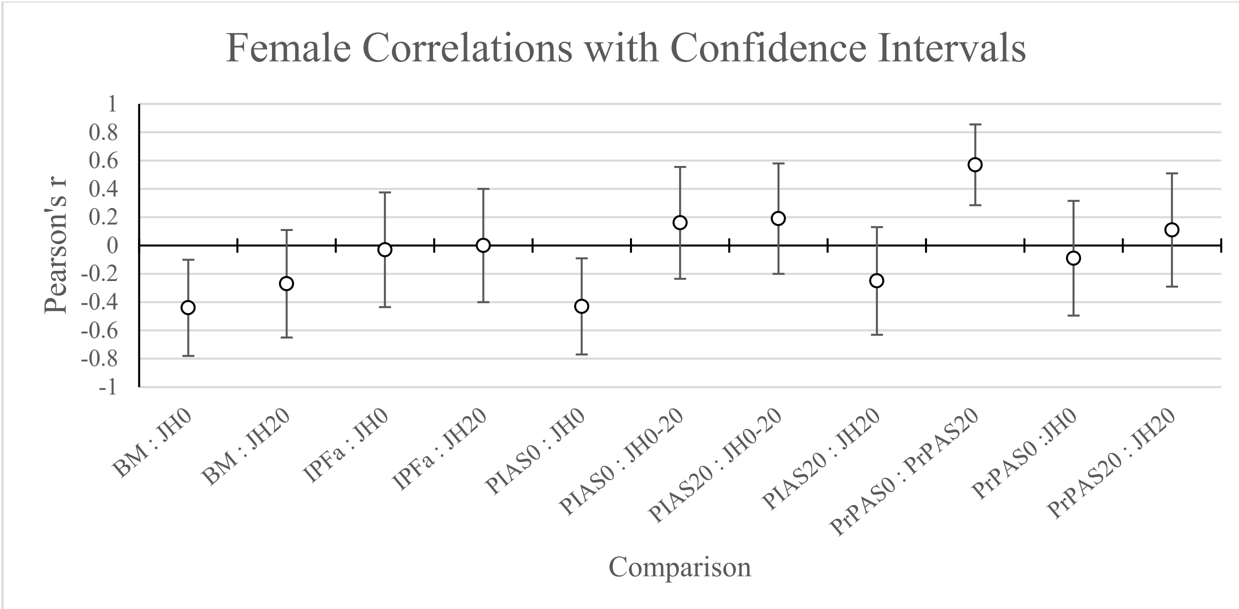
No statistically significant correlations were found between PrPSA0, PrPSA20, PIAS0, nor PIAS20 with IPFa in males (r = 0.15 [0.09, 0.21], 0.22[0.17, 0.28], 0.00 [-0.06, 0.06], -0.30 [-0.36, -0.25]; respectively) and females (r = -0.01 [-0.10, 0.09], 0.10 [0.01, 0.19], -0.12 [-0.21, -0.03], -0.01 [-0.08, 0.10]; respectively) (see Figure 4.8 and Figure 4.9).

Figure 4.8 Male Correlations with Confidence Intervals



Note: BM = Body Mass; JH0 = Unweighted Jump Height; JH20 = Weighted Jump Height; JH0-20 = Percent drop-off from unweighted jump height to weighted jump height; IPFa = Allometrically Scaled Isometric Mid-thigh Pull Peak Force; PIAS0 = Unweighted positive impulse asymmetry score; PIAS20 = Weighted positive impulse asymmetry score; PrPAS0 = Unweighted propulsive phase impulse asymmetry score; PrPAS20 = Weighted propulsive phase impulse asymmetry score

Figure 4.9 Female Correlations with Confidence Intervals



Note: BM = Body Mass; JH0 = Unweighted Jump Height; JH20 = Weighted Jump Height; JH0-20 = Percent drop-off from unweighted jump height to weighted jump height; IPFa = Allometrically Scaled Isometric Mid-thigh Pull Peak Force; PIAS0 = Unweighted positive impulse asymmetry score; PIAS20 = Weighted positive impulse asymmetry score; PrPAS0 = Unweighted propulsive phase impulse asymmetry score; PrPAS20 = Weighted propulsive phase impulse asymmetry score.

Females had a statistically significant correlation between BM and JH0 ($r = -0.44$ [-0.72, -0.04], $p = 0.03$) and males did not ($r = -0.13$ [-0.44, 0.21], $p = 0.46$). Neither males nor females produce a statistically significant correlation between JH20 and BM ($r = 0.11$ [-0.23, 0.43], -0.27 [-0.61,0.15]; $p = 0.53$, 0.20; respectively). However, IPFa in males produced statistically significant correlations between JH0 ($r = 0.35$ [0.02, 0.61], $p = 0.04$) and JH20 ($r = 0.44$ [0.13, 0.67], $p < 0.01$), whereas females produced no such relationship with IPFa ($r = -0.03$ [-0.43, 0.38], 0.00 [-0.40,0.40]; $p = 0.89$, 0.99; respectively). Additionally, males had a statistically significant correlation between PIAS20 and the percent difference between JH0 and JH20 ($r = 0.35$ [0.02, 0.61]; $p = 0.04$), whereas females did not reach statistical significance ($r = 0.19$ [-0.23, 0.55], $p = 0.38$). Interestingly, PIAS0 did not produce a statistically significant correlation between the percent difference of JH0 and JH20 for males (r = 0.08 [-0.26, 0.40], p = 0.65) nor females (r = 0.16 [-0.26, 0.53], p = 0.35).

Discussion

The purpose of this study was to investigate the relationship of asymmetry from both the propulsive phase and the positive impulse phase with jump height from unweighted and weighted jumps from collegiate soccer players. In addition, the inclusion of both male and female athletes produced an auxiliary question of sex differences. These data illustrate the negative relationship of increasing asymmetry in the positive impulse phase has on CMJ performance. As well, a notable finding was that the propulsive phase impulse asymmetry does not produce statistically significant correlations with jump height performances. The negative relationship of PIAS and CMJ performance was expected and illustrates that more symmetrical positive impulses produce greater total impulses leading to greater jumping performances. Although the literature is equivocal, the relationships between CMJ performance and PrPAS, agrees with previous findings investigating the propulsive phase (Bell et al., 2014). Males and females have differing performance levels with similar asymmetry. This combined with the ability of strength training to improve the coordination of muscle activation patterns (Behringer et al., 2011; Carroll et al., 2001), provides further evidence for the motor coordination aspect of asymmetry and the possibility of sport specific asymmetry development.

Interpretation of these results do come with limitations as no injury data were made available for this study nor were currently injured soccer athletes assessed. Previous injuries may influence the relationship of asymmetry measures to performance even with all athletes being cleared by the athletic training staff. As such, athletes recovering from a recent injury, even though cleared to participate, may still display differing relationships to these variables (Hart et al., 2019). Additionally, these data are applicable to collegiate soccer athletes and more research is needed to expand these finding to other levels of soccer athletes and differing sports.

Using PIAS is a novel approach to the asymmetry relationship to performance question and yields promising results that may clarify discrepancies previously published about asymmetry from ground reaction forces. The propulsive phase alone is not a good indicator of CMJ performance asymmetry and should be combined with the braking phase. This stands to reason as the utilization of the stretch-shortening cycle influences the concentric contraction. Additionally, this may help explain the negligible relationship between CMJ asymmetry and isometric strength found in this study which is in line with previous investigations (Bailey et al., 2015a; Jones & Bampouras, 2010). Differing motor demands elicit different asymmetry results. However, strength training has shown to enhance muscle spindle utilization, increase reciprocal inhibition (Aagaard et al., 2002), and improve coordination (Behringer et al., 2011; Bazyler et al., 2014). Together, this suggests that dynamic strength measures which include an eccentric component could have a stronger relationship to CMJ asymmetry (Maloney, 2019), especially during the positive impulse phase. It should also be noted that strength training specificity and degree of transfer to performance may play a role in altering asymmetry (Carroll et al., 2001; Suarez et al., 2019).

Asymmetry levels are similar between the sexes, but performances are not. The similar asymmetry between males and females may be explained by, and support the theory of, soccer specific asymmetry (Sannicandro et al., 2011). It is possible that previous studies investigating asymmetry using athletes from multiple sports experienced lower correlations due to the differing demands of each sport which may have differing asymmetry thresholds. With females having a high correlation between BM and jump heights and low correlations between IPFa and jumping performances, overall strength may have played a role in the lack of correlation between PIAS and jump performance in the weighted jumps. This indicates that the 20 kg selection for assessing weighted jump asymmetries may not be the most appropriate weight for individuals below a certain maximum strength level, though more research is needed in this area. These results are similar to disparities found between males and females in previous asymmetry research (Bailey et al., 2015b; Benjanuvatra et al., 2010; Kozinc & Šarabon, 2020). Overall, males seem to have better control of their body mass than females, which may be related to strength differences (Bailey et al., 2015a; Bailey et al., 2015b). This is supported by males producing a stronger correlation in PIAS20 to JH20 than PIAS0 to JH0.

Asymmetry is correlated between similar tasks and developing an asymmetry profile of an athlete from multiple tasks could theoretically be used to assist in understanding the overall implications asymmetry has on performance. Practitioners should use caution when comparing these results to other studies as the calculation used for assessing asymmetry does have an impact on assigning thresholds and recommendations. It is important to note that the current study implemented a calculation that yields lower asymmetry score results than studies that used a single limb or half of the sum of both limbs in the denominator. Assessing asymmetry is a simple addition to currently monitored dGRF profiles and may be used to spot unexpected adaptations in a longitudinal manner, though more research is needed in this area.

Conclusion

Coaches and practitioners should use caution when assessing asymmetry as the test needed may change depending on the population. It is recommended to assess asymmetry under both unloaded and loaded conditions when applicable. Additionally, asymmetry during the entire positive impulse phase should be used in the calculation of asymmetry instead of the propulsive only phase.

References

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Neural adaptation to resistance training: changes in evoked V-wave and H-reflex responses. *Journal of Applied Physiology*, 92(6), 2309-2318.

Bailey, C., Sato, K., Burnett, A., & Stone, M. (2015a). Carry-over of force production symmetry in athletes of differing strength levels. *Journal of Strength and Conditioning Research*, 29(11), 3188-3196.

Bailey, C., Sato, K., Burnett, A., & Stone, M. (2015b). Force-production asymmetry in male and female athletes of differing strength levels. *International Journal of Sports Physiology and Performance*, 10(4), 504-508.

Bazyler, Bailey, Chiang, Sato, & Stone. (2014). The effects of strength training on isometric force production symmetry in recreationally trained males. *Journal of Trainology*, 6-10.

Behringer, M., Vom Heede, A., Matthews, M., & Mester, J. (2011). Effects of strength training on motor performance skills in children and adolescents: a meta-analysis. *Pediatric exercise science*, 23(2), 186-206.

Bell, D. R., Sanfilippo, J. L., Binkley, N., & Heiderscheit, B. C. (2014). Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. *Journal of strength and conditioning research*, 28(4), 884.

Benjanuvatra, N., Lay, B., Alderson, J., & Blanksby, B. (2010). Comparison of ground reaction force asymmetry in one-and two-legged countermovement jumps. *The Journal of Strength & Conditioning Research*, 27(10), 2700-2707.

Bishop, C., Turner, A., & Read, P. (2018). Effects of inter-limb asymmetries on physical and sports performance: a systematic review. *Journal of Sports Sciences*, 36(10), 1135-1144.

Bussey, M. (2010). Does the demand for asymmetric functional lower body postures in lateral sports relate to structural asymmetry of the pelvis? *Journal of science and medicine in sport*, 13(3), 360-364.

Carroll, K. M., Wagle, J. P., Sole, C. J., & Stone, M. H. (2019). Intrasession and intersession reliability of countermovement jump testing in division-I volleyball athletes. *The Journal of Strength & Conditioning Research*, 33(11), 2932-2935.

Carroll, T. J., Benjamin, B., Stephan, R., & Carson, R. G. (2001). Resistance training enhances the stability of sensorimotor coordination. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 268(1464), 221-227.

Chavda, S., Bromley, T., Jarvis, P., Williams, S., Bishop, C., Turner, A., . . . Mundy, P. (2018). Force-time characteristics of the countermovement jump: Analyzing the curve in Excel. *Strength & Conditioning Journal*, 40(2), 67-77.

Comfort, P., Dos'Santos, T., Jones, P., McMahon, J., Suchomel, T., Bayzler, C., & Stone, M. H. (2019). Normalization of early isometric force production as a percentage of peak force during multijoint isometric assessment. *International journal of sports physiology and performance*, 15(4), 478-482.

Dos'Santos, T., Thomas, C., Jones, P., & Comfort, P. (2017). Asymmetries in single and triple hop are not detrimental to change of direction speed. *Journal of Trainology*, 6(2), 35-41.

Guiard, Y. (1987). Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model. *Journal of motor behavior*, 19(4), 486-517.

Hoffman, J. R., Ratamess, N. A., Klatt, M., Faigenbaum, A., & Kang, J. (2007). Do bilateral power deficits influence direction-specific movement patterns? *Research in Sports Medicine*, 15(2), 125-132.

Impellizzeri, F., Rampinini, E., Maffiuletti, N., & Marcora, S. (2007). A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Medicine and Science in Sports and Exercise*, 39(11), 2044-2050.

Jones, P., & Bampouras, T. (2010). A comparison of isokinetic and functional methods of assessing bilateral strength imbalance. *Journal of Strength and Conditioning Research*, 24(6), 1553-1558.

Kozinc, Z., & Šarabon, N. (2020). Inter-limb asymmetries in volleyball players: differences between testing approaches and association with performance. *Journal of Sports Science & Medicine*, 19(4), 745.

Kraska, J., Ramsey, M., Haff, G. G., Fethke, N., Sands, W., Stone, M. E., & Stone, M. H. (2009). Relationship between strength and un-weighted and weighted vertical jump height. *International Journal of Sport Physiology and Performance*, 4(4), 461-473.

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physics*, 69(11), 1198-1204.

Madruga-Parera, M., Bishop, C., Fort-Vanmeerhaeghe, A., Beltran-Valls, M., Skok, O., & Romero-Rodríguez, D. (2020). Interlimb asymmetries in youth tennis players: Relationships with performance. *The Journal of Strength & Conditioning Research*, 34(10), 2815-2823.

Maloney, S. J. (2019). The relationship between asymmetry and athletic performance: A critical review. *The Journal of Strength & Conditioning Research*, 33(9), 2579-2593.

Maloney, S., Richards, J., Nixon, D., Harvey, L., & Fletcher, I. (2017). Do stiffness and asymmetries predict change of direction performance? *Journal of sports sciences*, 35(6), 547-556.

Maulder, P., & Cronin, J. (2005). Horizontal and vertical jump assessment: reliability, symmetry, discriminative and predictive ability. *Physical therapy in Sport*, 6(2), 74-82.

Rouissi, M., Chtara, M., Owen, A., Chaalali, A., Chaouachi, A., Gabbett, T., & Chamari, K. (2016). Effect of leg dominance on change of direction ability amongst young elite soccer players. *Journal of sports sciences*, 34(6), 542-548.

Sannicandro, I., Piccinno, A., Rosa, R., & Pascalis, S. (2011). Functional asymmetry in the lower limb professional soccer players. *British Journal of Sports Medicine*, 45(4), 370-370.

Sato, K., & Heise, G. (2012). Influence of weight distribution asymmetry on the biomechanics of a barbell back squat. *The Journal of strength & conditioning research*, 26(2), 342-349.

Sole, C., Mizuguchi, S., Sato, K., Moir, G., & Stone, M. (2018). Phase characteristics of the countermovement jump force-time curve: a comparison of athletes by jumping ability. *Journal of Strength of Conditioning Research*, 32(4): 1155-1165.

Stone, M. H., O'Bryant, H. S., Hornsby, G., Cunanan, A., Mizuguchi, S., Suarez, D. G., . . . Pierce, K. P. (2019). The use of the isometric mid-thigh pull in the monitoring of weightlifters: 25+ years of experience. *UKSCA Journal: Professional Strength and Conditioning*, 54, 10-26.

Suarez, D., Dylan, G., Wagle, J., Cunanan, A., Sausaman, R., & Stone, M. H. (2019). Dynamic correspondence of resistance training to sport: A brief review. *Strength and conditioning journal*, 41(4), 80-88.

Chapter 5. Longitudinal Changes in Bilateral Ground Reaction Force Asymmetry in Collegiate Male Soccer Players

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Abstract

The magnitude of asymmetry during a given task should decrease the performance for that task. With increasing evidence of asymmetry in all human movements, it is likely that there are thresholds of detrimental asymmetry. Some evidence suggests that decreased asymmetry is related increased strength or strength training, but little is known about the changes that occur over time. Thus, the purpose of this study is to observe the changes to asymmetry in collegiate male soccer players ($n = 12$) over the course of three years. With the assumption that all human movement produces asymmetry, these athletes were divided into high and low asymmetry groups for further analysis. Body masses and jump heights all produced statistically significant ($p < 0.05$) changes over time. Combined results produced no statistically significant changes over time in asymmetry, however, when split into groups the high asymmetry group did produce statistically significant ($p < 0.01$) decreased asymmetry over time. Effect size (ES) calculations indicate trends showing that the athletes starting out with higher asymmetry values demonstrated greater improvements in jump heights over time. Athletes with higher asymmetry showed little difference in initial jump height (ES < 0.17) but ended with greater differences (ES > 0.44). With the possibility that asymmetry is more related to motor competency of a given task, high asymmetry scores may be an indicator for greater performance potential in the future.

Introduction

Spontaneous symmetry breaking is a theory in physics stating that even a completely symmetrical physical system can spontaneously end in an asymmetric state (Kibble, 2015). The human body, always in constant fluctuation, is comprised of systems attempting to balance one another to reach a specific goal. Athletic performance appears to “fit” this theory and some asymmetry is always expected. As well, asymmetry itself is variable among differing performance activities (Bailey C. , Sato, Burnett, & Stone, 2015; Benjanuvatra, Lay, Alderson, & Blanksby, 2010; Maloney S. J., 2019) and it is likely there are thresholds of acceptable asymmetry (Bazyler et al., 2014; Maloney, 2019), but they have yet to be defined.

While many investigations have attempted to define relative side-to-side differences (Bell et al., 2014; Benjanuvatra et al., 2010; Dos’Santos et al., 2017; Madruga-Parera et al., 2020; Maulder & Cronin, 2005) by either determining a dominant leg or by simply subtracting the values of one specified leg from the values of the other leg. However, the seemingly task dependent nature of asymmetry may call for a more absolute approach (Sato & Heise, 2012; Bishop et al., 2021). Additionally, it has been suggested that jumping impulse is a more sensitive measure of asymmetry (Menzel et al., 2013) and that the asymmetry during the positive impulse phase (see Chapter 4) has the highest correlative values to jumping performance.

Although longitudinal evidence is lacking, some research has produced evidence that asymmetries are not associated with maximal strength tasks (Sato & Heise, 2012; Bailey et al., 2015a) but may be more indicative of motor competency of a given task (Maloney, 2019). However, Bazyler et al. (2014) have suggested that bilateral asymmetry during isometric mid-thigh pulls may be influenced by strength-training status. Longitudinal evidence of changes, or lack thereof, in asymmetry can greatly impact the interpretation of asymmetry results by adding context to differences found in athletes with varying training ages. For these reasons, the purpose of this study is to track the yearly changes of bilateral asymmetry in male collegiate soccer players.

Methods

Athletes for this study were selected from the ongoing athlete research repository database of NCAA D-I men's soccer team (height: 177.9 ± 7.4 cm; age: 19.5 ± 1.2; body mass: 76.2 ± 10.5). To be included each athlete must have participated in the fall pre-season testing in three consecutive years. A total of 12 athletes were selected. Before the start of each jump, a standing system mass value was obtained for a minimum of 1.0 s. This produced the body mass values for this study when taken before the unweighted jump. Height measurements were collected using a stadiometer.

Absolute asymmetry was calculated by subtracting the lowest impulse value from the highest impulse value then dividing by the sum of the impulses multiplied by 100 ([Maximum value – minimum value] / SUM x 100) (Bazyler et al., 2014; Sato & Heise, 2012). Overall magnitude of asymmetry during the positive impulse phase was used to create the positive impulse asymmetry score (PIAS) for each jump using the previously mentioned absolute asymmetry equation.

Groups were divided by the mean of overall asymmetry which was produced by the summation of the unweighted jump positive impulse asymmetry score (PIAS0) with the weighted jump positive impulse asymmetry score (PIAS20). This produced a group with higher than average asymmetry (HIGH) and lower than average asymmetry (LOW).

To assess year-to-year changes and group differences 2-way mixed ANOVAs were calculated. Post hoc analyses were performed using the Holm-Bonferroni adjustment. Effect sizes were estimated using Cohen's d. Greenhouse-Geisser corrections were used if sphericity was violated. Initial group differences were assessed using Welch's T-tests. Paired sample T-tests were used to assess differences in unweighted and weighted values. Alpha was set to 0.05 for all calculations.

Results

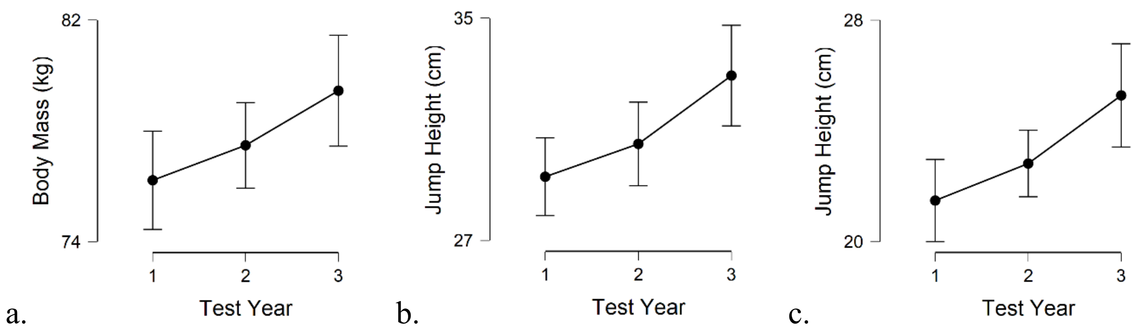
Descriptive statistics for all variables assessed can be found in Table 5.12. Assumptions of homoscedasticity, independence of observations, and normality of distribution were met for all variables. Paired sample T-tests revealed statistically significant differences ($p < 0.01$) in JH0 and JH20, but not in PIAS0 and PIAS20. Statistically significant changes from year 1 (Y1) to year 3 (Y3) in body mass (BM) ($p = 0.03$), unweighted jump height (JH0) ($p < 0.01$), and weighted jump height (JH20) ($p < 0.01$) were found (see Figure 5.10). No statistically significant changes were detected from Y1 to year 2 (Y2) in BM ($p = 0.63$), JH0 ($p = 0.59$), and JH20 ($p = 0.47$) nor for changes from Y2 to Y3 ($p = 0.27, 0.07, 0.06$; respectively). No statistically significant changes over time alone were produced from PIAS0 ($p = 0.06$) and PIAS20 ($p = 0.16$). However, large to moderate effect sizes (ES) from the Y1 to the Y3 were produced for PIAS0 (0.54) and PIAS20 (0.44) (see Figure 5.11). Moderate to small ES were found from Y1 to Y2 in PIAS0 (0.27) and PIAS20 (0.34), as well from Y2 to Y3 in PIAS0 (0.36) (see Table 5.13).

Table 5.12 Longitudinal Descriptive Data

		Year 1	Year 2	Year 3
	Body Mass (kg)	76.2 ± 10.5	77.5 ± 12.3	79.5 ± 13.65
CMJ0	Jump Height (cm)	29.3 ± 3.0	30.5 ± 3.4	32.9 ± 4.3
	PIAS	8.64 ± 4.92	7.18 ± 5.21	5.49 ± 3.51
CMJ20	Jump Height (cm)	21.5 ± 3.5	22.8 ± 2.8	25.3 ± 2.7
	PIAS	7.81 ± 3.86	6.27 ± 4.33	5.89 ± 3.09

Note: Reported in Mean ± SD; PIAS = positive impulse asymmetry score; CMJ0 = Unweighted countermovement jump; CMJ20 = weighted countermovement jump.

Figure 5.10 Combined Yearly Performance and Body Mass Changes



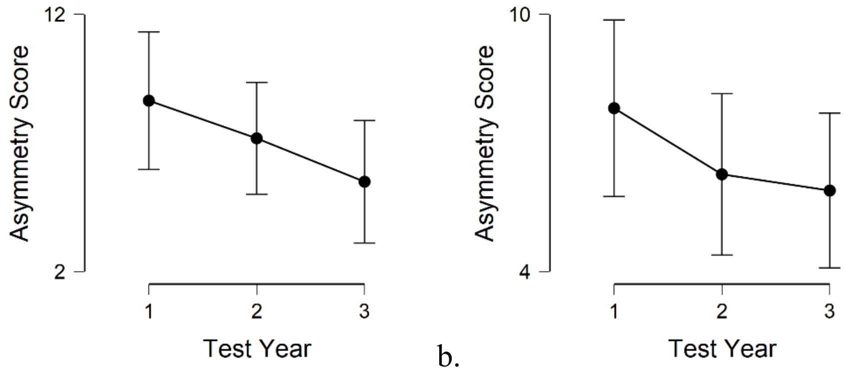
Note: a. = Body mass (kg); b. = Unweighted jump height; c. = Weighted jump height

Table 5.13 Combined Effect Sizes

		Effect Sizes		
		T1 to T2	**T2 to T3**	**T1 to T3**
CMJ0	PIAS	0.27	0.36	0.54
	Jump Height	0.41	0.63	0.99
CMJ20	PIAS	0.34	0.10	0.44
	Jump Height	0.53	0.69	0.94

Note: PIAS = Positive impulse asymmetry score; CMJ0 = Unweighted countermovement jump; CMJ20 = Weighted countermovement jump.

Figure 5.11 Combined Yearly Asymmetry Changes



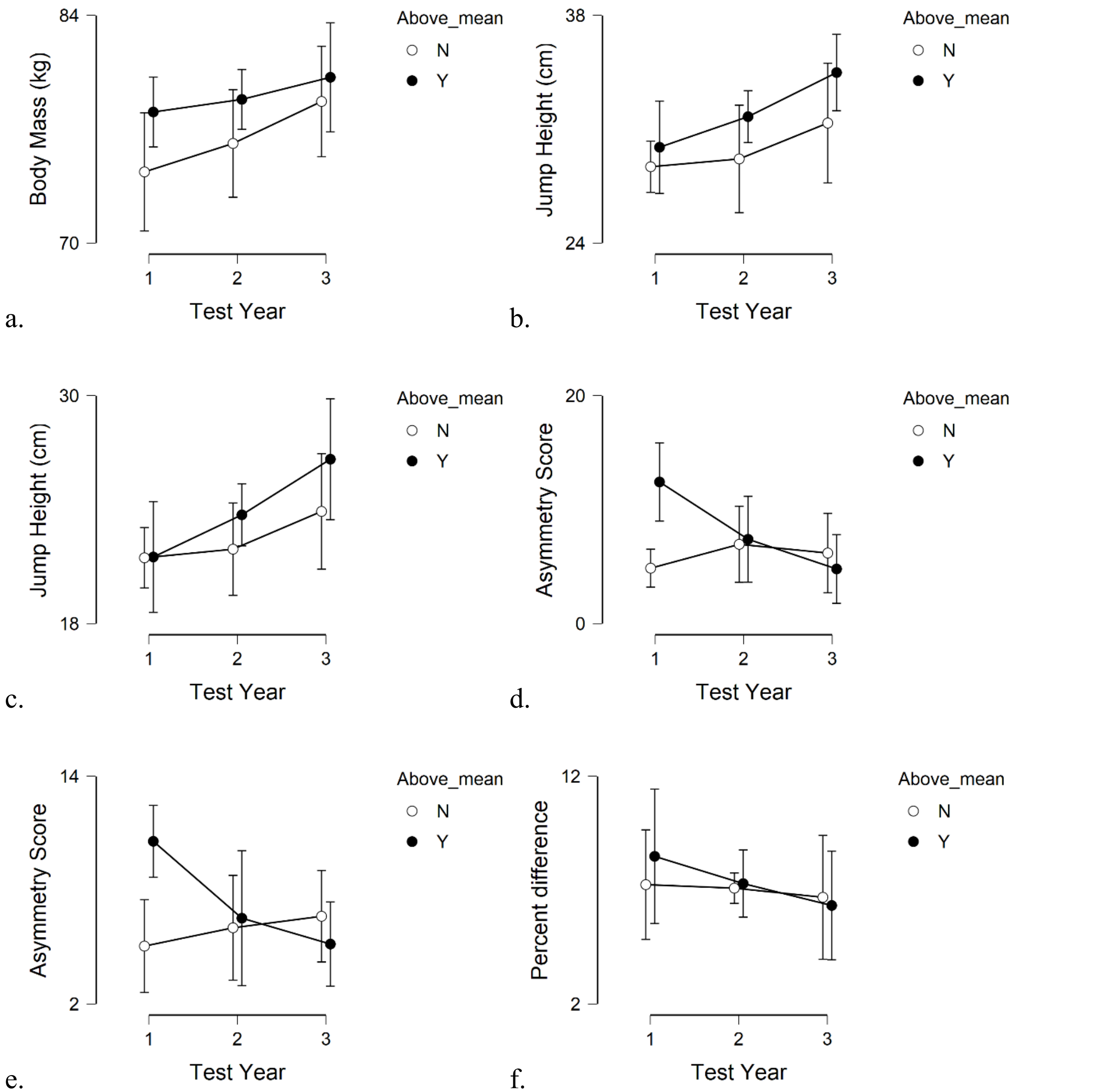
Note: a. = Unweighted jump; b. = Weighted jump

Table 5.14 Effect Sizes Between High and Low Asymmetry Groups

	Between Group Effect Sizes		
	T1	T2	T3
Body Mass (kg)	0.15	0.11	0.06
Unweighted Jump Height (cm)	0.17	0.37	0.44
Weighted Jump Height (cm)	0.01	0.30	0.46
0-20%diff	0.28	0.05	0.08
PIAS0*	0.91	0.05	0.17
PIAS20*	0.78	0.07	0.20

*Note: * = statistically significant differences ($p<0.05$) for Year*Group interaction; PIAS0 = Unweighted positive impulse asymmetry score; PIAS20 = Weighted positive impulse asymmetry score; 0-20%diff = The percent difference from the unweighted jump height to the weighted jump height.*

Figure 5.12 Changes Overtime by Group



Note: N = below mean asymmetry score; Y = above mean asymmetry score; a. = Body mass (kg); b. = Unweighted jump height; c. = Weighted jump height; d. = Unweighted positive impulse asymmetry score; e. = Weighted positive impulse asymmetry score; f. = The percent difference from the unweighted jump height to the weighted jump height.

When split into HIGH and LOW asymmetry groups statistically significant differences were found between initial PIAS0 ($p = 0.01$) and PIAS20 ($p = 0.04$), but no other variables.

Statistically significant year by group interactions were found in PIAS0 ($p < 0.01$) and PIAS20 ($p < 0.01$), but no other variable reached statistical significance. The HIGH group produced statistically significant changes from Y1 to Y3 in both PIAS0 ($p = 0.02$) and PIAS20 ($p = 0.04$) but not for Y1 to Y2 ($p = 0.20, 0.21$) not Y2 to Y3 ($p = 0.81, 0.97$). The between group ES (see Table 5.14) for each year does indicate a trend of increased group differences in JH0 and JH20 with decreased differences in PIAS0 and PIAS20 (see Figure 5.12). In fact, ES show that between group differences increase year over year in performance variables but decrease in PIAS measures.

Discussion

This retrospective analysis provides a unique glimpse into the trends of bilateral jumping asymmetry over time. The findings from this study show that as jump heights and power outputs increased asymmetry was mostly reduced, athletes with higher PIAS show a greater capacity for improvement, and that asymmetry has little fluctuations once a threshold is reached.

Practitioners should expect a general decline in PIAS over time. However, athletes starting out with lower PIAS may have little to no fluctuations. This may be partly due to developed motor coordination patterns which may be representative of their previous training experience (Behringer et al., 2011). As athletes progressed, ES indicate that there is a larger gap between athletes starting out with higher asymmetry than those that did not. It is possible that the type of training these athletes engaged in over three years not only increased explosive strength and power, as represented by their increase unweighted and weighted jumps, but was also specific enough to alter motor control aspects leading to less asymmetry and better jumpers.

It may be more effective to monitor weighted jumping performance asymmetries as they may be more representative of COD activities during higher speeds (Kraska et al., 2009). As well, stronger individuals may not be challenged enough by unweighted jumps to trigger asymmetry patterns (see Chapter 4). With the HIGH group achieving similar PIAS values to the LOW group after the first year, this suggests there is a threshold of detrimental asymmetry to performance. However, athletes with higher asymmetry may have a greater potential for improvement demonstrated by the increasing performance ES from year-to-year.

Limitations for this study include the lack of complete representation for the HIGH and LOW groups. With some athletes in each group being close to the mean, this may skew results. While assessing a standard threshold for detrimental asymmetry is of importance, that was beyond the intent of this study. Another limitation to this study was the lack of between year injury data which was not made available for this study.

Conclusion

Athlete monitoring programs that commonly assess the jumping ground reaction forces of athletes can include the calculation of PIAS score with a simple addition to data already being collected. The collection of PIAS can provide more evidence as to why an athlete is not performing as expected in a jumping assessment and may be used to identify athletes with higher potential for improvements.

References

Bailey, C., Sato, K., Burnett, A., & Stone, M. (2015). Carry-over of force production symmetry in athletes of differing strength levels. Journal of Strength and Conditioning Research, 29(11), 3188-3196.

Bazyler, Bailey, Chiang, Sato, & Stone. (2014). The effects of strength training on isometric force production symmetry in recreationally trained males. Journal of Trainology, 6-10.

Bell, D. R., Sanfilippo, J. L., Binkley, N., & Heiderscheit, B. C. (2014). Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. Journal of strength and conditioning research, 28(4), 884.

Benjanuvatra, N., Lay, B., Alderson, J., & Blanksby, B. (2010). Comparison of ground reaction force asymmetry in one-and two-legged countermovement jumps. The Journal of Strength & Conditioning Research, 27(10), 2700-2707.

Bishop, C., Lake, J., Papadopoulos, K., Turner, A., & Read, P. (2021). Interlimb asymmetries: The need for an individual approach to data analysis. The Journal of Strength & Conditioning Research, 35(3), 695-701.

Dos'Santos, T., Thomas, C., Jones, P., & Comfort, P. (2017). Asymmetries in single and triple hop are not detrimental to change of direction speed. Journal of Trainology, 6(2), 35-41.

Hortobágyi, T., Taylor, J. L., Petersen, N. T., Russell, G., & Gandevia, S. C. (2003). Changes in segmental and motor cortical output with contralateral muscle contractions and altered sensory inputs in humans. *Journal of neurophysiology, 90*(4), 2451-2459.

Kibble, T. W. (2015). Spontaneous symmetry breaking in gauge theories. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 373(2032).

Kraska, J., Ramsey, M., Haff, G. G., Fethke, N., Sands, W., Stone, M. E., & Stone, M. H. (2009). Relationship between strength and un-weighted and weighted vertical jump height. International Journal of Sport Physiology and Performance, 4(4), 461-473.

Madruga-Parera, M., Bishop, C., Fort-Vanmeerhaeghe, A., Beltran-Valls, M., Skok, O., & Romero-Rodríguez, D. (2020). Interlimb asymmetries in youth tennis players: Relationships with performance. The Journal of Strength & Conditioning Research, 34(10), 2815-2823.

Maloney, S. J. (2019). The relationship between asymmetry and athletic performance: A critical review. The Journal of Strength & Conditioning Research, 33(9), 2579-2593.

Maulder, P., & Cronin, J. (2005). Horizontal and vertical jump assessment: reliability, symmetry, discriminative and predictive ability. Physical therapy in Sport, 6(2), 74-82.

Menzel, H. J., Chagas, M. H., Szmuchrowski, L. A., Araujo, S. R., de Andrade, A. G., & de Jesus-Moraleida, F. R. (2013). Analysis of lower limb asymmetries by isokinetic and vertical jump tests in soccer players. The Journal of Strength & Conditioning Research, 27(5), 1370-1377.

Sato, K., & Heise, G. (2012). Influence of weight distribution asymmetry on the biomechanics of a barbell back squat. The Journal of strength & conditioning research, 26(2), 342-349.

Sayers, S. P., Harackiewicz, D. V., Harman, E., Frykman, P., & Rosenstein, M. (1999). Cross-validation of three jump power equations. Medicine and science in sports and exercise, 31(4), 572-577.

Chapter 6. Summary and Conclusion

Asymmetries are a reliable measure for most dGRF variables in vertical jumping. Caution should be used when assessing asymmetries during the unweighting phase as some metrics are much less reliable than others. Overall, impulse is the most promising measure of asymmetry and combining the braking phase with the positive propulsive phase has the highest correlation to jumping performance.

While much of the asymmetry research has focused on the propulsive phase, actions during the braking phase influence the SSC utilization. Seemingly, capturing the PIAS may be the best method in the determination of asymmetry for CMJ, but more research is needed to extrapolate these results to other performance measures. As well, this research has shown that unweighted and weighted jump asymmetries may be necessary to capture depending on the athletes as males had stronger relationships with asymmetry and weighted jump heights, whereas females produced stronger relationships within the unweighted jumps. This is likely a relationship to neuromotor pathways that are developed through strength training rather than strength alone as there are no significant relationships between CMJ asymmetry and isometric mid-thigh pulls.

The relationship between asymmetry and training experience is indicated by the decrement in asymmetry over time with regular training. A well-developed strength training program can improve performance and might also aid in reducing excessive bilateral asymmetries in athletes of differing sports (Bazyler et al., 2014; Gabbett, 2016; Impellizzeri et al., 2007; Zouita et al., 2016;). As well, motor control may be a driving factor of asymmetry. Bilateral training may impact the crossed effects of motor and sensory activity (Hortobágyi et al, 2003) thus enhancing the coordination between limbs to improve performance. This may also explain why athletes with higher asymmetry values realized high levels of improvement after one year, but then leveled off. More research is needed to determine if skill training alone may reduce asymmetries, but this dissertation presents a foundation for future studies.

References

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Neural adaptation to resistance training: changes in evoked V-wave and H-reflex responses. *Journal of Applied Physiology*, 92(6), 2309-2318.

Arboix-Alió, J., Busquets, A., Aguilera-Castells, J., de Pablo, B., Montalvo, A., & Fort-Vanmeerhaeghe, A. (2020). Relationship between inter-limb asymmetries and physical performance in rink hockey players. *Symmetry*, 12(12), 2035.

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports medicine*, 26(4), 217-238.

Bailey, C., Sato, K., Burnett, A., & Stone, M. (2015a). Carry-over of force production symmetry in athletes of differing strength levels. *Journal of Strength and Conditioning Research*, 29(11), 3188-3196.

Bailey, C., Sato, K., Burnett, A., & Stone, M. (2015b). Force-production asymmetry in male and female athletes of differing strength levels. *International Journal of Sports Physiology and Performance*, 10(4), 504-508.

Balloch, A. (2018). Evaluation of kinetic and kinematic variables during a countermovement jump to assess neuromuscular status in team-sport athletes. *Journal of Australian Strength and Conditioning*, 26(1): 49-56.

Barber, S. D., Noyes, F. R., Mangine, R. E., & Hartman, W. (1990). Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Orthopaedics and Related Research* (1976-2007), 255, 204-214.

Bazyler, Bailey, Chiang, Sato, & Stone. (2014). The effects of strength training on isometric force production symmetry in recreationally trained males. *Journal of Trainology*, 6-10.

Behringer, M., Vom Heede, A., Matthews, M., & Mester, J. (2011). Effects of strength training on motor performance skills in children and adolescents: a meta-analysis. *Pediatric exercise science*, 23(2), 186-206.

Bell, D. R., Sanfilippo, J. L., Binkley, N., & Heiderscheit, B. C. (2014). Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. *Journal of strength and conditioning research*, 28(4), 884.

Benjanuvatra, N., Lay, B., Alderson, J., & Blanksby, B. (2010). Comparison of ground reaction force asymmetry in one-and two-legged countermovement jumps. *The Journal of Strength & Conditioning Research*, 27(10), 2700-2707.

Bini, R. R., & Hume, P. A. (2015). Relationship between pedal force asymmetry and performance in cycling. *Journal of sports medicine and physical fitness*, 55, 898-982.

Bishop, C., Brashill, C., Abbott, W., Read, P., Lake, J., & Turner, A. (2019). Jumping asymmetries are associated with speed, change of direction speed, and jump performace in elite academy soccer players. *Journal of Strength and Conditioning Research*.

Bishop, C., Lake, J., Papadopoulos, K., Turner, A., & Read, P. (2021). Interlimb asymmetries: The need for an individual approach to data analysis. *The Journal of Strength & Conditioning Research*, 35(3), 695-701.

Bishop, C., Read, P., Chavda, S., & Turner, A. (2016). Asymmetries of the lower limb: The calculation conundrum in strength training and conditioning. *Strength & Conditioning Journal*, 38(6), 27-32.

Bishop, C., Read, P., McCubbine, J., & Turner, A. N. (2018a). Vertical and horizontal asymmetries are related to slower sprinting and jump performance in elite youth female soccer players. *Journal of strength and conditioning research*.

Bishop, C., Turner, A., & Read, P. (2018b). Effects of inter-limb asymmetries on physical and sports performance: a systematic review. Journal of Sports Sciences, 36(10), 1135-1144.

Bussey, M. (2010). Does the demand for asymmetric functional lower body postures in lateral sports relate to structural asymmetry of the pelvis? *Journal of science and medicine in sport*, 13(3), 360-364.

Carroll, K. M., Wagle, J. P., Sole, C. J., & Stone, M. H. (2019). Intrasession and intersession reliability of countermovement jump testing in division-I volleyball athletes. *The Journal of Strength & Conditioning Research*, 33(11), 2932-2935.

Carroll, T. J., Benjamin, B., Stephan, R., & Carson, R. G. (2001). Resistance training enhances the stability of sensorimotor coordination. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 268(1464), 221-227.

Chavda, S., Bromley, T., Jarvis, P., Williams, S., Bishop, C., Turner, A., Lake, J., & Mundy, P. (2018). Force-time characteristics of the countermovement jump: Analyzing the curve in Excel. *Strength & Conditioning Journal*, 40(2), 67-77.

Comfort, P., Dos'Santos, T., Jones, P., McMahon, J., Suchomel, T., Bayzler, C., & Stone, M. H. (2019). Normalization of early isometric force production as a percentage of peak force during multijoint isometric assessment. *International journal of sports physiology and performance*, 15(4), 478-482.

Cronin, J. B., McNair, P. J., & Marshall, R. N. (2000). The role of maximal strength and load on initial power production. *Medicine & Science in Sports & Exercise*, 32(10), 1763-1769.

De la Motte, S. J., Lisman, P., Gribbin, T., Murphy, K., & Deuster, P. (2017). A systematic review of the association between physical fitness and musculoskeletal injury risk: part 3 – flexibility, power, speed, balance, and agility. *Journal of Strength and Conditioning Research*, 33(6), 1.

Dos'Santos, T., Thomas, C., Jones, P., & Comfort, P. (2017). Asymmetries in single and triple hop are not detrimental to change of direction speed. *Journal of Trainology*, 6(2), 35-41.

Exell, T. A., Irwin, G., Gittoes, M., & Kerwin, D. (2012). Implications of intra-limb variability on asymmetry analyses. *Journal of Sports Sciences*, 30(4), 403-409.

Exell, T., Irwin, G., Gittoes, M., & Kerwin, D. (2017). Strength and performance asymmetry during maximal velocity sprint running. *Scandinavian journal of medicine & science in sports*, 27(11), 1273-1282.

Furlong, L., & Harrison, A. J. (2014). Assessment of lower limb symmetry: differences during isometric and stretch-shortening cycle tasks.

Gabbett, T. (2016). The training—injury prevention paradox: should athletes be training smarter and harder? *British Journal of Sports Medicine*, 50(5), 273-280.

Gathercole, R., Sporer, B., Stellingwerff, T., & Sleivert, G. (2015). Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *International Journal of Sports Physiology and Performance*, 10: 84-92.

Guiard, Y. (1987). Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model. *Journal of motor behavior*, 19(4), 486-517.

Hart, L. M., Cohen, D., Patterson, S., Springham, M., Reynolds, J., & Read, P. (2019). Previous injury is associated with heightened countermovement jump force-time asymmetries in professional soccer players. *Translational Sports Medicine*, 2(5), 256-262.

Hart, N., Nimphius, S., Weber, J., Spiteri, T., Rantalainen, T., Dobbin, M., & Newton, R. (2017). Musculoskeletal asymmetry in football athletes: a product of limb function over time. *Medicine and science in sports and exercise*, 48(7), 1379-1387.

Hoffman, J. R., Ratamess, N. A., Klatt, M., Faigenbaum, A., & Kang, J. (2007). Do bilateral power deficits influence direction-specific movement patterns? *Research in Sports Medicine*, 15(2), 125-132.

Hortobágyi, T., Taylor, J. L., Petersen, N. T., Russell, G., & Gandevia, S. C. (2003). Changes in segmental and motor cortical output with contralateral muscle contractions and altered sensory inputs in humans. *Journal of neurophysiology*, 90(4), 2451-2459.

Impellizzeri, F., Rampinini, E., Maffiuletti, N., & Marcora, S. (2007). A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Medicine and Science in Sports and Exercise*, 39(11), 2044-2050.

Jones, P., & Bampouras, T. (2010). A comparison of isokinetic and functional methods of assessing bilateral strength imbalance. *Journal of Strength and Conditioning Research*, 24(6), 1553-1558.

Kaçoğlu, C. (2019). Relationship between lower extremity strength asymmetry and jump and sprint performance. *Türk Spor ve Egzersiz Dergisi*, 21(2), 204-210.

Kibble, T. W. (2015). Spontaneous symmetry breaking in gauge theories. *Philosophical Transactions of the Royal Society A: Mathematical*, Physical and Engineering Sciences, 373(2032).

Knapik, J., Bauman, C., Jones, B., Harris, J., & Vaughn, L. (1991). Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *The American Journal of Sports Medicine*, 19(1): 76-81.

Knezevic, O. M., Mirkov, D. M., Nedeljkovic, A., & Jaric, S. (2014). Asymmetries in explosive strength following anterior cruciate ligament reconstruction. *The Knee*, 21(6), 1039-1045.

Kobayashi, Y., Kubo, J., Matsubayashi, T., Matsuo, A., Kobayashi, K., & Ishii, N. (2013). Relationship between bilateral differences in single-leg jumps and asymmetry in isokinetic knee strength. *Journal of applied biomechanics*, 29(1), 61-67.

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of chiropractic medicine*, 15(2), 155-163.

Kozinc, Z., & Šarabon, N. (2020). Inter-limb asymmetries in volleyball players: differences between testing approaches and association with performance. *Journal of Sports Science & Medicine*, 19(4), 745.

Kraska, J., Ramsey, M., Haff, G. G., FEthke, N., Sands, W., Stone, M. E., & Stone, M. H. (2009). Relationship between strength and un-weighted and weighted vertical jump height. International *Journal of Sport Physiology and Performance*, 4(4), 461-473.

Kyritsis, P., Bahr, R., Landreau, P., Miladi, R., & Witvrouw, E. (2016). Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *British journal of sports medicine*, 50(15), 946-951.

Lake, J. P., Lauder, M. A., & Smith, N. A. (2011). Does side dominance affect the symmetry of barbell end kinematics during lower-body resistance exercise? *Journal of strength and conditioning research*, 25, 872-878.

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physics*, 69(11), 1198-1204.

Lockie, R. G., Callaghan, S., Berry, S., Cooke, E., Jordan, C., Luczo, T., & Jeffriess, M. (2014). Relationship between unilateral jumping ability and asymmetry on multidirectional speed in team-sport athletes. *The Journal of Strength & Conditioning Research*, 28(12), 3557-3566.

Madruga-Parera, M., Bishop, C., Fort-Vanmeerhaeghe, A., Beltran-Valls, M., Skok, O., & Romero-Rodríguez, D. (2020). Interlimb asymmetries in youth tennis players: Relationships with performance. *The Journal of Strength & Conditioning Research*, 34(10), 2815-2823.

Maloney, S. J. (2019). The relationship between asymmetry and athletic performance: A critical review. *The Journal of Strength & Conditioning Research*, 33(9), 2579-2593.

Maloney, S., Richards, J., Nixon, D., Harvey, L., & Fletcher, I. (2017). Do stiffness and asymmetries predict change of direction performance? *Journal of sports sciences*, 35(6), 547-556.

Maulder, P., & Cronin, J. (2005). Horizontal and vertical jump assessment: reliability, symmetry, discriminative and predictive ability. *Physical therapy in Sport*, 6(2), 74-82.

Menzel, H. J., Chagas, M. H., Szmuchrowski, L. A., Araujo, S. R., de Andrade, A. G., & de Jesus-Moraleida, F. R. (2013). Analysis of lower limb asymmetries by isokinetic and vertical jump tests in soccer players. *The Journal of Strength & Conditioning Research*, 27(5), 1370-1377.

Nicol, C., Avela, J., & Komi, P. (2006). The stretch-shortening cycle: a model to study naturally occurring neuromuscular fatigue. *Sports Medicine*, 36(11): 977-999.

Nunn, K., & Mayhew, J. L. (1988). Comparison of three methods of assessing strength imbalances at the knee. *Journal of Orthopaedic & Sports Physical Therapy*, 10(4), 134-137.

Owens, E., Serrano, A., Ramsey, M., Mizuguchi, S., Johnston, B., & Stone, M. H. (2011). Comparing lower-limb asymmetries in NCAA DI male and female athletes. *The Journal of Strength & Conditioning Research*, 25, S44-S45.

Pérez-Castilla, A., García-Ramos, A., Janicijevic, D., Miras-Moreno, S., De la Cruz, J., Rojas, F., & Cepero, M. (2021). Unilateral or bilateral standing broad jumps: which jump type provides inter-limb asymmetries with a higher reliability? *Journal of Sports Science and Medicine*, 20(2), 317-327.

Read, P., Oliver, J., Myer, G., De Ste Croix, M., & Llyod, R. (2018). The effects of maturation on measures of asymmetry during neuromuscular control tests in elite male youth soccer players. *Pediatric exercise science*, 30(1), 168-175.

Robinson, R. O., Herzog, W., & Nigg, B. M. (1987). Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *Journal of manipulative and physiological therapeutics*, 10(4), 172-176.

Rouissi, M., Chtara, M., Owen, A., Chaalali, A., Chaouachi, A., Gabbett, T., & Chamari, K. (2016). Effect of leg dominance on change of direction ability amongst young elite soccer players. *Journal of sports sciences*, 34(6), 542-548.

Sannicandro, I., Piccinno, A., Rosa, R., & Pascalis, S. (2011). Functional asymmetry in the lower limb professional soccer players. *British Journal of Sports Medicine*, 45(4), 370-370.

Sannicandro, I., Rosa, R., Pascalis, S., & Piccinno, A. (2012). The determination of functional asymmetries in the lower limbs of young soccer players using the countermovement jump. The lower limbs asymmetry of young soccer players. *Science & Sports*, 27(6), 375-377.

Sato, K., & Heise, G. (2012). Influence of weight distribution asymmetry on the biomechanics of a barbell back squat. *The Journal of strength & conditioning research*, 26(2), 342-349.

Schiltz, M., Lehance, C., Maquet, D., Bury, T., Crielaard, J. M., & Croisier, J. (2009). Explosive strength imbalances in professional basketball players. *Journal of Athletic Training*., 44, 39-47.

Schorderet, C., Allet, L., & Hilfiker, R. (2020). The role of the dominant leg while assessing balance performance. A systematic review and meta-analysis. *Gait & Posture*.

Shorter, K. A., Polk, J. D., Rosengren, K. S., & Hsiao-Wecksler, E. T. (2008). A new approach to detecting asymmetries in gait. *Clinical Biomechanics*, 23(4), 459-467.

Simon, A., & Ferris, D. (2008). Simon, A. M., & Ferris, D. P. (2008). Lower limb force production and bilateral force asymmetries are based on sense of effort. *Experimental Brain Research*, 187(1), 129-138.

Sole, C., Mizuguchi, S., Sato, K., Moir, G., & Stone, M. (2018). Phase characteristics of the countermovement jump force-time curve: a comparison of athletes by jumping ability. *Journal of Strength of Conditioning Research*, 32(4): 1155-1165.

Stiffler, M., Bell, D., Sanfilippo, J., Hetzel, S., Pickett, K., & Heiderscheit, B. (2017). Star excursion balance test anterior asymmetry is associated with injury status in division I collegiate athletes. *Journal of Orthopaedic & Sports Physical Therapy*, 47(5), 339-346.

Stone, M. H., O'Bryant, H. S., Hornsby, G., Cunanan, A., Mizuguchi, S., Suarez, D. G., South, M., Marsh, D., Haff, G., &Pierce, K. P. (2019). The use of the isometric mid-thigh pull in the monitoring of weightlifters: 25+ years of experience. *UKSCA Journal: Professional Strength and Conditioning*, 54, 10-26.

Stone, M. H., Plisk, S., & Collins, D. (2002). Strength and conditioning: Training principles: evaluation of modes and methods of resistance training-a coaching perspective. *Sports Biomechanics*, 1(1), 79-103.

Stone, M. H., Sanborn, K., O'Bryant, H., Hartman, M., Stone, M. E., Proulx, C., Ward, B., & Hruby, J. (2003). Maximum strength-power-performance relationships in collegiate throwers. *The Journal of Strength & Conditioning Research*, 17(4), 739-745.

Suarez, D., Dylan, G., Wagle, J., Cunanan, A., Sausaman, R., & Stone, M. H. (2019). Dynamic correspondence of resistance training to sport: A brief review. *Strength and conditioning journal*, 41(4), 80-88.

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports Medicine*, 46(10), 1419-1449.

Whyte, E., Kennelly, P., Milton, O., Richter, C., O'Connor, S., & Moran, K. (2017). The effects of limb dominance and a short term, high intensity exercise protocol on both landings of the vertical drop jump: implications for the vertical drop jump as a screening tool. *Sports Biomechanics*, 17(4), 541-553.

Wong, P., Chamari, K., Chaouachi, A., Wisløff, U., & Hong, Y. (2007). Difference in plantar pressure between the preferred and non-preferred feet in four soccer-related movements. *British journal of sports medicine*, 41(2), 84-92.

Zifchock, R. A., Davis, I., Higginson, J., & Royer, T. (2008). The symmetry angle: a novel, robust method of quantifying asymmetry. *Gait & posture*, 27(4), 622-627.

Zouita, S., Zouita, A., Kebsi, W., Dupont, G., Ben Abderrahman, A., Salah, F., & Zouhal, H. (2016). Strength training reduce injury rate in elite young soccer players during one season. *Journal of Strength and Conditioning Research*, 30(5), 1295-1307.

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Painter, K. B., Haff, G. G., Triplett, N. T., Stuart, C., Hornsby, G., Ramsey, M. W., ... & Stone, M. H. (2018). Resting hormone alterations and injuries: Block vs. DUP weight-training among D-I track and field athletes. *Sports*, 6(1), 3.

Painter, K. B., Haff, G. G., Ramsey, M. W., Triplett, T. , Mcbride, J., Stuart, C., Sands, W. A., and Stone, M. H. (2012). Strength gains: block versus daily undulating periodization weight training among track and field athletes. *International journal of sports physiology and performance*, 7(2), 161-169.

Painter, K. B., Haff, G. G., Ramsey, M. W., Triplett, T. , Mcbride, J., Stuart, C., Sands, W. A., Stone, M. E., and Stone, M. H. (2011). Comparison of traditional versus daily undulating periodized training among D-I collegiate throwers: an exploratory study. *The Journal of Strength & Conditioning Research*, 25, S116-S117.

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