Middlesex University
London Sport Institute

Inter-limb Asymmetry: Longitudinal Monitoring and Associations with Speed and Change of Direction Speed in Elite Academy Soccer Players

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Supervisors: Dr. Paul Read and Professor Nic James

SUBMISSION FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

This work is being submitted in fulfilment for the degree of Doctor of Philosophy within the field of strength and conditioning.

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ABSTRACT

Inter-limb asymmetry has been a popular topic of investigation in recent years, with the majority of studies reporting the prevalence of asymmetry during different test protocols in athlete and non-athlete populations, and between genders. However, such information does little to inform practitioners as to whether asymmetry should be of any concern. To more fully examine the current body of evidence pertaining to asymmetry, a systematic review was completed as part of this thesis, in an attempt to determine the association between asymmetry and measures of athletic performance. Results showed that asymmetry was often associated with reduced athletic performance, especially when measured during the sport-specific task.

The findings of the systematic review also highlighted some important considerations for future research. Specifically, it was observed that the association between asymmetry and measures of athletic performance has been reported at single time points only, with a distinct lack of data to examine how asymmetry varies over time and if a change in asymmetry corresponds to changes in athletic performance. In addition, limited studies had investigated the link between asymmetry and fatigue. This information would help practitioners by determining if measurement of asymmetry is useful as part of the ongoing monitoring process.

The aim of study 1 was to use the unilateral isometric squat, unilateral countermovement (CMJ) and unilateral drop jumps (DJ), in a test-retest design, to determine test reliability, the magnitude of asymmetry for both the mean and best scores, and the consistency of asymmetry direction. Within and between-session reliability showed good to excellent relative reliability for all tests and metrics (intraclass correlation coefficient [ICC] = 0.81-0.98) and for the most part, acceptable absolute reliability (coefficient of variation [CV] = 2.3-13.7%). When calculated from the best trial, significant

differences in asymmetry were present for impulse at 0.3 s during the isometric squat (p = 0.04; effect size [ES] = -0.60) and for ground contact time during the DJ (p = 0.04; ES = 0.54). No significant differences in asymmetry were evident when calculating from mean scores. The level of agreement indicating how consistently asymmetry favoured the same limb between test sessions was fair to substantial for the isometric squat, moderate to substantial for the CMJ, and fair to moderate for the DJ. Given the test-retest design of this study, it was concluded that most metrics in each test are reliable for detecting asymmetry, although the isometric squat did show higher within-session CV values than the jump tests. In addition, given no training intervention was conducted, it is suggested that the average of all trials was a more appropriate method to calculate asymmetry.

Study 2 carried forward the unilateral CMJ and DJ tests, in addition to 5, 10, 30 m and 505 change of direction speed (CODS) tests to track seasonal variation in performance and asymmetry during pre, mid and end of season time points in a group of 18 under-23 elite academy soccer players. The unilateral isometric squat was not carried forward for the remainder of testing procedures due to time constraints in a professional soccer club setting. Associations between jumping asymmetry and speed/CODS tests were examined at each time point, and changes in asymmetry and changes in speed/CODS performance were also examined through associative analysis. When assessing the relationship between asymmetry and performance tests, no meaningful correlations were evident at pre or mid-season (ρ = -0.32 to 0.37). However, at the end of season, significant relationships were found between DJ height asymmetry and 5 m (ρ = 0.63; p < 0.008), 10 m (ρ = 0.62; p < 0.008) and 505 on the right limb (ρ = 0.65; p < 0.008). When assessing relationships between changes in asymmetry and changes in performance tasks, no significant relationships were found between changes in asymmetry and changes in speed or CODS performance (ρ = -0.44 to 0.56). A median split technique was also used to create high and low asymmetry groups for pre, mid, and end of season, respectively. At all time points, significant differences in asymmetry were found between groups for all jump metrics ($p < 0.01$). For speed/CODS tests, significant differences were reported at the end-season time point between groups when using DJ height asymmetry for 10 m (high asymmetry = 1.84 ± 0.13; low asymmetry = 1.72 ± 0.07; $p < 0.05$; ES = -1.15), 505 left (high asymmetry = 2.26 ± 0.05; low asymmetry = 2.19 ± 0.09; $p < 0.05$; ES = -0.96) and 505 right (high asymmetry = 2.30 ± 0.11; low asymmetry = 2.18 ± 0.05; $p < 0.01$; ES = -1.40). No other significant differences in speed or CODS were present between groups. Despite these findings at the end of the season suggesting significant relationships, the cumulative results of this study and specifically the inconsistencies shown, indicate that asymmetry is largely independent of speed and CODS, both at single time points and when monitored over time.

Seasonal variation of jump scores and asymmetry were also reported. Unilateral jump data showed significant reductions in CMJ height and concentric impulse at mid-season on both limbs and for peak force on the left limb only. DJ height showed no meaningful changes between time points; however, ground contact time and reactive strength index (RSI) showed significant improvements at the end of the season, compared to both previous time points. When monitoring asymmetry, the group mean value showed no significant differences throughout the season with corresponding trivial to small ES (range = -0.60 to 0.55). However, poor to substantial levels of agreement were reported across the season for the direction of asymmetry, in both jump tests. These data indicate that when monitoring the magnitude of asymmetry alone, group mean values do not reflect the potential inconsistencies in limb dominance over time. By also monitoring the direction of asymmetry, this more accurately highlights its task and variable nature, and allows practitioners to account for inherent changes in limb dominance throughout the season.

The final experimental chapter (study 3), examined the effects of acute fatigue on asymmetry in elite under-18 male soccer players. A repeated measures design was used, where unilateral CMJ and unilateral DJ tests were performed before and immediately after five soccer matches. Global positioning system (GPS) data were also collected for each match to assess relationships and interactions between asymmetry and in-game soccer actions. Unilateral CMJ height and concentric impulse showed significant reductions post-matches ($p < 0.01$; ES: -0.67 to -0.69), but peak force did not (ES: -0.05 to -0.13). DJ height and reactive strength also showed significant reductions post-matches ($p < 0.01$; ES: -0.39 to -0.58). No significant reductions in asymmetry were present at the group level, but individual responses were highly variable. Match related variables were almost always not associated with asymmetry. However, significant correlations were evident between post-match reactive strength asymmetry and relative high speed running only ($\rho = 0.44$; $p < 0.008$). These findings indicate that data derived from unilateral jump tests are more sensitive than asymmetry scores in their ability to detect a real change immediately post soccer competition. Thus, practitioners should be cautious about using asymmetry as a marker to determine acute fatigue following soccer match-play.

In conclusion, the findings from this thesis suggest that: i) it may be more favourable to calculate asymmetry scores from an average of all trials, rather than from the best trial; ii) monitoring the group mean value (magnitude) disguises the inherent variability associated with asymmetry; iii) monitoring the direction of asymmetry allows practitioners to account for individual variation; iv) although relationships between asymmetry and speed/CODS/in-game soccer actions do exist, they are not consistent over time and in-response to acute fatigue from soccer match-play. Cumulatively, and given the highly varied response of asymmetry, individual monitoring is recommended but further research is required to more fully understand the usefulness of this approach. Specifically, relationships with injury and a more mechanistic approach to understanding why asymmetry is present, is suggested.

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LIST OF ABBREVIATIONS

CMJ = countermovement jump

DJ = drop jump

ICC = intraclass correlation coefficient

CV = coefficient of variation

ES = effect size

CODS = change of direction speed

RSI = reactive strength index

GPS = global positioning system

IMTP = isometric mid-thigh pull

SLCMJ = single leg countermovement jump

vGRF = vertical ground reaction force

RFD = rate of force development

D = dominant

ND = non-dominant

SEM = standard error of the measurement

ACL = anterior cruciate ligament

m = metres

m/s = milliseconds

cm = centimetres

S&C = strength and conditioning

N = Newtons

SJ = squat jump

SSC = stretch shortening cycle

EMG = electromyography

GCT = ground contact time

n = number

rpm = revolutions per minute

s = seconds

kg = kilograms

SD = standard deviation

CI = confidence intervals

$m \cdot min^{-1}$ = metres per minute

HSR = high speed running

CHAPTER 1: PREFACE

1.1 Introduction

Inter-limb asymmetry can be defined as the difference in performance or function of one limb relative to the other (Keeley et al. 2011). Numerous avenues have been explored on this topic including reporting inter-limb differences between different populations such as genders (Bailey et al. 2015) and age groups (Read et al. 2018). In addition, multiple testing modalities have been used to report limb differences across different physical characteristics. For strength tasks, inter-limb asymmetries have been reported during the isometric squat or mid-thigh pull (IMTP) (Hart et al. 2012; Dos'Santos et al. 2017a), isokinetic dynamometry (Costa Silva et al. 2015; Ruas et al. 2015) and the back squat exercise (Hodges et al. 2011; Sato and Heise, 2012). For jump tasks, asymmetry has been reported during the CMJ (Bailey et al. 2013; Bell et al. 2014), DJ (Maloney et al. 2016; Maloney et al. 2017), their associated unilateral versions (Bishop et al. 2018a; Bishop et al. 2019b) and various hop tasks (Bishop et al. 2018c; Read et al. 2018; Kryitsis et al. 2016). When collating the aforementioned literature, it appears evident that asymmetry is both population and task-specific.

Historically, it appears a strong focus has been placed on empirical studies that have been conducted on inter-limb asymmetries that are present in previously injured populations. Specifically, a large body of evidence exists relating to knee function after the occurrence of anterior cruciate ligament injuries (Barber et al. 1990; Davies et al. 2019; Dos'Santos et al. 2019a; Greenberger and Paterno, 1995; Jordan et al. 2015 King et al. 2018; Kotsifaki et al. 2019; Kryitsis et al. 2016; Noyes et al. 1991; Reid et al. 2007; Rohman et al. 2015), with a wide variety of testing protocols used post-injury. For example, single leg, triple and crossover hop tests and isokinetic dynamometry appear to be commonly used to assess knee function and leg strength. However, a common occurrence in such studies is the use of single metrics and/or outcome measures from the selected test protocols (e.g., jump distance from a single leg or triple hop test). In addition to this, such studies often suggest the need to minimize inter-limb differences to < 15% (Barber et al. 1990; Greenberger and Paterno, 1995; Noyes et al. 1991) or more recently, < 10% (Kryitsis et al. 2016; Rohman et al. 2015), to mitigate potential injury risk. Given asymmetry is known to be task-specific, the use of outcome measures alone provides little information about how tests are performed. Furthermore, the notion of task-specificity is likely to preclude the use of a single blanket threshold being used when interpreting inter-limb asymmetry values, and has recently been suggested as a somewhat flawed concept (Bishop, 2020a; Bishop et al. 2020b). Thus, future research on the topic of inter-limb asymmetry and injury risk or occurrence, is advised to investigate and report multiple metrics within a given test in order to more clearly elucidate an athlete's rehabilitation status.

Despite the large body of literature in the area of injury occurrence, it is still unclear if asymmetry is something to be concerned about from a performance reduction perspective. With that in mind, numerous studies have investigated the associations between inter-limb asymmetry and surrogate measures of athletic performance (e.g., jump, sprint and CODS performance) with mixed findings. For example, both Bishop et al. (2018c) and Maloney et al. (2017) reported significant associations with linear speed (r = 0.49-0.59) and CODS performance (r = 0.60), respectively, signifying that larger side-to-side differences were associated with slower time to completion in these tests. In contrast, Lockie et al. (2014) and Dos'Santos et al. (2017b) reported no meaningful correlations between asymmetry and speed or CODS performance. Thus, it appears that conflicting findings are evident throughout the literature. Further to this, these relationships have only been reported at a single time point, with a distinct lack of longitudinal data available (Bishop et al. 2018e). With only single time point data currently available, tracking asymmetry over time and determining whether these relationships are consistent seems important to understand, if we should be aiming to reduce these side-to-side differences.

In a sport like soccer, time-motion analysis data has shown that on average, players can perform up to 15 jumps (Nedelac et al. 2014), 168 high-intensity actions (Taylor et al. 2017) and between 1200-1400 changes of direction (Bangsbo, 1992) per match. Given the chaotic and reactive nature of soccer, and the inherent positional differences, it seems highly unlikely that an equal amount of loading will occur on each limb. Thus, the presence of inter-limb asymmetries are to be expected in soccer athletes, with mean values previously shown to range from 5.8-12.5% during jump tests (Bishop et al. 2018a; Bishop et al. 2018c; Bishop et al. 2019b; Bishop et al. 2019d). This is in part reinforced by Hart et al. (2016), who showed that asymmetry is often prevalent as a consequence of competing in a single sport over time in team sport athletes.

An additional factor for consideration is trying to understand why asymmetry has occurred in soccer athletes. Whilst longitudinal associations with athletic performance measures are meaningful and necessary, they do not provide insight into the association with in-game soccer demands. GPS data records information pertaining to the movement patterns that occur during matches (e.g., distance covered, explosive distance, high speed running). This can provide practitioners with an understanding of the external workload players are completing. Testing asymmetry both pre and post-matches would provide practitioners with a more meaningful understanding of how asymmetry responds to in-game demands. In addition, reporting the associations between inter-limb differences and GPS variables would offer a greater understanding as to whether asymmetry is related to external workloads, potentially identifying whether asymmetry can be considered as a useful metric as part of the acute monitoring process.

1.2 Overview of Thesis and Chapter/Study Outlines

This thesis is structured as a series of previously published manuscripts, which investigated the long-term associations between asymmetry and speed and CODS performance in elite academy soccer players, and subsequently, the interaction between asymmetry and repeated soccer match-play.

Figure 1.1. Schematic overview of chapters in this thesis.

Chapter 2: Literature Review

Considerations for practitioners when selecting tests to measure asymmetry.

As previously mentioned, numerous test protocols have been used to measure and quantify asymmetry. Given that all studies in this thesis aimed to report inter-limb differences from either strength and/or jumping tasks, a review of the literature enabled some critique of which tests and metrics might be considered for the detection of inter-limb asymmetries. Key factors for consideration were also included such as athlete requirements and test reliability. In addition, given the specific requirements associated with force plate testing, specific test instructions have been provided to guide robust data collection procedures.

Chapter 3: Literature Review

Inter-limb asymmetries: Understanding how to calculate differences from bilateral and unilateral tests.

An overview of the literature has shown that numerous mathematical equations have been used to calculate inter-limb asymmetry. Given the high degree of variation in the literature and the inherent differences in the outcomes from each formula, this provides challenges for practitioners in understanding which equation may be the most appropriate one for their circumstances. In addition, given reporting inter-limb asymmetry values is a common theme throughout all empirical studies in this area, it was critical we understand the most appropriate method of calculation. We propose that there may be differences in the formulas required to calculate between-limb asymmetry from bilateral and unilateral tests. This review aims to clarify which formulas could be selected when profiling asymmetry from both bilateral and unilateral tests.

Chapter 4: Literature Review

Additional factors affecting jump tests and asymmetry (seasonal variation and fatigue).

A review of the literature highlighted that seasonal variation in jump tests is evident and highlights that meaningful changes in jump performance do occur throughout a competitive season in team sport athletes. Noting that longitudinal monitoring was a priority throughout this thesis, it stands to reason that changes in asymmetry are also likely to be evident when monitoring over time. Secondly, with jump tests commonly used as a tool to detect neuromuscular status in response to fatigue, it is surprising that limited evidence is available to examine how asymmetry and limb-dominance is effected by a preceding bout of sports-specific activity. Thus, this chapter reviews and critically evaluates previous research which has used jump tests to detect seasonal variations and changes in jump performance during the acute periods following simulated and soccer competition.

Chapter 5: Systematic Review

Association between inter-limb asymmetries on measures of physical and sports performance: A systematic review.

The prevalence of inter-limb asymmetries has been reported in numerous studies across a wide range of sports and physical qualities; however, few have analysed their effects on physical and sports performance. A systematic review of the literature was undertaken using the Medline and SPORT Discus databases, with all articles required to meet a specified criteria based on a quality review. Eighteen articles met the inclusion criteria, relating participant asymmetry scores to physical and sports performance measures. The findings of this systematic review indicate that inter-limb differences in strength may be detrimental to jumping, kicking and cycling performance. When inter-limb asymmetries are quantified during jumping based exercises, they have been primarily used to examine their association with change of direction speed with mixed findings. Inter-limb asymmetries have also been quantified in anthropometry, sprinting, dynamic balance and sport-specific actions, again with inconsistent findings. However, all results have been used from single time points, with no longitudinal investigations into asymmetry present to date. Furthermore, no studies have looked at how changes in asymmetry correspond to changes in physical performance over the course of a competitive season. Thus, further research in this regard is warranted.

Chapter 6: Study 1

Using unilateral strength, power and reactive strength tests to monitor the magnitude and direction of asymmetry: A test-retest design.

The 'magnitude of asymmetry' refers to the percentage value frequently reported in the literature and is a result of the mathematical equation used to calculate differences between limbs. The 'direction of asymmetry' refers to which limb produces the larger value (during strength and jump tasks) and provides an indication of limb dominance. Typically, studies on asymmetry have focused on reporting values for outcome measures-based data (e.g., jump height or distance), with limited in-depth information on asymmetry using force plates. Furthermore, there are almost no studies which have accounted for the direction of asymmetry in the statistical analysis, noting that either limb could produce the larger score in healthy populations and this could fluctuate at each test session as no inherent constraints are present (i.e., the absence of injury). Therefore, the aims of the present study were threefold: 1) to determine the test-retest reliability of unilateral strength and jumping-based tests that can be used to quantify asymmetries, 2) determine whether any significant differences exist for asymmetry between test sessions and, 3) determine how consistently asymmetries favour the same side between tests sessions.

Chapter 7: Study 2

Seasonal variation and longitudinal associations between asymmetry and speed and change of direction speed performance.

Previous studies reporting the prevalence of asymmetry and its associations with measures of athletic performance have done so only at a single time point, with a distinct lack of longitudinal data on asymmetry. Study 1 highlighted the variable nature of asymmetry between tasks and test sessions. Thus, to provide a more meaningful understanding of the changing nature of asymmetry, two tests (unilateral CMJ and unilateral DJ) were used to quantify limb differences at pre, mid and end of season time points in elite academy soccer players. In order to understand the associations with athletic performance, speed (5, 10 and 30 m) and CODS (505) performance were also conducted at each time point so that repeated associative analysis could be conducted. Furthermore, this enabled changes in asymmetry to be computed in relation to changes in speed and CODS performance. This provided insight into whether associated increases or decreases in asymmetry corresponded to increases or decreases in speed and CODS, and whether any existing relationships were consistent across a full competitive soccer season.

Chapter 8: Study 3

Effects of repeated soccer match-play on unilateral jump performance and inter-limb asymmetries.

Thus far, only one study has investigated the effects of a soccer match on inter-limb asymmetry. Results showed large increases in asymmetry immediately after and at 24 hours' post-match. However, this was only for a single match. Further to this, results were not interpreted considering the external workloads players performed during the match.

Given the variable nature of asymmetry, a repeated measures design which included external workload data would provide a more meaningful understanding of the interaction between inter-limb asymmetry and soccer match-play. Therefore, the aims of this study were to: 1) determine the effects of soccer match-play on unilateral jump performance and inter-limb asymmetries and, 2) examine associations between asymmetry and commonly reported external load variables collected during five soccer matches.

Chapter 9: Conclusions, Practical Applications and Directions for Future Research

This chapter provides a summary of all the key messages that can be understood from each preceding chapter in the thesis and outlines areas of future research which could be considered on the topic of inter-limb asymmetry.

CHAPTER 2: LITERATURE REVIEW

2.0 Considerations for selecting field-based strength and power fitness tests to measure asymmetries

2.1 Introduction

Multiple studies have reported the prevalence of asymmetries during a variety of jumping (Bell et al. 2014; Fort-Vanmeerhaeghe et al. 2016; Hoffman et al. 2007; Sugiyama et al. 2014) and strength-based (Bailey et al. 2013; Greenberger et al. 1995; Newton et al. 2006; Ruas et al. 2015; Sato and Heise, 2012) assessments. However, a critical analysis of their utility for measuring inter-limb differences and clear guidelines for implementation are sparse. The CMJ and single leg CMJ (SLCMJ) have most commonly been used (Bell et al. 2014; Ceroni et al. 2012; Jones and Bampouras, 2010; Lockie et al. 2014; Stephens et al. 2007). Previous data also indicate that measures of strength, such as the back squat (Flanagan and Salem, 2007; Newton et al. 2006; Sato and Heise, 2012), isometric squat or IMTP (Bailey et al. 2015; Dos'Santos et al. 2017a; Hart et al. 2012), and isokinetic knee flexion or extension (Costa Silva et al. 2015; Dickin and Too, 2006; Ruas et al. 2015) have shown adequate sensitivity to identify between-limb differences. Furthermore, these differences in strength and jumping tasks have been associated with decrements in physical performance (Bailey et al. 2013; Bell et al. 2014; Yoshioka et al. 2010), sport-specific tasks (Hart et al. 2014), and increased injury risk (Impellizzeri et al. 2007). Therefore, when profiling athletes for the presence of asymmetry, a battery of strength and power tests may be required in order to build a meaningful understanding of between-limb differences and how this may vary from task to task.

A number of factors should be considered prior to the selection of tests to measure asymmetry. These include test reliability to ensure there is adequate precision, potential associations with reductions in performance or heightened injury risk, and the requirements of the athlete within the context of their sport. For example, ski athletes perform their sport bilaterally and it may be logical to choose bilateral tests when quantifying asymmetries in strength and jumping tasks (Jordan et al. 2015). However, team sports such as soccer and rugby hold a greater degree of unpredictability in an athlete's movement patterns; thus, unilateral testing or a combination of both may be most applicable. Additional reasons such as experience of the tester, ease of testing equipment and cost effectiveness should also be considered and will be discussed later in this review.

This section provides an overview of the current literature pertaining to test methodology for asymmetry measurement and critically examines a variety of strength and jumping-based tasks in their utility to quantify asymmetries. Finally, an evidenced-based test battery has been proposed which is suggested as a basis for future experimental research.

2.2 Strength Tests

Testing of strength asymmetry has comprised of both isolated and multi-joint assessment modes, and one of the key considerations for practitioners to consider is reliability of their data. Two studies have investigated vertical ground reaction force (vGRF) asymmetries during the back squat. Newton et al. (2006) used 14 NCAA softball players to perform three back squats at 80% 1RM and reported average vGRF asymmetries of 6.02%. Hodges et al. (2011) examined vGRF asymmetry during the first and last two repetitions in each set of a training session that was comprised of 5 sets of 8 repetitions at 90% of their 8RM in healthy adults. Mean inter-limb differences (across all sets) were reported to be 4.3% for the first two repetitions and 3.6% for the final two repetitions. The results from these two studies indicate that vGRF asymmetries are typically low during the back squat for college and healthy adult populations, although further research is required to examine the reliability of inter-limb differences during the back squat as a test protocol.

The isometric squat or IMTP have also been used to measure asymmetry (Bailey et al. 2013; Bailey et al. 2015; Bazyler et al. 2014; Dos'Santos et al. 2017a; Hart et al. 2012), with peak vGRF (Bailey et al. 2013; Bazyler et al. 2014; Hart et al. 2012), impulse and rate of force development (RFD) (Dos'Santos et al. 2017a; Hart et al. 2012; Kawamori et al. 2006) most commonly reported. Due to the restricted timeframe within sporting movements that athletes have to produce force (Aagaard, 2003), these physical characteristics can be considered an important diagnostic; however, the reliability of measurement may be questionable. Hart et al. (2012) measured the reliability of peak force, mean force and RFD during bilateral and unilateral isometric squats and results are shown in Table 2.1. However, the subjects used in this study were not of a specific sporting background and as such may produce more variation in their results due to a possible lack of familiarity with testing protocols (Saloikidis et al. 2009), as seen on the non-dominant limb.

Table 2.1. Intraclass correlation coefficients (ICC) and coefficient of variations (CV) for peak force, mean force, and RFD (over 250 m/s) during bilateral and unilateral isometric squats (adapted from Hart et al. 2012).

Test/Metric	CV (%)	ICC
Isometric Squat (bilateral):		
Peak Force	3.6	0.97
Mean Force	8.4	0.91
Rate of Force Development	15.2	0.94
Isometric Squat (unilateral-D):		
Peak Force	4.7	0.96
Mean Force	6.1	0.95
Rate of Force Development	14.5	0.93
Isometric Squat (unilateral-ND):		
Peak Force	3.6	0.98
Mean Force	9.3	0.83
Rate of Force Development	45.5	0.36

D = dominant; ND = non-dominant.

Dos Santos et al. (2017) investigated the prevalence of strength asymmetries between professional rugby league and collegiate athletes using the IMTP. All subjects performed three unilateral trials on each limb with peak force and impulse at different time intervals reported. Results showed strong reliability for unilateral peak force (ICC = 0.94; CV = 4.7-5.0%), but more variability for impulse (ICC = 0.82-0.88; CV = 9.3-11.6%). Significant differences ($p < 0.05$) between dominant and non-dominant limbs for both groups of athletes were reported, suggesting that the unilateral IMTP was a valid and reliable method for determining strength asymmetries across athletes of different levels (Dos'Santos et al. 2017a). In addition, reliability data has also been reported for both males (n = 31) and females (n = 32) during the IMTP. Bailey et al. (2015) reported an ICC range of 0.68-0.98

for multiple variables including peak force, impulse at different time points, and RFD although individual ICC values were not specified for the tested metrics. The standard error of the measurement (SEM), which is an indication of a score's accuracy (Weir, 2005), was also reported and the highest variability was noted for impulse at 50 milliseconds. Although individual ICC's were not reported, the SEM is a measure of absolute reliability and it could be argued, a more important measure. With that in mind, lower levels of reliability for impulse are in agreement with the findings of Dos Santos et al. (2017). Furthermore, the sample was divided into stronger and weaker sub-groups with SEM reported as a percentage for the mean asymmetry values. Significant differences were evident ($p < 0.05$) between groups for peak force (0.07 vs. 0.13%) and RFD (0.45 vs. 0.70%). The authors stated that strength may be a more influential factor than sex when calculating asymmetries during the IMTP due to the increased variability and inter-limb differences seen in the weaker group (Bailey et al. 2015).

Isokinetic dynamometry is another alternative for practitioners who wish to measure both inter and intra-limb strength asymmetries in isolated joint actions (such as knee flexion or extension). Research is available to analyse the presence of asymmetries in different populations ranging from collegiate (Jones and Bampouras, 2010; Kobayashi et al. 2013; Newton et al. 2006) to professional athletes (Costa Silva et al. 2015; Ruas et al. 2015; Schiltz et al. 2009); however, surprisingly none of these studies included reliability data.

When selecting appropriate tests to measure asymmetry, practitioners should consider their ecological validity. For example, bilateral assessments may be more suitable for a powerlifter, to ensure task specificity is being adhered to. Conversely, team sport athletes are required to undertake multiple unilateral sporting actions such as running and changing direction; therefore, it seems logical to suggest some form of unilateral strength testing when calculating asymmetries. The type of muscle actions and speeds of movement involved in the sport are also a consideration in test selection. Isokinetic testing has the potential advantage of measuring asymmetries across a range of muscle actions (concentric and eccentric) and speeds unilaterally, potentially providing a more complete picture of strength asymmetries. In addition, specific joint ranges of motion can be utilised to determine torque-angle analysis of asymmetry, especially for athletes who might be returning from injury (Costa Silva et al. 2015; Ruas et al. 2015). However, when considering healthy athletes, strength during single joint actions are not fully representative of compound movement patterns (Bennell et al. 1998), which are more characteristic of the actions required during the execution of the majority of sporting tasks. Furthermore, isokinetic dynamometry testing requires expensive equipment which may not be practically viable for many athletes, teams or practitioners. Until recently, it could have been argued that this notion held true for the use of force plates; however, more recently affordable (and portable) versions are now available increasing their utility for field testing large numbers of athletes (Lake et al. 2018b).

2.3 Jump Tests

When determining asymmetries using jump tests, a variety of bilateral and unilateral tests have frequently been used (Bell et al. 2014; Bolgla and Keskula, 1997; Impellizzeri et al. 2007; Jones and Bampouras, 2010; Kobayashi et al. 2013; Pain, 2014; Reid et al. 2007; Rohman et al. 2015; Yoshioka et al. 2010), and again, test reliability must be considered. Benjanuvatra et al. (2013) aimed to differentiate between the bilateral CMJ and SLCMJ for assessing asymmetries in impulse and vGRF. The authors suggested using the SLCMJ over the bilateral CMJ when quantifying asymmetries because it places a greater emphasis on force production from one limb with slower subsequent movement velocities. In turn, this increased emphasis on force production may provide a stronger indication of deficits in physical capacity. In bilateral tasks, compensatory strategies may be more prevalent which may have the potential to mask existing between-limb differences. Furthermore, multiple sporting actions such as jumping, sprinting and changing direction occur unilaterally; thus, the notion of specificity is kept to the sporting task if asymmetries are tested for unilaterally. Therefore, single leg tasks may provide a more accurate reflection of true inter-limb asymmetries for healthy team sport athletes, in particular. Despite this critique between bilateral and unilateral test measures, reliability data for multiple metrics during unilateral test measures is under-explored.

Meylan et al. (2009) reported strong reliability for measures of jump height and distance during the SLCMJ and lateral jumps. ICC's ranged from 0.91-0.98 across both genders in healthy adults. Furthermore, CV ranges fell between 2.7-7.2%, suggesting that multi-directional, unilateral jumps are a reliable method for assessing jump height and distance, which can be subsequently used to calculate between-limb differences. Strong reliability has also been noted in youth athletes for measures of peak force and power during the SLCMJ (Ceroni et al. 2012), with ICC's ranging from 0.88-0.97. Consequently, unilateral vertical jump assessments appear to be reliable tests across adult and youth populations.

The reliability of various single leg hop tests have also been measured within previous research (Bolgla and Keskula, 1997; Reid et al. 2007; Ross et al. 2002). Common variations include the single leg hop (for distance), triple hop, 6 m timed hop, and crossover hop (Figure 2.1). The single leg hop would appear to be the most reliable of these four tests with ICC's ranging from 0.92-0.96 and SEM's of 4.56-4.61 cm, with more variability present in the 6 m timed hop (ICC = 0.66-0.92) (Bolgla and Keskula, 1997; Reid et al. 2007; Ross et al. 2002). Despite their similarities, it has been suggested that more than one hop test should be considered when quantifying asymmetries (Noyes et al. 1991) because of the different demands they each pose. Considering the previously reported strong reliability of the triple hop test (ICC = 0.88-0.97), and notably lower SEM values when compared to the crossover hop (11.17 vs. 17.74 cm) (Reid et al. 2007; Ross et al. 2002), the rebound nature of the task may provide a more ecologically valid representation of unilateral tasks for athletes in running and jumping based sports.

However, it must be acknowledged that the triple hop test likely places a greater physical demand on athletes and should be used with caution if plyometric training experience is low. In addition, more recent literature has highlighted that the single leg hop test is insufficient when aiming to identify deficits in physical capacity for athletes returning from an anterior cruciate ligament (ACL) injury (Kotsifaki et al. 2019). This is supported in a recent study by King et al. (2018) who showed that distance asymmetry from the single leg hop test over-estimated the rehabilitation status of 156 ACL injured patients, compared to the single leg DJ test. When tested at ~9 months post surgery, the single leg hop test exhibited distance asymmetry values of 6%, whereas the single leg DJ showed asymmetry values of 21 and 22% for jump height and reactive strength, respectively. In addition, a recent review by Davies et al. (2019) suggested that measuring distance alone does not provide an indication of jump strategy; thus, measuring metrics beyond outcome measures alone should also be considered by practitioners.

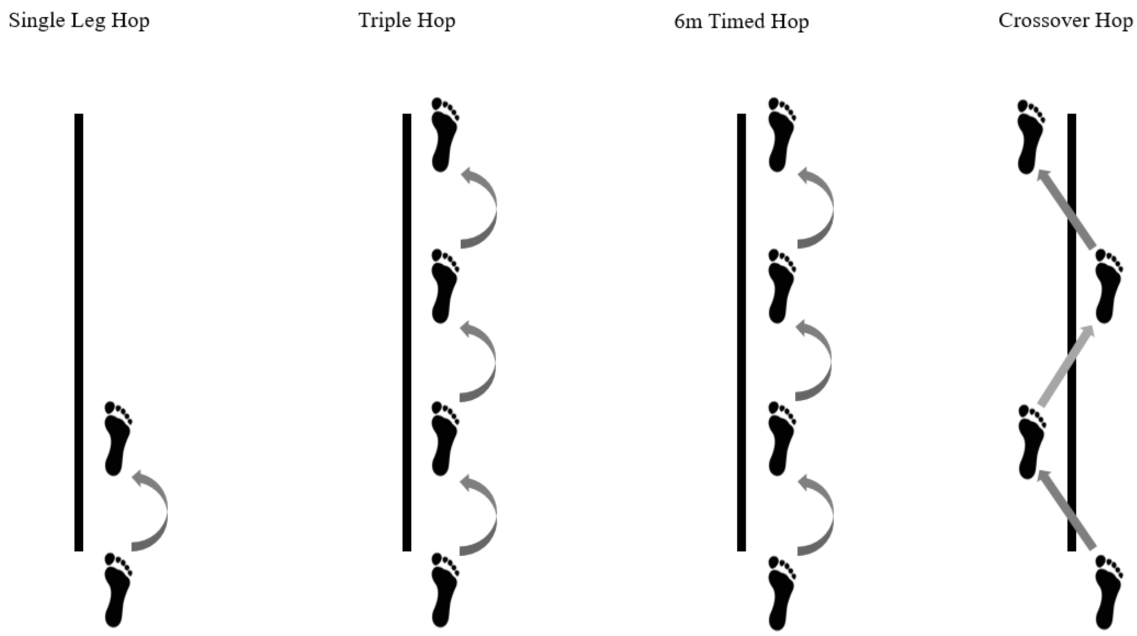


Figure 2.1. Diagrammatic representation of four commonly used hop tests to determine asymmetries. The single leg hop requires one maximal jump landing on the same limb. Failure to land without falling over or 'bouncing forward' requires the test to be retaken. The triple hop assesses maximal distance for three hops in a rebounding pattern. A stable landing must also be demonstrated for the final hop. The 6m timed hop positions timing gates at 0 and 6m and asks subjects to hop on one limb as fast as they can for the total distance; thus, reporting an outcome of time. The crossover hop requires three maximal hops (for distance) in a diagonal pattern. A stable landing must also be demonstrated on the final hop.

It would appear that only recently, bilateral DJ have been used to report asymmetries. Maloney et al. (2016) showed asymmetries as high as 59.7% for leg stiffness, whilst within-session reliability (CV) was 5% for vGRF. However, CV's were noticeably higher for negative centre of mass displacement and vertical stiffness (12 and 13%, respectively), although this may have been attributed to the sample not being an athletic population and therefore, greater test familiarity potentially required. Although not used for asymmetry detection, test-retest reliability (using the ICC) has previously been reported in the DJ for measures of peak and mean force (0.86-0.98), jump height (0.99), and ground contact times (0.98) (Cronin et al. 2004; Flanagan et al. 2008), indicating strong rank-order repeatability. However, further research is warranted to examine the reliability of these variables with respect to asymmetry.

While the majority of the available literature pertaining to the reliability of drop jumping tasks is focused on bilateral variations, the single leg DJ has also recently been examined (Maloney et al. 2016). The authors reported similar levels of asymmetry as the bilateral test (~55%) and showed within-session CV's of 2% for vGRF, indicating small variability between trials in a non-athletic population. Stalbom et al. (2007) investigated the reliability of impulse, mean and peak force during the single leg DJ and found ICC's ranged from 0.74-0.96 and all CV's < 10%. Although both studies indicate acceptable levels of reliability, procedures were conducted from 18 and 20 cm boxes respectively. Bilateral DJ measures are frequently conducted from a height of 30 cm (Flanagan et al. 2008; Joseph et al. 2008; Kristianslund and Krosshaug, 2013), but the increased physical demand associated with a unilateral version would suggest that lower box heights may be more appropriate. This is supported by Maloney et al. (2016) who described how the required short ground contact times (< 250 m/s) could not be maintained when dropping from heights of 30 and 45 cm when testing unilaterally.

2.4 Speed and Change of Direction Speed Tests

Recently, there has also been a rise in the number of studies reporting side-to-side differences during speed and CODS tests. For example, when considering linear speed, Haugen (2018) reported inter-limb asymmetry for 14 kinematic stride metrics (e.g., step length, step rate, contact time, touchdown angle, maximum thigh flexion, horizontal ankle velocity, to name a few) in 22 elite Norwegian sprinters. When considering all metrics collectively, inter-limb asymmetries were ≤ 6%. This low level of asymmetry is likely a by-product of the sample being elite and therefore, highly skilled at sprinting. This is further supported by all CV values being ≤ 6% across the reported metrics, indicating both the homogenous nature of the sprinters and strong reliability of the data. In contrast, Meyers et al. (2017) investigated force, stiffness and spatiotemporal asymmetries during a 35-m sprint test in 344 youth males, aged 11-16. Side-to-side differences ranged from 2.3-12.6%, with relative leg stiffness exhibiting significantly higher asymmetry than all other variables. Furthermore, test reliability was reported using the ICC (0.79-0.86) and CV (3.8-5.0%) indicating acceptable levels of reliability in a youth sample, as well.

When considering CODS, the assessment of asymmetry is scarce with side-to-side differences typically reported for the metric of total time and showing acceptable test variability across a range of populations. For example, Madruga-Parera et al. (2019) used a 20-m test involving two 180° changes of direction as previously outlined by Meylan et al. (2009), in youth handball athletes. Test variability (CV) was ≤ 2.2% indicating strong reliability, with comparable CV scores also shown in numerous studies using total time, during a variety of CODS tests (Bishop et al. 2018a; Bishop et al. 2019b; Bishop et al. 2019d; Dos'Santos et al. 2017b; Dos'Santos et al. 2019b). Thus, it appears total time is a stable metric for the assessment of CODS performance. However, the aforementioned research has also shown that inter-limb asymmetries are typically low for this metric (all < 5%), which may indicate that total time is not a particularly sensitive metric to detect existing imbalances, which has been suggested recently (Madruga-Parera et al. 2019). To support this further, Dos'Santos et al. (2019b) measured asymmetries from the 505 test, using total time and the change of direction deficit (COD deficit). The COD deficit is calculated by subtracting the total time from a linear speed test from the total time of a

CODS test, of equivalent distance (Nimphius et al. 2013), and is suggested to be a more appropriate measure of CODS performance, as some athletes may be able to mask their poor COD ability through superior acceleration performance. Results from Dos'Santos et al. (2019b) reported mean asymmetries of -2.3% for total time, but -11.9% for the COD deficit, with the authors suggested that this metric may be more sensitive at detecting existing between-limb differences compared to total time. However, it is worth highlighting that larger asymmetries will always be noted for the COD deficit, by virtue of calculating the difference from smaller numbers. In essence, once the linear sprint time is subtracted from the CODS total time, the absolute difference between limbs will remain the same, but the relative percentage difference will increase, by virtue of having smaller values in the subsequent calculation. More recently, Thomas et al. (2020) used 3-D motion analysis and force platforms to quantify asymmetry in a range of kinematic and kinetic variables during a 505 test using 52 team sport athletes. Significant asymmetries ($p < 0.05$) were evident between limbs for knee abduction angle, peak horizontal and peak vGRF, but no meaningful differences were evident between limbs for total time. Thus, further highlighting the need to investigate metrics beyond outcome measures during CODS tests as well.

Thus, it appears that measures of time are likely to be stable when computing reliability of speed and CODS tests; however, their ability to detect large inter-limb asymmetries may be questionable. In line with suggestions for jump testing, future research should consider a wider variety of metrics such as force and leg stiffness (for linear speed) and COD deficit, force and kinematic variables (for CODS), where possible.

2.5 Interpreting Asymmetry Scores

Determining critical thresholds for asymmetry that are linked to reductions in performance or heightened injury risk provides strength and conditioning (S&C) coaches with useful data to design targeted training interventions for athletes. The available body of literature suggests that asymmetries are task-specific, meaning that practitioners should not expect to see the same inter-limb differences across different tests for the same physical quality. This is supported by Jones and Bampouras, (2010) who reported that asymmetries varied across tasks with differences of 4.47 and 12.43% for jump and strength tests, respectively. Furthermore, Schiltz et al. (2009) reported strength and power asymmetries of 6.5 and 12% in professional basketball players during isokinetic and DJ testing respectively; thus, justifying undertaking tests across multiple physical competencies.

Where strength asymmetries are concerned, Bailey et al. (2013) reported negative associations with jump performance when strength differences of 6.6% were seen from the IMTP. Hart et al. (2014) noted significantly reduced performance in kicking accuracy with asymmetries of 8% measured using the unilateral isometric squat. However, with limited data relating specifically to asymmetries in strength and their effects on performance outcomes, a specific threshold cannot be substantiated at this time. For jump testing, asymmetries > 10% have been associated with a 9 cm reduction in jump height (Bell et al. 2014); whereas, inter-limb differences ~10% in jump height (Lockie et al. 2014) and power (Hoffman et al. 2007) have shown minimal association with CODS performance. This provides further support for task-specificity pertaining to asymmetries, making it challenging to draw definitive conclusions regarding critical thresholds during jumping-based tasks as well.

2.6 Testing Battery

Based on the aforementioned evidence, a testing battery has been proposed for the assessment of asymmetries in strength and jumping-based tasks (Table 2.2). With strength being of undeniable importance in athletic performance (Suchomel et al. 2016), and jumping tasks occurring frequently in sporting actions (Hewit et al. 2012; Nedelac et al. 2014), testing inter-limb differences for both competencies seems logical and may allow for a more complete picture of asymmetries. In addition, Table 2.3 provides an overview of instructions for each test so that practitioners can adhere to the methods that are likely to elicit the most reliable results. It should be noted that determining inter-limb asymmetries during sprinting and CODS tasks would also provide S&C coaches with useful information. However, the literature pertaining to asymmetries and these physical qualities is scarce and further research in these areas is required before any suggestions are made.

Table 2.2. Proposed testing battery for the assessment of asymmetries during strength and jump tests.

Physical Quality	**Suggested Metrics**	**Selected Test**	**Testing Equipment**
Strength tests	Peak/mean force, RFD, impulse	IMTP or isometric squat (+ SL variations)	Force plates
Jump tests	Peak/mean force, impulse, jump height or distance	CMJ, BJ and DJ (+ SL variations)	Force plates (or OptoJump/jump mat), measuring tape
Linear/CODS tests	Total time, peak/mean force, stiffness, COD deficit, kinematic variables	30m sprint (with splits at 5, 10, 20m), 505 test	Dual beam electronic timing gates, video/motion analysis

RFD = rate of force development; IMTP = isometric mid-thigh pull; SL = single leg; CMJ = countermovement jump; BJ = broad jump; DJ = drop jump; CODS = change of direction speed.

Table 2.3. Instructions for how to administer different tests which can be used for the measurement of asymmetry.

Test	Procedural Instructions
Isometric mid-thigh pull	Previous literature has outlined the knee angle to be set at 125° and the hip angle at 175° (Bailey et al. 2013), with 180° representing full extension at both joints. Joint angles can be measured manually using a goniometer and weightlifting straps can be used to ensure a more secure grip on the bar. Once the position is assumed, athletes should be instructed to pull "as hard and as fast as possible" (Dos'Santos et al. 2017a) which may aid in producing reliable results for variables such as RFD when measuring on force plates. For the unilateral version of this test, Dos Santos et al. (2017) suggested that the non-stance limb be flexed to ~90° at the knee joint.
Isometric squat	Hip and knee angles should be set at 140° with the bar resting on the upper trapezius muscle (as per standard high-bar back squat technique) (Hart et al. 2012; Hart et al. 2014). Athletes should be instructed to push "as hard and as fast as possible" which may aid in producing reliable results for variables such as RFD when measuring on force plates. For the unilateral version of this test, although not specified by Hart et al. (Hart et al. 2012; Hart et al. 2014), it seems logical to ask athletes to flex their non-working limb's knee joint to ~90°, as suggested for the unilateral IMTP procedures.
Countermovement jump	Hands should be fixed onto hips so as to minimise any contribution from the upper body. Upon instruction, the athlete can dip to a self-selected depth during the countermovement prior to accelerating vertically as fast as possible. Lower limbs should remain extended at all times during the flight phase of the jump before landing back on the force plate, OptoJump or jump mat, as per take-off position. The same procedures should be followed for unilateral versions of this test.
Broad jump	Hands should be fixed onto hips so as to minimise any contribution from the upper body. Upon instruction, the athlete can dip to a self-selected depth during the countermovement prior to accelerating horizontally as fast as

	possible, with the aim being to jump as far as possible (i.e., a standing long jump). Trials are void and must be repeated if athletes are unable to stabilise on landing. When measuring distance, the reading should be taken (to the nearest centimetre) from the rear most heel closest to the start position. The same procedures should be followed for unilateral versions of this test.
Drop jump	Hands should be fixed onto hips so as to minimise any contribution from the upper body. Athletes start on top of a box, next to the force platform, OptoJump or jump mat. Upon instruction, athletes step off the box landing on the centre of the measuring device. Literature has emphasised key instructions of 'minimising ground contact time whilst jumping as high as you can' (Maloney et al. 2016; Maloney et al. 2017) with box heights often reported at 30 or 40 cm during bilateral versions of this test (Maloney et al. 2016; Pain, 2014). The DJ requires increased technical competency in comparison to the CMJ (Pedley et al. 2017). Thus, when performing unilaterally, it is likely that box heights should be lowered to account for increased eccentric loading on each limb and maintenance of fast ground contact times (Maloney et al. 2016). Box heights of 15 cm (Pain, 2014) and 18 cm (Maloney et al. 2016; Maloney et al. 2017) have been used in recent studies.
Linear and change of direction speed tests	The equipment typically used during these tests are dual beam electronic timing gates, with instructions to start 0.3-0.5 m behind the first set of gates to avoid breaking the first electronic beam prematurely (Maloney et al. 2017; Bishop et al. 2018a; Bishop et al. 2019b). Athletes should be encouraged to complete the tests 'as fast as they can' with the outcome measure of total time reported. Where possible, the use of video or motion analysis may enable variables such as flight time, contact time and kinematics to be determined; thus, enabling the calculation of additional metrics such as force and stiffness (Hobara et al. 2013) and knee abduction angles (Thomas et al. 2020).

2.7 Practical Considerations for Testing

Regardless of whether asymmetries are being calculated for strength or jumping tests, there are additional test considerations that practitioners should be aware of. Firstly, experience of the tester must be considered. It is common for certain tests to have specific requirements that aid in the standardisation of procedures. For example, it is often suggested that athletes should pull "as hard and as fast as possible" when performing the IMTP test (Dos'Santos et al. 2017a); therefore, some level of experience or familiarity is required to know that this will likely elicit favourable results in variables such as RFD, especially. Secondly, the ease of testing equipment must also be deliberated and it is likely that different considerations exist for strength and jump tests. For example, without twin force plates it is impossible to gauge information pertaining to vGRF asymmetries during exercises such as the back squat. Whilst an alternative solution is to test for asymmetries using isokinetic dynamometry, this method may not be practically viable for many practitioners. Therefore, calculating asymmetries in strength will likely require force plates. For jump tests, many alternative options exist (see Table 2.2); however, force plates should still be considered a favourable option with multiple metrics available, which will help to build a clearer picture of jump strategy. Alternatively, equipment such as OptoJump can be used to calculate asymmetries in metrics such as jump height, ground contact time, and reactive strength. Therefore, if practitioners are unable to access force plates, viable alternatives do exist for jump testing in the field. Practitioners constrained by budgetary restrictions require simpler and more cost-effective methods whereby jump mats may be the default option. However, more recently, mobile technology in the form of the My Jump app has also been shown to be valid and reliable for jump testing (Balsalobre-Fernandez et al. 2015). Therefore, whilst the gold standard is always preferable, measurement of asymmetries during jump tests should be considered by all practitioners regardless of budgets due to the wide range of options available.

2.8 Conclusion

The aforementioned evidence would indicate that there are advantages to choosing isometric squats or the IMTP (both bilateral and unilateral variations) when quantifying asymmetries in strength. Measuring peak force in particular would appear to be reliable across multiple populations, and the isometric squat has shown that higher asymmetries are associated with negative impacts on sport-specific tasks, and performance. When combined with the fact that force plates are more easily accessible in the field due to the creation of more cost-effective versions, and dynamometry measures are often not practically viable, the IMTP or isometric squat are the favourable options when quantifying asymmetries in strength. Once practitioners have determined the most reliable and appropriate test from the battery of jump tests, this will help to streamline future test protocols when determining inter-limb differences. Practitioners should keep in mind that asymmetries have been frequently shown to be both task-dependent and highly variable; thus, it is suggested that the use of thresholds is not considered when collecting and interpreting asymmetry data.

CHAPTER 3: LITERATURE REVIEW

3.0 Inter-limb asymmetries: Understanding how to calculate differences from bilateral and unilateral tests.

3.1 Introduction

Inter-limb asymmetries have been a common source of investigation in recent years and refers to the concept of comparing the performance or function of one limb in respect to the other (Keeley et al. 2011). A recent systematic review examining the effects of between-limb differences on physical and sporting performance demonstrated equivocal findings (Bishop et al. 2018e). In summary, larger lower limb asymmetries in strength may be indicative of reduced jumping ability and power output (Bailey et al. 2013; Rannama et al. 2015); however, when these differences were quantified during jumping tasks, their effect on locomotive activities appears inconclusive (Hoffman et al. 2007; Lockie et al. 2014; Maloney et al. 2017). From an injury perspective, a threshold of > 15% has been indicated to heighten injury risk (Barber et al. 1990; Noyes et al. 1991), but this value has largely been derived from comparisons of jump performance between currently injured athletes and matched controls, with a paucity of evidence to support this notion using prospective cohort analysis. Given the inconsistency in these findings, further research is warranted to examine the effects of asymmetry on both injury and performance-based outcomes.

Multiple methods exist to quantify inter-limb asymmetries and will likely be dictated by a range of factors (Bishop et al. 2018d; Bishop et al. 2017b; Bishop et al. 2016). Such considerations include the needs of the athlete, availability of testing equipment, and reliability of the chosen test (Bishop et al. 2017b). Once these factors have been accounted for (and assuming an asymmetry profile is required), practitioners must consider whether inter-limb differences are best quantified bilaterally or unilaterally. The needs analysis of the athlete or sport will provide some clarification to this question and determine if both methods are utilized as part of an athlete test battery. Once the appropriate tests have been selected, an asymmetry profile can be created; however, it is essential that the calculation used to quantify between-limb differences matches the specifics of the test method.

Recent literature has critically examined the utility of commonly used equations to quantify inter-limb asymmetries (Bishop et al. 2016). However, no distinction was made on whether these equations can be used for both bilateral and unilateral tests. Thus, the primary aim of this section is to provide a clearer understanding of how to select the appropriate calculation method for both bilateral and unilateral tests, and some considerations for interpreting the results.

3.2 Equations to calculate inter-limb asymmetries

Recent literature (Bishop et al. 2016) has highlighted nine possible equations to quantify inter-limb asymmetries (Table 3.1). With multiple formulas available, definitive conclusions pertaining to the most appropriate one is not always apparent. Furthermore, with such inconsistencies present, comparisons across the literature regarding asymmetry thresholds and their associated effects on physical performance or injury risk are almost impossible to conclude. Therefore, a more consistent approach is warranted so that results are comparable over time. Once the appropriate equation has been identified, it is assumed that it can be applied to any test that quantifies inter-limb asymmetries, whether it is bilateral or unilateral. However, this may not necessarily be the case and this point can be illustrated by examining the force-time curves of a bilateral CMJ and SLCMJ, respectively.

Table 3.1. Different equations for calculating asymmetries using hypothetical jump height scores of 25 and 20 cm (taken from Bishop et al. (2016) and re-used with permission from Wolters Kluwer).

Asymmetry Name	Equation	Asymmetry (%)	Reference
Limb Symmetry Index 1 (LSI-1)	(NDL/DL) x 100	80	Ceroni et al. (2012)
Limb Symmetry Index 2 (LSI-2)	(1 – NDL/DL) x 100	20	Schiltz et al. (2009)
Limb Symmetry Index (LSI-3)	(Right – Left)/0.5(Right + Left) x 100	22.22	Bell et al. (2014) Marshall et al. (2015)
Bilateral Strength Asymmetry (BSA)	(Stronger limb – Weaker limb)/ Stronger limb x 100	20	Nunn et al. (1998) Impellizzeri et al. (2007)
Bilateral Asymmetry Index 1 (BAI-1)	(DL – NDL)/(DL + NDL) x 100	11.11	Kobayashi et al. (2013)
Bilateral Asymmetry Index 2 (BAI-2)	(2 x (DL – NDL)/(DL + NDL)) x 100	22.22	Wong et al. (2007) Sugiyama et al. (2014)
Asymmetry Index (AI)	(DL – NDL)/(DL + NDL/2) x 100	22.22	Robinson et al. (1987) Bini and Hume, (2014)
Symmetry Index (SI)	(High – Low)/Total x 100	11.11	Shorter et al. (2008) Sato and Heise, (2012)
Symmetry Angle (SA)	(45° – arctan (L/R))/90° x 100	7.04	Zifchock et al. (2008)

DL = dominant limb; NDL = non-dominant limb.

3.3 Quantifying asymmetries during bilateral tests

Figure 3.1 shows two separate vertical force traces (one for each limb) during the CMJ. For this example, the green line represents both the left/ND limb vGRF and the red one the right/D limb. The subject's bodyweight is 800 Newtons (N) with an average of 420 and 380 N being distributed on the right and left limbs respectively during the quiet standing period (1-2 seconds), prior to the initiation of the jump. When these figures are accounted for (by subtracting from the peak propulsive force value labelled in the graph), the left limb's force is equal to 405.12 N; the right limb's is 556.61 N making the sum force for the propulsive phase of the jump to be 961.73 N. When 556.61 and 405.12 are divided by 961.73 (and multiplied by 100), 57.88% and 42.12% of the force is being performed by the right and left limbs, respectively, at that moment. Therefore, the difference between limbs is 151.49 N and when this is divided by the sum force (and multiplied by 100) an asymmetry of 15.75% exists in this example.

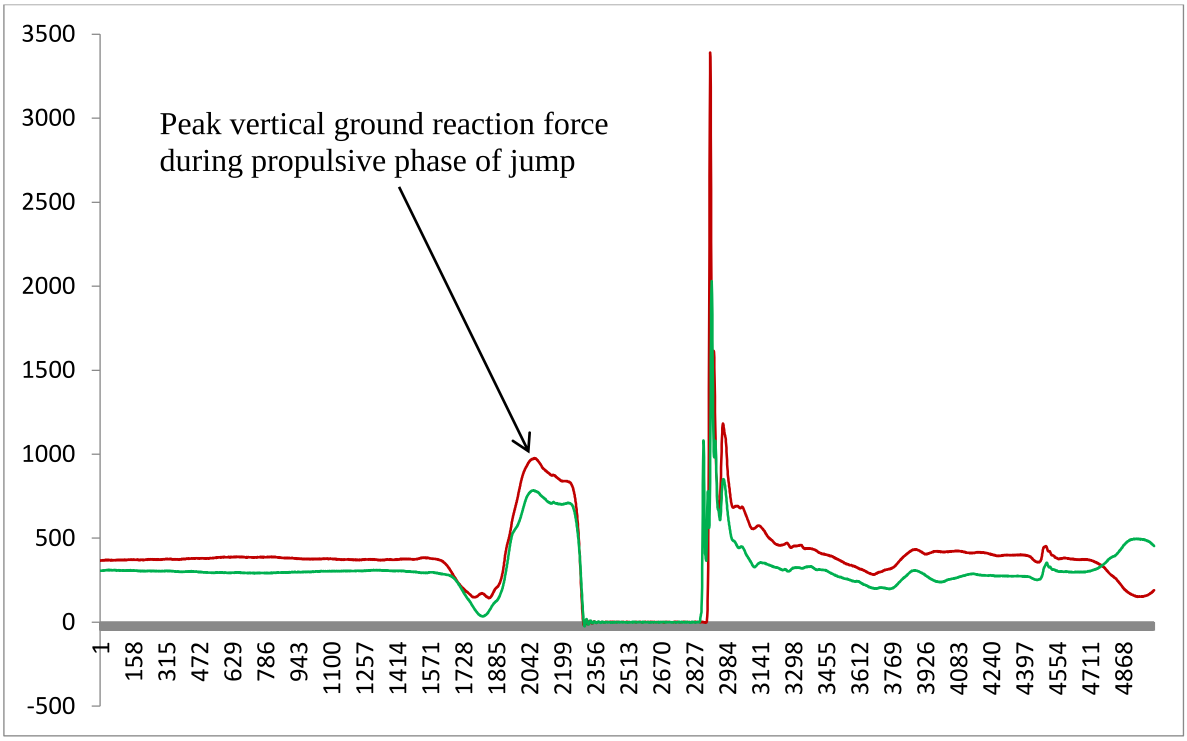


Figure 3.1. Example force trace for each limb during a CMJ (extracted from PASCO Capstone software). Red line denotes right/dominant limb, green line denotes left/non-dominant limb.

Essentially, because any differences in force between limbs are always relative to the sum force value, it is suggested we should not choose most of the suggested equations in Table 3.1. Doing so would create a different/inaccurate asymmetry outcome relative to the sum force (as portrayed in Table 3.2). Noting that only four different outcomes are possible from all nine equations (shown in Table 3.1), four have been selected that will produce different values regardless of the data applied to the formulas. Therefore, when quantifying inter-limb asymmetries during bilateral tests, it appears that only two equations correctly calculate the 15.75% asymmetry value; the Bilateral Asymmetry Index 1 and Symmetry Index. However, it should be noted that the SI defines limbs via highest and lowest scores which may be prone to change depending on factors such as injury history and training or competition requirements (Sprague et al. 2014). Whilst this equation will always quantify bilateral asymmetries accurately, practitioners should be mindful of the highest score changing between limbs. Therefore, the Bilateral Asymmetry Index 1 may be the most appropriate equation for quantifying asymmetries during bilateral tests, which has been suggested previously (Bishop et al. 2016).

Table 3.2. Asymmetry values for the CMJ data using different equations (which has an accurate inter-limb asymmetry of 15.75%).

Asymmetry Name	Equation	Asymmetry (%)
Bilateral Strength Asymmetry	(556.61 – 405.12)/556.61 x 100	27.22
Bilateral Asymmetry Index 1	(556.61 – 405.12)/556.61 + 405.12) x 100	15.75 *
Bilateral Asymmetry Index 2	(2 x (556.61 – 405.12)/(556.61 + 405.12)) x 100	31.50
Symmetry Angle	(45 – arctan (405.12/556.61))/90 x 100	9.95

* denotes that the outcome is accurate to the CMJ data

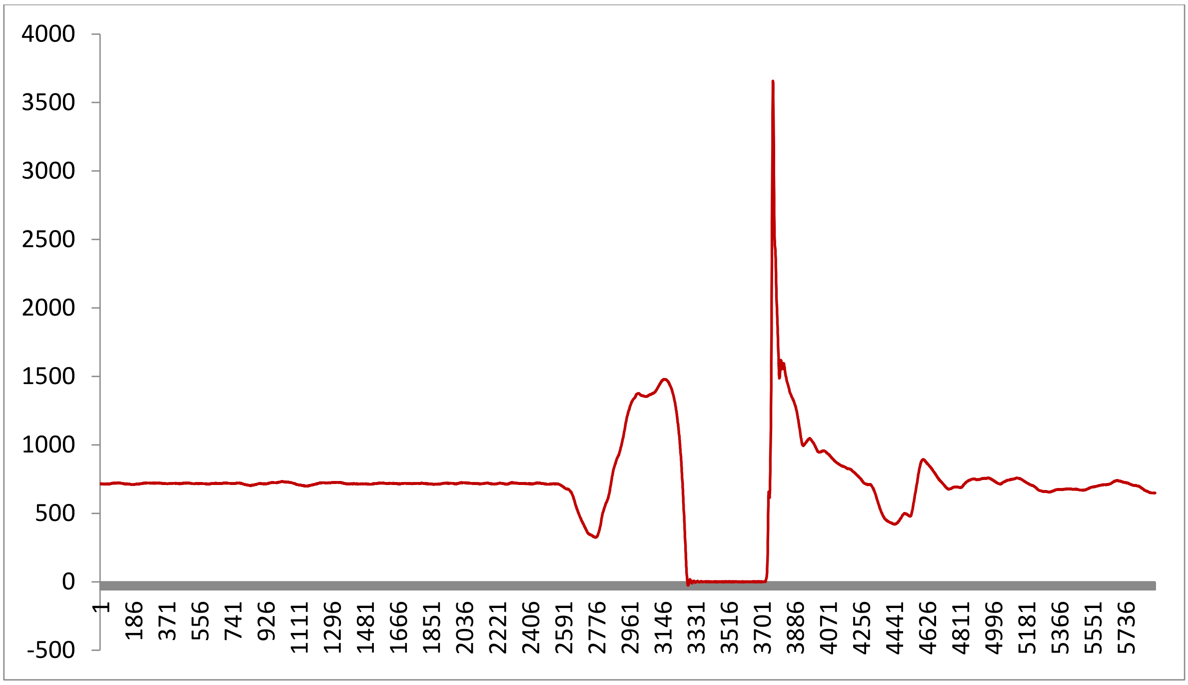
3.4 Quantifying asymmetries during unilateral tests

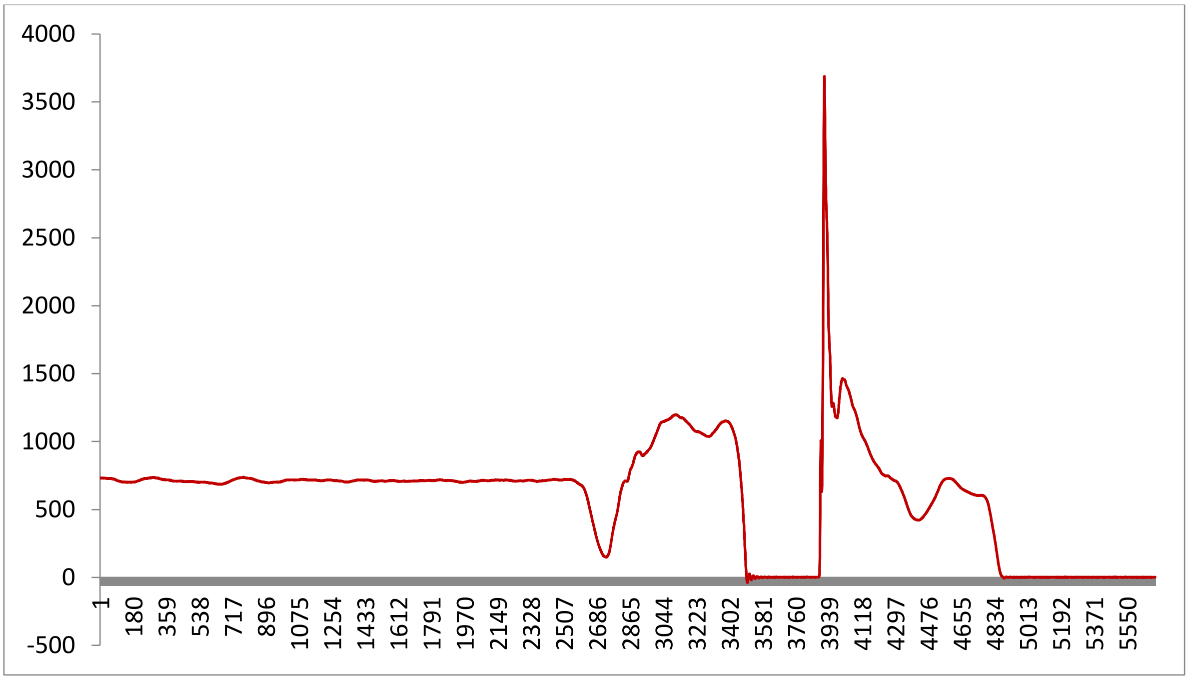
Figures 3.2 and 3.3 provide example force traces for the SLCMJ on the right and left limbs respectively for the same subject seen in Figure 3.1. Once body mass is taken into consideration (subtracting 800 N), net peak vGRF for the right limb (Figure 3.2) is 679.69 N and 397.76 N on the left (Figure 3.3).

Initially, it may be thought that less restriction applies as to which equation can be used to calculate the inter-limb asymmetry in vGRF. The SLCMJ is a unilateral test and thus, no contribution exists from the opposing limb and the force is distributed solely on the designated test-leg, potentially providing a more accurate representation of 'true' inter-limb asymmetries (Benjanuvatra et al. 2013; Bishop et al. 2017b). However, practitioners should be mindful that some of the equations presented in Table 3.1 still provide an inaccurate asymmetry score. Noting that an asymmetry is merely a percentage difference between limbs at a given time point, it is surprising to see such variation in values. Using the SLCMJ example, the percentage difference between the right (679.69 N) and left (397.76 N) scores is 41.48%. This can be computed by an alternative equation which merely expresses the difference between these values as fractions of 100%.

- Percentage difference method: 100/(max value)*(min value)*-1+100
- SLCMJ example (Figures 2a and 2b): 100/(679.69)*(397.76)*-1+100 = 41.48%

Using the percentage difference method, once the minimum value has been computed, this will provide an outcome of symmetry (in this instance 58.52%). Multiplying by -1 and then adding 100, simply moves the value to the opposite end of the spectrum, creating an asymmetry score of 41.48%. Given that percentages are always out of 100, this method provides the same outcome as if fractions were calculated, putting the larger value as the denominator. Similar to the CMJ example, the same four equations have been used in Table 3.3. Any equation from Table 3.3 that does not produce an outcome of 41.48% is likely calculating the percentage difference incorrectly. Therefore, the proposed equations to use when quantifying asymmetries from unilateral tests are the Bilateral Strength Asymmetry or percentage difference method.





Figures 3.2 and 3.3. Example force traces for the SLCMJ. Figure 3.2 (top) represents the right/D limb and Figure 3.3 (bottom) for the left/ND limb.

Table 3.3. Asymmetry values for the SLCMJ data using different equations (which has an accurate inter-limb asymmetry of 41.48%).

Asymmetry Name	Equation	Asymmetry (%)
Bilateral Strength Asymmetry	(679.69 – 397.76)/679.69 x 100	41.48 *
Bilateral Asymmetry Index 1	(679.69 – 397.76)/(679.69 + 397.76) x 100	26.17
Bilateral Asymmetry Index 2	(2 x (679.69 – 397.76)/(679.69 + 397.76)) x 100	52.16
Symmetry Angle	(45 – arctan (397.76/697.69))/90 x 100	16.36

* denotes that the outcome is accurate to the SLCMJ data

3.5 Additional Considerations for Interpreting Asymmetry Scores

One important point to consider involves interpreting the asymmetry outcome. Exell et al. (2012) highlighted that an inter-limb asymmetry may only be considered 'real' if the value is greater than the intra-limb variability within that specified movement. During testing, variability is quantified via the CV which provides practitioners with an indication of typical error between trials (Turner et al. 2015). Testing protocols generally depict that at least three trials should be performed when testing athletes so that the inherent variability can be accounted for (Turner et al. 2015). In the CMJ example used in this article, the asymmetry in peak vGRF is 15.75%. Assuming that the CV was less than the asymmetry value, it could be concluded that the asymmetry score was real. Whilst an asymmetry would still be considered real in this instance with a CV of 10-15%, acceptable CV values have been suggested as < 10% (Cormack et al. 2008). With that in mind, if variability is calculated as substantially > 10%, practitioners may wish to consider whether their test protocols require refining, further familiarization is needed, instructions were sufficiently clear or whether the athlete's warm up and rest intervals were inadequate (Bishop et al. 2017b; Turner et al. 2015).

Moreover, although recent literature highlighted such issues as being important considerations for reliable asymmetry testing (Bishop et al. 2017b), the majority of this information pertains to within-session reliability. Asymmetries have been suggested to be highly task-specific (Exell et al. 2012; Maloney et al. 2016); thus, the notion of between-session consistency and longitudinal tracking in respect to asymmetries becomes arguably more important, as noted in previous literature (Bishop et al. 2018e). For example, if the notion of task-specificity is accepted, it is plausible that test protocols can remain consistent within each test session (with CV values < 10%), but the asymmetry outcome may vary considerably. At present, the distinct lack of longitudinal data relating to asymmetries make suggestions on this issue somewhat anecdotal. However, with asymmetry being both task and variable-specific, practitioners may wish to consider reporting and comparing asymmetries in respect to the CV and are advised to consider how these scores fluctuate over time.

When calculating asymmetries, a variety of approaches have been used which define limb differences in terms of dominance, strength, preference, or simply a right or left distinction (Bishop et al. 2016). For example, studies pertaining to soccer frequently define the dominant limb as the favoured 'kicking leg' (Costa Silva et al. 2015; Ruas et al. 2015), which seems valid considering the nature of such a task. However, recent research has highlighted poor levels of agreement (40%) between perceived limb dominance and the highest score attained (Fort-Vanmeerhaeghe et al. 2016). In addition, Zifchock et al. (2008) suggested that numerous asymmetry equations emphasise the use of a 'reference value' (such as the D limb or highest score). However, a recent systematic review by Dos'Santos et al. (2019a) suggested that limb dominance should be defined as the limb with the highest score, as this will enable the correct mathematical calculation of asymmetry, if it is computed. Furthermore, given the task-dependent nature of asymmetry, it is highly plausible that the dominant or highest-performing limb may change over time; thus, ensuring consistent calculations of between-limb differences are essential.

3.6 Conclusion

In summary, bilateral or unilateral tests can be used to quantify inter-limb asymmetries. If bilateral tests are utilised, it is important that the appropriate equation is selected given that between-limb differences are always presented in relation to the sum total for any reported metric. The Bilateral Asymmetry Index 1 and Symmetry Index appear to be the only formulas that will accurately quantify asymmetries during bilateral tasks. If unilateral tests are selected, the Bilateral Strength Asymmetry or percentage difference method accurately calculates inter-limb differences and should be the chosen formulas. Finally, the interpretation of asymmetry scores is an important consideration. A comparison with test variability and longitudinal tracking of these differences may be crucial to understanding their importance as part of a continued monitoring process with athletes.

CHAPTER 4: LITERATURE REVIEW

4.0 Additional factors affecting asymmetry

4.1 Introduction

So far, the literature review has shown that factors such as test reliability and athlete requirements are key considerations when aiming to measure asymmetry, and multiple equations have been used when calculating side-to-side differences. However, there are also additional considerations for practitioners which may affect inter-limb asymmetries. For example, when considering soccer athletes, recent literature has highlighted the increased physical demand with a greater number of high intensity actions occurring in recent years (Bush et al. 2014; Taylor et al. 2017). In addition, fixture congestion will vary depending on the time of the season, with a tendency for reduced recovery between matches during the middle of the season (Barnes et al. 2014; Carling et al. 2012), and both acute and chronic fatigue have been shown to result in reductions in athletic performance (Kraemer and Ratamess, 2004).

The concept of fatigue is challenging to define, which likely makes the measurement of fatigue equally challenging. Seminal research has defined fatigue as an acute exercise-induced decline in muscle force or power (Asmussen, 1979; Edwards, 1981). However, it is important to recognise that complications within such a definition may also exist. Firstly, fatigue can still be present with no reduction in muscle force and has been termed ‘prolonged low-frequency force depression’ (Bruton et al. 2008). Secondly, when aiming to quantify performance in a given task under fatigued conditions, the assumption exists that the motivation of the participants remains optimal (Place and Millet, 2020). This is unlikely to be the case and when considering competitive match-play in soccer, the simple notion of winning and losing may be a potential factor when defining changes in performance, under fatigued conditions.

Thus, given the possible seasonal variation in athletic performance throughout the season, monitoring performance longitudinally or during repeated time points seems especially relevant for practitioners. An overview of the available literature pertaining to these factors has been outlined below.

4.2 Monitoring Seasonal Variations in Performance and Asymmetry Using Jump Tests

Numerous studies have used jump tests to track changes in neuromuscular status in team sport athletes (Claudino et al. 2016; Gathercole et al. 2015a; Gathercole et al. 2015b; Gathercole et al. 2015c); however, few have reported seasonal variation or monitored performance longitudinally. In sports such as soccer, multiple factors exist which may impact a players' ability to perform optimally during surrogate measures of athletic performance (e.g., sprinting, CODS, jumping), such as: training status, injuries, fixture congestion, accumulated fatigue, and limb dominance. Thus, data collected at a single time point are unlikely to be fully representative of the athletes' physical status across the entirety of the competitive season. Therefore, monitoring jump performance over time is recommended and provides a more accurate representation of the imposed demands soccer athletes are exposed to.

Available literature reporting seasonal variation in soccer athletes is sparse. Casajus (2001) used CMJ and squat jump (SJ) at two different time points (September and February) in 15 professional soccer players. Results showed no significant changes in jump height for either test. Equally, only two time points were measured, which does not represent the full duration of a competitive season. Williams et al. (2011) tested CMJ performance in youth academy soccer players (under 12 – under 16s) twice throughout the season (October and April). Results were reported as percentage change and when all age groups were combined, on average a 7% improvement in jump height was shown throughout the season. However, it is important to note that the largest increase was shown for the under-12 group (~9%), with all other age categories reporting positive changes < 5%. Although speculative, the larger increases in jump height seen in the youngest age group may be explained by a potential learning effect. Youth players are likely to have undertaken test protocols less frequently and increased exposure may present itself with somewhat false improvements, as they learn how to perform the tests appropriately. Similarly, reductions in both motor control and physical outputs are often seen during maturation (Lloyd et al. 2016), which may explain why larger improvements were not seen for the older age groups.

Other studies have also assessed players at more than two time points to more fully examine seasonal changes in performance. Haugen (2017) showed mean CMJ height of 37.4 ± 4.0 cm for pre-season, 38.1 ± 4.0 cm in-season, and 38.6 ± 3.9 cm in the off-season, with significant differences evident between pre-season and off-season in 44 Norwegian professional soccer players. Finally, Caldwell and Peters, (2009) reported seasonal variation data for a male semi-professional soccer team (n = 13), testing at 5 stages over a 12-month period. CMJ height with an arm swing was monitored (in cm) at the end of one season (57 ± 4.0), before pre-season of the following season (54 ± 3.2), end of pre-season (56 ± 3.7), middle of the season (57 ± 3.4) and end of the season (57 ± 3.4). Data were analysed by comparing the results at one time point to the results of the previous one, with significant changes noted between all time points, except the final two. These data provide evidence that athletes are likely to improve their jump performance as the season progresses, with reduced performance often seen near the start of a competitive season, confirming from the findings of Williams et al. (2011) and Haugen (2017).

When interpreting these data, it is important to recognise that all the aforementioned studies reported jump height data only. Previous research has shown that even when fatigued, athletes can manipulate their jump strategy and still achieve the same jump height (Bromley et al. 2018; Cormack et al. 2008; Gathercole et al. 2015a; Young et al. 2011). In contrast, when considering the CMJ, metrics such as net impulse (defined as net force multiplied by time) provide practitioners with an indication of jump strategy, which has been recognised as offering meaningful information relating to how jumps are performed (Ruddock et al. 2015; Winter et al. 2014; McMahon et al. 2018). The relevance here being that jump height alone may not be sensitive enough to detect changes in jump performance over time. Thus, an understanding of how athletes perform a jump may provide meaningful changes relating to neuromuscular fatigue or readiness to perform, that outcome measures alone cannot detect. Therefore, the addition of strategy-based metrics such as impulse for monitoring changes in jump performance over time, is advised and in line with recent suggestions (Chavda et al. 2018; Gathercole et al. 2015a; McMahon et al. 2018). In addition, the available evidence suggest that bilateral jump tests have been used to track changes in jump height. Thus, literature to describe the seasonal variation for unilateral jump tests (inclusive of strategy-based metrics) appears unavailable, with research needed to determine whether they are also sensitive enough to detect changes throughout a competitive season.

As previously suggested, an additional advantage of selecting unilateral jump tests, is the ability to calculate inter-limb asymmetry data. Previous literature has highlighted that asymmetry is highly variable (Bishop et al. 2018b; Bishop et al. 2019b; Dos'Santos et al. 2017b; Jones and Bampouras, 2010; Lockie et al. 2014; Maloney et al. 2016); thus, investigating the consistency of asymmetry would enable practitioners to understand how usable it is as part of the continued monitoring process with athlete populations. Secondly, numerous studies have reported associations between jump asymmetries and measures of athletic performance (Bishop et al. 2018c; Bishop et al. 2019d; Dos'Santos et al. 2017b; Lockie et al. 2014; Loturco et al. 2019); however, all of these studies have reported associations at a single time point and often the time of season is not stated. Given the observed seasonal variations in jump performance (Caldwell and Peters, 2009; Haugen 2017; Williams et al. 2011) and the potential for heightened asymmetry in response to increased match and training demands, it seems prudent to examine asymmetry at different points throughout a soccer season to more clearly elucidate how these factors may impact performance. The paucity of longitudinal data to report how asymmetry changes over time has recently been highlighted (Bishop et al. 2018e), and it stands to reason that if changes in asymmetry were associated with changes in athletic performance tasks over time, this would provide more meaningful information for practitioners as to the relevance of existing between-limb differences. In addition, with soccer match-play likely to exhibit acute changes in jump performance (Harper et al. 2016; Hughes et al. 2013), it seems plausible that this would also result in changes in asymmetry. However, to the authors' knowledge, this has not been investigated across the course of a competitive soccer season.

4.3 Using Jump Tests to Detect Fatigue from Training, Simulation or Competition

Jump tests are commonly used to monitor changes in neuromuscular status. For example, a meta-analysis by Claudino et al. (2016) highlighted 63 variables had been used across 151 studies in the CMJ alone, with the aim of monitoring neuromuscular status. All 63 variables had been used to monitor changes in jump performance, but only jump height and peak power have been used to detect fatigue (Claudino et al. 2016); thus, a more in-depth examination of various jump metrics is warranted in this regard.

An additional point to consider is the type of preceding stimulus used to elicit fatigue. Numerous studies have used simulated training protocols (Harper et al. 2016; Hughes et al. 2013; Nedelac et al. 2013; Robineau et al. 2012; Stone et al. 2016; Thomas et al. 2017), whilst others have examined the changes following competition (Bromley et al. 2018; Krustrup et al. 2010; Nedelac et al. 2014; Silva et al. 2013; Thorlund et al. 2009). Simulations benefit from practitioners being able to control the external load players are exposed to; however, they do not reflect the reactive and chaotic nature of game situations. Thus, the responsiveness of specific jump tasks/metrics post competition may provide meaningful information for practitioners, especially in the context of asymmetry. Some players will be exposed to repeated movement patterns owing to the positions they play; thus, leading to inherent limb dominance during certain tasks (e.g., a wide midfield player who must 'cut inside' in the same direction repeatedly during a match). Thus, asymmetry should be expected in soccer players and the forthcoming information will provide an overview of both simulated and game protocols, highlighting the need to understand the importance of jump testing in relation to competitive match-play.

4.3.1 Detecting Fatigue from Simulation Protocols

Hughes et al. (2013) included 17 semi-professional soccer players who performed a simulated soccer protocol. Specifically, players were required to perform 6 x 16-minutes of varied intensity exercise, with three minutes of rest between sets and a 15-minute rest between the third and fourth sets. Each 16-minute bout required players to intermittently walk, jog, run and sprint (with changes of direction). Mean CMJ height was 29.8 ± 3.1 cm before the simulation and 27.7 ± 3.3 cm post simulation, representing a statistically significant change ($p < 0.05$). Harper et al. (2016) used 10 university soccer players to complete a 120-minute soccer match simulation (90-minutes + 30-minutes of extra time).

CMJ height was tested at five time points: before the simulation, at the end of the first half, before the start of the second half, end of the second half, and at the end of extra time. Jump height was lower just before the start of the second half compared to before the simulation (-12.5%), the end of the first half (-8.3%), and interestingly, the end of the second half (-6.7%). Although speculative, it seems the likely reason for reduced jump performance at the start of the second half, may have been that players remained seated for the entire 15-minute half-time period, with no additional warm up conducted prior to re-testing. Further to this, jump height at the end of 120-minutes was significantly lower than before the simulation ($p = 0.027$).

Nedelac et al. (2013) used 12 professional soccer players who completed a 90-minute soccer-specific aerobic field test, as originally proposed by Small et al. (2010), on both artificial and grass surfaces. Jump height was also recorded for the CMJ and SJ tests at baseline, immediately post, 24 and 48 hours' post. No significant interaction existed between playing surfaces; thus, the forthcoming data has been pooled. For the SJ, jump height reduced by 5.4-8.4% (immediately post), 2.8-3.5% (24 hours), and 1.0-4.6% (48 hours), with statistical significance only reached immediately post. For the CMJ, jump height reduced by 4.7-5.2% (immediately post), 3.7-4.4% (24 hours), and 1.7-2.4% (48 hours), with statistical significance again only reached immediately post. These data unsurprisingly indicate that the largest decrements in jump performance can be expected immediately post-competition. However, these data relate to bilateral jumping only, with no data available pertaining to how asymmetry changed at each time point.

Robineau et al. (2012) used eight volunteers from a sport science department in a French university and simulated a 90-minute match with a 15-minute half time period. The simulation was split up into 5-minute intervals consisting of walking, slow running, fast running and repeated sprints, repeated for the duration of the simulation. CMJ and SJ height were measured pre-simulation, at half time, and post-simulation. For the SJ, jump height (in cm) was 34.6 ± 3.9 (pre), 32.8 ± 4.1 (half time) and 31.8 ± 4.5 (post), with half time and post-simulation scores significantly lower than pre-simulation. For the CMJ, jump height (in cm) was 35.9 ± 3.7 (pre), 34.4 ± 3.6 (half time) and 34.1 ± 4.2 (post), with no meaningful differences between time points.

Stone et al. (2016) used the exact same simulation protocols outlined by Hughes et al. (2013) with eight male Welsh division 1 soccer players on both artificial and grass surfaces. The CMJ (jump height in cm) and maximal rebound jump test were tested at pre, post, 24 and 48 hours post simulation on both surface types. The rebound jump test consisted of 5 maximal CMJ's, with RSI subsequently calculated by dividing jump height by contact time for each repetition and then using an average of all trials (Lloyd et al. 2009). There was no interaction effect between playing surfaces for either jump test; thus, the forthcoming information provides a range of scores at each time point, representing data for both surface types. For the CMJ, jump height (in cm) ranged from 29.35-30.33 (pre), 27.42-29.29 (post), 28.65-29.58 (24 hours) and 31.06-31.96 (48 hours), with no meaningful differences evident between time points. In contrast, RSI ranged from 1.32-1.33 (pre), 1.22 on both surfaces (post), 1.37-1.40 (24 hours) and 1.36-1.49 (48 hours), with post-simulation values representing a significant reduction in RSI ($p < 0.05$). These data indicate that fast stretch shortening cycle (SSC) tests may be more sensitive at detecting changes in jump performance and provide different information to those that emphasise slow SSC function; thus, assessment of both jump types seems warranted.

This is further supported by Oliver et al. (2008) who assessed changes in SJ, CMJ and DJ performance after 42-minutes of soccer-specific exercise in 10 youth soccer players. Although post-testing revealed significant reductions of 1.4, 3.0 and 2.3 cm in the SJ, CMJ and DJ tests, respectively; impact force during the DJ was the only force variable to show significant reductions post-exercise (p < 0.05). In addition, surface electromyography (EMG) data showed significant reductions in muscle activity post-exercise during the DJ test, but not during the CMJ or SJ. These data showed that although outcome measures responded in a similar fashion, force and muscle activity may be influenced by the stretch-shortening cycle. In turn, this highlights the relevance of the DJ test when monitoring changes in response to exercise. However, this study also used the bilateral DJ, with no information available investigating whether the single leg DJ would respond in the same way.

Finally, Thomas et al. (2017) used 15 semi-professional soccer players and performed a 90-minute soccer simulation protocol, consisting of 2 x 45-minute halves of varying intensity exercise in an indoor synthetic track. Specifically, players were required to jog at 55% of their VO_{2max} (previously determined), back-pedal, run (95% VO_{2max}) and sprint 20 m shuttles to an audible beep. Jump performance was measured using the CMJ (height), DJ from a 30 cm box (RSI) and broad jump (distance) at pre, post, 24, 48 and 72 hours post simulation. Results are presented in Table 4.1, with Cohen's *d* ES used to interpret change relative to pre-test results. The reader should note that data for the broad jump at the 72-hour time point is missing because the authors reported that data for this test had returned to baseline levels at the 48-hour testing point.

Table 4.1. Test scores ± standard deviations and Cohen's *d* ES data for jump tests throughout the 72-hour recovery period (adapted from reported results in Thomas et al. 2017).

Jump Test	Pre	Post	24-h	48-h	72-h
CMJ (cm)	38.8 ± 4.3	34.0 ± 5.0	36.8 ± 4.3	36.9 ± 4.2	37.3 ± 4.1
d		1.04	0.46	0.44	0.36
RSI ($cm \cdot s^{-1}$)	161 ± 22	126 ± 19	144 ± 24	144 ± 23	156 ± 26
d		1.73	0.74	0.75	0.24
BJ (m)	2.38 ± 0.11	2.23 ± 0.11	2.32 ± 0.14	2.37 ± 0.13	-
d		1.36	0.47	0.24	-

CMJ = countermovement jump; cm = centimetres; RSI = reactive strength index; $cm \cdot s^{-1}$ = centimetres relative to contact time; BJ = broad jump; m = metres.

The above data shows that the largest decrement in jump scores occurs immediately post-testing, as represented by the moderate to large ES. At 24-48 hours, small changes in jump scores were evident for the CMJ and broad jump, with moderate reductions still evident for RSI. These data indicate that testing immediately post-match is likely to portray the largest changes in performance, and should be considered if jump testing is deemed an appropriate method of detecting neuromuscular status. This is further supported by Nedelac et al. (2013) and Stone et al. (2016) who showed that significant reductions in jump height for the CMJ and SJ (Nedelac et al. 2013) and RSI (Stone et al. 2016) were only evident immediately post-simulation. Finally, it is worth noting that the ES for RSI was notably greater than jump height during the CMJ, which may again indicate that fast and slow SSC protocols may show different responses to simulation protocols. In addition, with RSI being dependent on both jump height and time spent on the ground, this also provides an indication of jump strategy using a fast SSC type test. Thus, and in line with the findings from Oliver et al. (2008), and suggestions for the CMJ, these data suggest that the DJ is likely a suitable test for detecting acute changes in jump performance post exercise.

4.3.2 Detecting fatigue from Competition

Krustrup et al. (2010) investigated how jump height from the CMJ responded to three competitive matches using 23 Danish female premier league players. When reporting changes in jump height, data for all matches were pooled and showed non-significant reductions (pre: 35 ± 1 cm, range = 30-41 cm; post: 36 ± 1 cm, range = 31-43 cm). Given previous research has reported high game-to-game variability (Gregson et al. 2010), it may have been more beneficial to provide individual game results, accompanied with individual player scores and this should be considered for future research.

Nedelac et al. (2014) investigated the effects of four home matches on CMJ height performance at 24, 48 and 72 hours post matches. Firstly, baseline CMJ values were established over two test sessions prior to all matches; however, details of how far in advance test sessions were conducted, was not provided. Further to this, all values were pooled together for all matches, with mean jump height values (in cm) of 39.9 ± 2.2 (baseline), 36.9 ± 2.9 (24 hours), 37.3 ± 3.4 (48 hours) and 37.4 ± 2.4 (72 hours). All reductions were significant compared to baseline ($p < 0.001$) and represented moderate to large changes in jump height (d = 1.03-1.22). Given previous research (albeit from simulation protocols) has shown the largest decrements in jump performance immediately post (Nedelac et al. 2013; Stone et al. 2016; Thomas et al. 2017), it would have been useful to report changes in jump data at this time point as well. Doing so would provide a more complete picture of how quickly soccer players recover post-competition.

Silva et al. (2013) used seven Portuguese male outfield players and investigated how CMJ height was affected by a single match. Jump data were recorded 72 hours before the investigated match, 24, 48 and 72 hours post-match. Jump height (in cm) was 43.83 ± 2.40 (pre), 40.75 ± 1.80 (24 hours), 43.15 ± 2.30 (48 hours) and 43.60 ± 2.31 (72 hours), with the 24-hour time point significantly reduced ($p < 0.05$) compared to pre and 72 hours' post-match. These results are in contrast with Nedelac et al. (2014), who reported significant reductions in jump height at all comparable post-match time points; however, Silva et al. (2013) only reported data for a single match. Thus, multiple matches may provide a more meaningful understanding of changes in jump performance in response to competitive soccer matches. In addition, it could be argued that the use of baseline testing at 72 hours prior to a match is not a true baseline value, so far in advance of competition time.

Thorlund et al. (2009) investigated how CMJ performance responded to a single match by testing immediately after the game and again 4 days later (which served as the non-fatigued control condition) using nine academy soccer players (mean age = 17.6 ± 0.8 years). Test metrics included jump height, eccentric and concentric phase duration, peak and mean concentric force, and peak and mean concentric power. No significant differences were reported for any metrics; however, when considering percentage change, trends varied depending on the metrics reported. For example, jump height, eccentric and concentric duration phases showed reductions (2.1-5.2%), whilst peak and mean force/power showed small increases (1.4-4.7%). Despite a lack of meaningful differences, the methods used in this study could be questioned, with large parts of the temporal recovery period missing from testing (e.g., 24, 48 and 72 hours). Furthermore, given the small sample and single match analysed, this reinforces the need to investigate multiple matches to provide a clearer understanding of jump performance in response to competition.

All of the aforementioned test protocols in this section have utilised bilateral jump testing. To the authors knowledge, only a single study has investigated unilateral jump performance and asymmetry in response to a competitive soccer match. Bromley et al.

(2018) used the SLCMJ to test 14 academy soccer players pre, immediately post, 24, 48 and 72 hours post competitive match. Significant reductions ($p < 0.05$) in eccentric impulse, concentric impulse, peak force and peak landing force were evident at all time points on both limbs, with meaningful changes in jump height only evident on the left limb. When considering side-to-side differences across all metrics, small to very large increases in asymmetry were evident immediately post (d = 0.31-3.15), 24 hours' post (d = 0.50-2.80), trivial to small increases 48 hours' post (d = 0.01-0.47), and trivial to very large increases 72 hours post (d = 0.07-2.05). The increase in asymmetry at 72 hours was attributed to a light training session conducted prior to testing, noting that it is rare for elite academy soccer players do get more than 1-2 days' rest during the competitive schedule.

Despite the usefulness and novelty of using the unilateral CMJ and reporting changes in asymmetry by Bromley et al. (2018), it is worth noting that this was again for a single match only. Furthermore, to the authors' knowledge, there are no studies to date which have used the unilateral DJ test, to detect changes in jump performance post-soccer competition with the inclusion of strategy-based metrics such as ground contact time (GCT) and RSI, which also report changes in inter-limb asymmetry. Thus, further research in this regard is warranted to aid practitioners' understanding as to the efficacy of unilateral jump testing for the detecting of changes post competition.

4.4 Conclusion

In summary, there are a wide range of factors which may cause changes in performance to occur throughout a competitive season indicating that continued monitoring is required, as opposed to only a single time point. When asymmetry is considered, previous literature has highlighted that longitudinal data is missing and it is a highly variable concept. This further supports the need to measure performance longitudinally in order to determine whether asymmetry can be used as part of the continued monitoring process.

When using jump tests to detect fatigue either post competition or after simulation protocols, reductions in performance seem consistent. However, the majority of studies have used bilateral test methods and predominantly reported outcome measures such as jump height. Not all studies have monitored jump performance throughout a temporal recovery period (e.g., 72 hours); however, the majority of studies show that the greatest reductions in jump performance occur immediately post competition. Thus, justifying this as a key time point to monitor changes in jump performance. Furthermore, research is warranted using unilateral test methods, reporting metrics beyond jump height, and investigating the changes observed in asymmetry over repeated competitive bouts.

CHAPTER 5: SYSTEMATIC REVIEW

5.0 Associations between inter-limb asymmetries on measures of physical and sports performance: A systematic review.

5.1 Introduction

Within the literature, a stronger focus surrounding asymmetry and injury risk or occurrence appears to have been investigated when compared to physical or sports performance. Previous studies have identified the presence of inter-limb differences in a range of populations (Atkins et al. 2016; Ceroni et al. 2012; Impellizzeri et al. 2007; Maloney at al. 2016; Rohman et al. 2015), and a variety of sports such as sprinting (Meyers et al. 2017; Exell et al. 2016; Rumpf et al. 2014), kickboxing (Stanton et al. 2015), swimming (Evershed et al. 2014), basketball (Schiltz et al. 2009), and rowing (Buckeridge et al. 2012). In addition, some research has examined inter-limb asymmetries across a range of physical capacities including strength (Bailey et al. 2015; Bazyler et al. 2014; Sato and Heise, 2012), power (Bell et al. 2014; Benjanuvatra et al. 2013; Hoffman et al. 2007), and leg stiffness (Hobara et al. 2013; Maloney et al. 2015; Maloney et al. 2016). Intuitively, it is logical to assume that minimising these differences are desirable; however, determining whether this has a measurable effect on physical or sport performance remains unclear.

Available literature has shown that inter-limb asymmetries ~10% result in reductions in jump height (Bell et al. 2014) and are associated with slower CODS times (Hoffman et al. 2007), indicating that the reduction of these differences may be favourable. In contrast, other studies have shown conflicting results with no clear association with reduced physical performance (Bini and Hume, 2015; Lockie et al. 2014). The presence of heightened inter-limb asymmetries would be expected in sporting actions where preferred limb dominance is evident (Schiltz et al. 2009); although limited empirical data are available to support this notion (Hart et al. 2016). More clearly understanding the associations between inter-limb asymmetries and measures of physical and sports performance, will provide practitioners with important information for the design of targeted training strategies.

Therefore, the primary aim of this systematic review was to examine the available literature relating to inter-limb asymmetries and to critically evaluate their associations with physical and sport-specific performance. In addition, a 'Directions for Future Research' section has been provided offering guidelines on how to further progress and understand the topic of inter-limb asymmetries.

5.2 Methods

5.2.1 Literature Search Methodology

Original and review journal articles were retrieved from electronic searches of Medline and SPORT Discus databases. Figure 5.1 provides a schematic of the search methodology. The search strategy combined specific terms with the word 'asymmetries' so as to avoid excessive quantities of unrelated articles. These included: 'asymmetries and performance', 'asymmetries and strength', 'asymmetries and jumping', 'asymmetries and speed', 'asymmetries and changing direction', 'asymmetries and balance', 'asymmetries and running', and 'asymmetries and sport'. Additional searches were subsequently conducted in Google Scholar if full-text articles were not fully available; these allowed for articles to be found on ResearchGate™ if they were unavailable through the aforementioned search engines. Finally, using the full-text articles, reference lists were checked for additional research studies that were deemed suitable and had not been identified using the aforementioned methods. Inclusion criteria required studies to have related their asymmetry findings to a separate physical or sport performance metric and not just report the prevalence of asymmetries in the population sample tested. The final search date was 9 November, 2016.

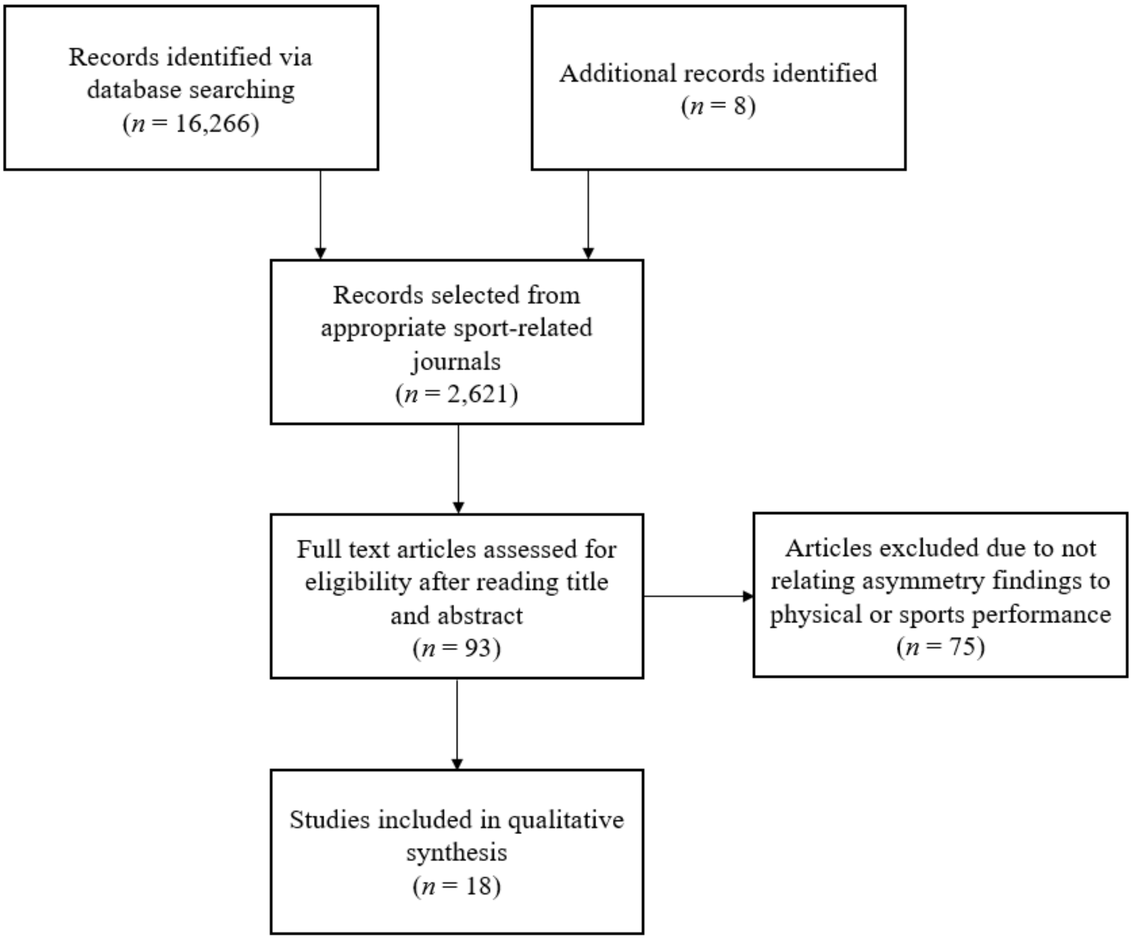


Figure 5.1. Flow diagram showing the identification and selection of studies in the available body of literature for the current review.

5.2.2 Grading Article Quality

A quality review was conducted in line with previous suggestions (Black et al. 2016). Each study was appraised using nine criteria (Table 5.1) and a scale of 0-2 (where zero equates to 'no', one equates to 'maybe' and two equates to 'yes'). The third criteria pertaining to the intervention being described was modified to 'procedures described' because none of the asymmetry studies identified in the final analysis included training interventions.

Therefore, due to the nature of studies associated with the topic of inter-limb asymmetries and their relationship with physical or sports performance, only correlational studies were deemed relevant and specific to the title and thus, included in the subsequent analysis. Total scores for each study were then converted to a percentage ranging from 0-100% (Tables 5.2-5.5). To be sure of an appropriate level of quality, only articles that scored > 75% were considered for the final analysis.

Table 5.1. Study quality scoring system (adapted from Black et al. 2016).

Criteria No.	**Item**	**Score**
1	Inclusion criteria stated	0-2
2	Subjects assigned appropriately	0-2
3	Procedures described	0-2
4	Dependent variables defined	0-2
5	Assessments practical	0-2
6	Training duration practical (acute vs. long term)	0-2
7	Statistics appropriate	0-2
8	Results detailed (mean, standard deviation, percent change, effect size)	0-2
9	Conclusions insightful (clear, practical application, future directions)	0-2
Total		0-18

Table 5.2. Summary of study methods that have highlighted an asymmetry in strength and the effects on physical performance.

Reference	Subjects	Asymmetry Tests / Metrics Measured	Performance Outcome Measures	Quality Score
Bailey et al. (2013)	College athletes (*n* = 36)	IMTP (PF symmetry index calculated on twin force plates)	SJ, SJ20, CMJ, CMJ20 (jump height and peak power)	83%
Hart et al. (2014)	Australian footballers (*n* = 31)	Isometric Squat (bilateral and unilateral)	10 drop punk kicks to a 20m target	100%
Rannama et al. (2015)	Competitive road cyclists (*n* = 16)	Isokinetic peak torque at 60, 180 and 240°·sec^{-1} Kinematic asymmetries also measured whilst pedalling (ankle, knee, hip, trunk, pelvis)	10-second isokinetic maximum power test (average power taken from 1-6 seconds for data analysis)	94%

IMTP = isometric mid-thigh pull, PF = peak force, SJ = squat jump, SJ20 = squat jump with 20Kg load, CMJ = countermovement jump, CMJ20 = countermovement jump with 20Kg load.

Table 5.3. Summary of study methods that have highlighted an asymmetry in jumping and the effects on physical performance.

Reference	Subjects	Asymmetry Tests / Metrics Measured	Performance Outcome Measures	Quality Score
Lockie et al. (2014)	Team sport athletes (*n* = 30)	SLCMJ, SL Broad Jump, SL Lateral Jump (jump height or distance)	20m (including 5 and 10m splits), left and right-turn 505, modified t-test	94%
Hoffman et al. (2007)	NCAA D3 football players (*n* = 62)	SLCMJ (power derived from force plate)	L-Run (performed in both directions to facilitate D and ND change of directions)	83%
Maloney et al. (2017)	Healthy adults (*n* = 18)	SLDJ (stiffness and jump height)	90° cutting task (on force plate)	100%

SL = single leg, SLCMJ = single leg countermovement jump, H = horizontal, DJ = drop jump, 3J = 3 jump test, NCAA = National Collegiate Athletic Association, D = dominant, ND = non-dominant.

Table 5.4. Summary of study methods that have highlighted an asymmetry in sport-specific actions and the effects on sporting performance.

Reference	Subjects	Asymmetry Tests / Metrics Measured	Performance Outcome Measures	Quality Score
Bini and Hume, (2015)	Cyclists and/or triathletes (*n* = 10)	Bilateral pedal forces measured via 'strain gauge' instrumented pedals	4km cycling time trial	83%
Liu and Jensen, (2012)	12 young children (age: 5-7) 12 older children (age: 8-10) 12 adults (age: 24-30)	5 x 15s cycling trials at 40, 60, 80, 100 and 120rpm (average angular velocity of crank) Metronome provided rhythmic feedback on cadence	Root mean square error (indication of how closely each subject matched a specified cycling cadence)	100%
Dos Santos et al. (2013)	Trained male swimmers (*n* = 18), split into fast (*n* = 9) and slow (*n* = 9) groups	2-minute tethered swim with 6 strokes (3 each side) analysed at 5-15, 55-65 and 110-120s (PF, MF, Impulse and RFD)	Best 200m front crawl time	100%
Morouço et al. (2015)	'High level' male swimmers (*n* = 18)	30s maximum effort tethered swim (PF, MF)	Best 50m front crawl time	94%
Barbieri et al. (2015)	Brazilian amateur futsal players	Metrics: kicking accuracy, foot and ball velocity	5 kicks of a rolling and stationary ball	89%

	(*n* = 10)			
Vieira et al. (2016)	Professional futsal players (*n* = 17)	Asymmetry test: Isokinetic dynamometry for knee extensors and flexors (60, 180, 300°·sec^{-1}) Metrics: accuracy, foot and ball velocity, linear velocity of ankle, knee and hip joints	Penalty kicks taken from the 2nd penalty mark	89%
Spratford et al. (2009)	Elite male goalkeepers (*n* = 6)	CoM velocity, ankle flexion, knee flexion, hip flexion, pelvis rotation, thorax rotation	3 dives per side at heights of 0.3, 0.9 and 1.5m high to a hanging ball	83%

PF = peak force, MF = mean force, RFD = rate of force development, CoM = centre of mass.

Table 5.5. Summary of study methods that have highlighted an asymmetry in dynamic balance, anthropometry, and sprinting and the effects on physical performance.

Reference	Subjects	Asymmetry Tests / Metrics Measured	Performance Outcome Measures	Quality Score
Gonzalo-Skok et al. (2015)	Elite youth basketball players (*n* = 15)	WBL (dorsiflexion) SBET	CMJ, SLCMJ, SL Hop, 25m, V-Cut and 180° CODS tests	94%
Bell et al. (2014)	NCAA athletes (*n* = 167)	DEXA, CMJ (peak force, peak power)	CMJ (jump height)	100%
Trivers et al. (2014)	Elite Jamaican track and field athletes (*n* = 73)	Knee and ankle joint width + foot length	Best performance times for each athlete's respective events (specified by 100m, > 100m events, hurdles/jumps)	100%
Meyers et al. (2017)	Male school children (aged 11-16)	Step length, step frequency, contact time, flight time, relative maximal force, relative vertical stiffness, relative leg stiffness	35m sprint time	100%
Exell et al. (2016)	Sprint trained athletes (*n* = 8)	Step velocity, step length, step frequency, minimum hip height, maximum knee lift, minimum knee angle, maximum hip extension,	Mean velocity (m/s)	100%

	touchdown distance, net horizontal and vertical impulse, maximum vertical force, mean support moment, net ankle/knee/hip work	

CMJ = countermovement jump, vGRF = vertical ground reaction force, WBL = weight bearing lunge test, SBET = star balance excursion test, SL = single leg, DEXA = dual energy x-ray absorptiometry.

5.3 Results

A total of 16,274 articles were initially returned, with each search's results further streamlined by way of journal relevance (a function that can be processed in Medline and SPORT Discus). Articles from any sport related journal were included in the initial filtering process and resulted in a total of 2,621 articles. The number of articles initially returned (and then filtered by journal relevance) is described for each search term below where the reported numbers represent the following: (Database = *n* [*n* by sport related journals]). 'Asymmetries and performance' (Medline = 6485 [264]; SPORT Discus = 652 [299]), 'asymmetries and strength' (Medline = 2586 [208]; SPORT Discus = 421 [289]), 'asymmetries and jumping' (Medline = 75 [29]; SPORT Discus = 78 [65]), 'asymmetries and speed' (Medline = 1573 [181]; SPORT Discus = 320 [210]), 'asymmetries and changing direction' (Medline = 24 [4]; SPORT Discus = 2 [2]), 'asymmetries and balance' (Medline = 1686 [170]; SPORT Discus = 197 [124]), 'asymmetries and running' (Medline = 585 [61]; SPORT Discus = 131 [87]), 'asymmetries and sport' (Medline = 433 [200]; SPORT Discus = 1018 [428]). The title and abstracts from these results subsequently identified 93 full text articles for consideration. Of the 18 articles included in the final analysis (see Tables 5.2-5.5 for details on study methodologies), 3 of these studies focused on asymmetries in strength, 3 examined asymmetries during jumping-based tasks, 7 during sporting actions, and 5 related asymmetries in dynamic balance, anthropometry, and sprinting to physical performance.

Furthermore, a wide range of performance outcome measures were employed to demonstrate the effects of inter-limb asymmetries on physical or sports performance (see Tables 5.2-5.5). It should be noted that multiple outcome measures are often tested in any one study; thus, some studies are counted more than once in the proceeding statistics. Categories of tests and the number of studies relating to each included: sprinting (5), jumping (4), change of direction speed (4), cycling (3), kicking based tasks (3), swimming (2), and 1 each specific to different track and field events and goalkeepers in soccer.

5.4 Discussion

The aim of this systematic review was to evaluate the available literature pertaining to inter-limb asymmetries and critically evaluate their association with measures of physical and sport performance. Inter-limb differences in strength, dynamic balance, and anthropometry appear to have a detrimental association with physical performance, whilst the evidence pertaining to jumping-based tasks is less conclusive. Mixed findings were also noted during sport-specific actions indicating that the effects of inter-limb asymmetry on sports performance may be task-specific.

5.4.1 Asymmetries during Strength Tasks

Bailey et al. (2013) reported mean asymmetries during the IMTP of 6.6 ± 5.1%, and moderate negative correlations between the peak force symmetry index and jump height (r = -0.39 to -0.52; $p < 0.01$) and peak power (r = -0.28 to -0.43; $p < 0.05$) during loaded and unloaded jumps. Whilst a large amount of variance remains unexplained, these data provide an indication that bilateral vGRF asymmetries of a greater magnitude may contribute to reduced vertical jump performance.

Asymmetries in strength have also been shown to have a detrimental effect on the performance of sport-specific skills including kicking and cycling. Hart et al. (2014) reported that larger asymmetries had a negative effect on kicking accuracy in Australian Rules football players. Athletes were required to kick a ball to an opposing player stood 20 m away with accuracy defined as the receiving player remaining stationary, or within an arm’s reach with only one step permitted during the catch. Any deviation from these criteria resulted in the kicker being categorised as 'inaccurate'. Peak force imbalance was measured via the unilateral isometric squat test, with the more accurate group of kickers demonstrating -1% difference between limbs (the minus sign indicating the support limb was stronger); whereas, the less accurate group showed inter-limb differences of 8% ($p < 0.05$). The stronger limb in the accurate group was the stance limb, which may indicate that a more stable athlete is able to perform unilateral, technical tasks with a greater degree of accuracy, although further research is warranted to fully corroborate this theory.

Finally, Rannama et al. (2015) measured peak torque asymmetries of the knee extensors (at $180°\cdot sec^{-1}$) in a group of competitive cyclists, which were negatively correlated ($r = -0.50$; $p < 0.05$) with power output during a 5-second maximal effort cycling test (Rannama et al. 2015). Trunk and pelvis kinematic asymmetries were also negatively correlated ($r = -0.65$ and -0.63 respectively; $p < 0.01$) with power, indicating that imbalances in quadriceps strength and trunk/pelvis joint angles may have a detrimental effect on power during maximal effort cycling. Cumulatively, it would appear that there is a negative relationship between inter-limb asymmetries in strength and jumping, kicking and sprint cycling performance. Further research should aim to quantify how much variance in 'loss of performance' can specifically be attributed to inter-limb asymmetries in strength.

5.4.2 Asymmetries during Jumping Tasks

Conflicting findings were shown in studies measuring the association between inter-limb asymmetries from jumping-based tasks and performance outcomes. Lockie et al. (2014) reported varying asymmetry scores for three different jump tests, highlighting the task-specific nature of physical performance tests. All jumps were performed unilaterally with inter-limb differences reported for CMJ height (10.4%), broad jump (3.3%), and lateral jump distances (5.1%). No significant correlations were found between asymmetry scores on any of the jumping tasks and sprint (*r* range = -0.004 to -0.176) or CODS tests (*r* range = < 0.001 to 0.189), indicating that inter-limb differences of such low magnitudes in these jump tests do not negatively impact sprint or COD performance.

Research from Hoffman et al. (2007) also showed no significant differences in the time to perform an L-run to the dominant or non-dominant side, in spite of a 9.7% peak power asymmetry between limbs during a SLCMJ. This was combined with weak correlations between the SLCMJ ND limb and the L-run for both D ($r = -0.36$; $p < 0.05$) and ND ($r = -0.37$; $p < 0.05$) directions. No significant relationships were shown when compared with the dominant limb of the SLCMJ. This may be due to the complexity of CODS tasks that require high levels of skill and are underpinned by multiple physical qualities (Sheppard and Young, 2006).

Maloney et al. (2017) examined the relationship between asymmetries measured during the SLDJ and a 90° cutting task. The sample was subsequently divided into fast and slow groups, with mean vertical stiffness and jump height asymmetry explaining 63% of the variance in performance during the cutting task ($r^2 = 0.63$; $p = 0.001$). Additionally, faster athletes portrayed significantly lower asymmetries for jump height ($p = 0.026$), but no other DJ asymmetry variables were statistically significant. These results indicate that minimising jump height asymmetry during the single leg DJ test could be advantageous to enhance cutting performance. Inter-limb asymmetries were also calculated for left and right total time during the CODS test, although no significant differences were noted. This is in line with more recent literature which suggests that total time during CODS tasks are not particularly sensitive at detecting side-to-side differences (Dos'Santos et al. 2019b; Madruga-Parera et al. 2019). In addition, it is worth noting that Maloney et al. (2017) used the 'median split' technique when reporting results, whereas Hoffman et al. (2007) and Lockie et al. (2014) did not utilise the same process which may account for some of the variation seen in the results. Such analysis enables practitioners to determine whether meaningful differences in performance exist between those with larger or smaller imbalances, and can be used to justify whether targeted training interventions might be warranted for individual athletes.

5.4.3 Sport-Specific Asymmetries

Bini and Hume, (2015) reported large inter-limb asymmetries for the resultant force (11-21%; $p < 0.01$) and effective force (36-54%; $p < 0.01$) in 10 competitive cyclists, with the latter being described as the angular impulse of the tangential force on the crank. A strong correlation ($r = -0.72$) was reported between asymmetries and effective force, whilst no association was observed for resultant force. These findings indicate that cyclists who displayed larger asymmetries in effective force may actually perform faster during a 4-km time trial. Individual asymmetries for pedal force varied across the sample, although no reason was identified as to why larger asymmetries corresponded to enhanced cycling performance (Bini and Hume, 2015). These results are unexpected as intuitively, larger asymmetries might be expected to be associated with reduced performance. However, this may not be as important in a sport such as cycling where total power output is likely to result in superior performance.

Liu and Jensen, (2012) calculated cycling asymmetries by comparing the average angular velocity of a cycle ergometer's crank at 90° and 270° for the right and left limb's respectively. Asymmetries were significantly lower for adults compared to older children ($p < 0.01$), with younger children showing significantly greater between-limb differences than both groups ($p < 0.01$). In addition, there were significant positive correlations between asymmetries and the root mean square error (ability to match speed to a specified cadence), indicating that as inter-limb differences increased, cycling performance decreased at every cadence (40 revolutions per minute [rpm]: $r = 0.53$; 60 rpm: $r = 0.56$; 80 rpm: $r = 0.56$; 100 rpm: $r = 0.40$ and 120 rpm: $r = 0.72$). In addition, asymmetries decreased as cadence increased, suggesting that slower speeds may require greater control with a more natural, cyclical motion favouring a faster cadence (Liu and Jensen, 2012).

Conflicting findings regarding the effects of asymmetry on swimming performance have also been reported. Dos Santos et al. (2013) analysed asymmetries during front crawl tethered (stationary) swimming reporting inter-limb differences for peak and mean force at different time points (beginning: 5-15s; middle: 55-65s; end: 110-120s) during a 2-minute swim. Furthermore, subjects were sub-divided into the fast and slow groups ($n = 9$ per group) based on their respective best 200 m times, with the faster group demonstrating significantly lower peak force (13.32 vs. 18.28%; $p = 0.017$) and mean force (7.01 vs. 10.08%; $p = 0.04$) asymmetries (Dos Santos et al. 2013). This perhaps indicates that heightened inter-limb differences in force production may be detrimental to swimming performance, with a median split technique again used to report the results. In contrast, Morouço et al. (2015) analysed elite level swimmers using a maximum effort 30-second tethered swim, also dividing the sample into fast and slow groups based on their best 50 m front crawl time. A mean asymmetry index of 19% (range = 3.3-48.5%) was reported and two-thirds of the sample showed asymmetries > 10%. When performance times were compared between groups, no difference in asymmetry was reported, with the authors concluding that inter-limb asymmetries do not negatively affect short-performance sprint swimming (Morouço et al. 2015). Interestingly, the conflicting findings between the two studies could be explained by the fact that regardless of swim time, the majority of swimmers in the Dos Santos et al. (2013) study exhibited inter-limb differences > 10%. Thus, asymmetry may not have been a decisive factor in deciding the performance outcome for this sample.

More definitive results have been reported for the sport of futsal in professional and amateur populations. Barbieri et al. (2015) analysed asymmetries during different kicking actions using both the dominant and non-dominant limbs. Significant differences in ball velocity ($p = 0.001$) and kicking accuracy ($p = 0.003$) were shown between limbs for both stationary and 'rolling ball' kicks, with larger asymmetries present in kicking accuracy (28-40%) than ball velocity (10-11%). Unsurprisingly, the rolling condition increased task complexity, highlighting substantially larger asymmetries. Vieira et al. (2016) also analysed kicking accuracy and ball velocity in addition to velocity for the ankle, knee, and hip joints in professional players. Supplementary isokinetic testing also identified significant differences ($p < 0.05$) in mean power at $180°\cdot sec^{-1}$, resulting in significantly higher ankle and ball velocities for the dominant limb. It is not surprising that the non-dominant limb demonstrates reduced kicking performance; however, it provides an impression that minimising asymmetries may be beneficial for equalising ball speed on both limbs. What is perhaps more applicable in this instance, is to suggest that players practice shooting using both limbs so that kicking accuracy can be enhanced on the non-dominant side. Kicking is most likely more reliant on skill execution than physical measures of performance such as strength and power; thus, there is no guarantee that reduced inter-limb asymmetries will automatically transfer to improved ball accuracy or velocity.

The effects of asymmetry on measures of goalkeeping performance have also been examined (Spratford et al. 2009). Test set up involved the placement of different footballs at 0.3, 0.9, and 1.5 m in height on both the preferred and non-preferred diving side for six elite goalkeepers. Subsequent analysis split the dive into three phases: initiation, take-off and ball contact which saw significant differences in various kinematic variables such as pelvis and thorax rotation between sides. The most notable outcome was that the non-preferred side experienced less hip extension at take-off and thus, the centre of mass travelled slower and less directly to the ball. It is unclear whether this reduced hip extension on the non-preferred side is a product of lower force or power production capabilities. However, it is in the interest of coaches to understand that a goalkeeper likely requires greater practice diving to their non-preferred side, which may be aided by the reduction of kinetic and kinematic asymmetries.

5.4.4 Asymmetries during Dynamic Balance, Anthropometry, and Sprinting Tasks

5.4.4.1 Dynamic Balance

Dynamic balance refers to "the ability to move and change directions under various conditions without falling" (Clark et al. 2012). Gonzalo-Skok et al. (2015) used the Y-Balance test to assess dynamic balance in young elite basketball players from a Spanish Division 1 academy. Composite score asymmetries in addition to those observed in the anterior and postero-medial directions were negatively correlated (r = -0.52 to -0.77; p < 0.05) with CMJ height; a key measure of basketball performance (Fort Vanmeerhaeghe et al. 2016; Read et al. 2014). In addition, dorsiflexion asymmetries (measured during a weight bearing lunge test) were negatively correlated (r = -0.52; p < 0.05) with a CODS test involving a 180° turn. Thus, there may be some association between asymmetries in dynamic balance and jump performance with further evidence suggesting that imbalances in ankle range of motion may also negatively affect CODS. It is plausible that more stable athletes (by virtue of better balance ability) should be able to exert a more even distribution of force during a jumping action. Similarly, the importance of optimal ankle dorsi-flexion should not be understated during CODS tasks. The action of changing direction requires some element of braking force prior to reapplying force in the desired directional change. Such kinetic forces are suggested to be accompanied by loading through the lower limb joints (flexion of the ankle, knee and hip) in order to successfully 'brake'. Reduced ankle dorsiflexion is almost certain to have a detrimental knock-on effect further up the kinetic chain; namely, unwanted movement patterns such as knee valgus become a much bigger risk which has been previously reported (Malliaras et al. 2006). Therefore, it would appear that the reduction of inter-limb differences in dynamic balance and ankle range of motion, may be associated with enhanced jumping and CODS performance.

5.4.4.2 Anthropometry

Further research has also linked asymmetries in lean mass to jumping performance. Bell et al. (2014) reported that thigh and shank lean mass asymmetry accounted for 20% of the variance in propulsive force asymmetry, and lean mass asymmetry of the pelvis, thigh, and shank accounted for 25% of power asymmetries, during a CMJ. Whilst a large amount of variance remains unexplained by these data, it was also reported that asymmetries in power > 10% during the CMJ resulted in decreased jump height of 9 cm ($d > 0.8$). Thus, inter-limb differences in lean mass may be partially responsible for force and power asymmetries and when the effects on jump height are considered, may act as a potential limitation to optimising jump performance.

Trivers et al. (2014) assessed anthropometric symmetry in elite Jamaican track and field athletes. Knee and ankle width asymmetries were reported to be 10.37 and 4.55%, respectively ($p < 0.05$); with regression analysis showing that asymmetries explained 5% of the variation in performance. These data indicate that lower limb symmetry in the ankle and knee joints has a limited effect on the performance of elite track and field athletes. However, the authors reported that a trend was evident for more symmetrical athletes to run faster during the 100 m, although this was not supported from a statistical significance standpoint. Whilst joint symmetry is likely to be somewhat dictated by athlete genetics, it is feasible that this may offer coaches some useful information pertaining to ‘talent identification' of track and field athletes, although more studies would be required to corroborate this suggestion, and greater emphasis should be placed on modifiable outcomes.

5.4.4.3 Sprinting

Recent data have examined asymmetries during maximal sprinting tasks in youth athletes (Meyers et al. 2017). In a sample of 344 school aged boys (age: 11-16), multiple asymmetry metrics were reported inclusive of step length, step frequency, contact time, flight time, relative maximum force, and relative vertical/leg stiffness. Mean asymmetries across all age groups and metrics were 2.3-12.6% and weak relationships were shown between the variety of asymmetry metrics (step frequency, step length, flight time, and vertical stiffness) and sprint velocity (r = -0.24 to 0.39; $p < 0.05$). These weak relationships may indicate that sprint speed is unlikely to be detrimentally affected, even when inter-limb differences are as high as ~12% in a healthy, youth population. However, it should be considered that no specific details were provided on the sporting backgrounds of the participants; only that they took part in 2 x 60-minute physical education classes as part of a school curriculum (Meyers et al. 2017). Consequently, any conclusions drawn from this study cannot be inferred to a homogenous, sporting sample of an equivalent or older age.

Similar results have been noted in adult sprint-trained athletes (Exell et al. 2016); where subjects were required to maximally sprint five trials of 60 m. Multiple kinetic and kinematic variables were reported (see Table 5.5) in respect to inter-limb asymmetries with results correlated to mean sprint velocity. Group mean data reported no significant relationships between kinetic asymmetry, kinematic asymmetry and mean sprint velocity. However, when each individual athlete's asymmetry profile was calculated, significant inter-limb differences were noted across a range of kinetic and kinematics variables. All kinematic asymmetry values were < 10%, step characteristics (step velocity, length and frequency) were all < 2%, whilst kinetic asymmetries were substantially larger, ranging from 0.1-93.2% (Exell et al. 2016). Despite these results further highlighting how task-specific inter-limb asymmetries can be, it is interesting to note that large kinetic asymmetries do not appear to be detrimental to mean sprint velocity in sprint-trained athletes.

5.5 Directions for Future Research

Further research is required in a wide range of populations to more clearly determine if detrimental effects are shown in a variety of physical and sporting tasks to examine if thresholds exist that are related to performance decrements. Also, the aforementioned studies have focused on the measurement of asymmetry at a single time point; thus, to the authors' knowledge, no data are available pertaining to longitudinal changes in asymmetry and their associations with measures of physical performance. So far, studies have focused on how inter-limb asymmetries change after a 6-8 week training intervention (Brown et al. 2017; Gonzalo-Skok et al. 2017; Bazyler et al. 2014; Sannicandro et al. 2014). Training methods have taken an integrated approach to correcting inter-limb differences with bilateral and unilateral strength, balance and core training all being used to effectively reduce asymmetries. However, no study to date has reported how asymmetries change over a longer time period, such as an entire season for team-sport athletes. Fitness testing often occurs at multiple time points throughout a year for team sport athletes (pre, mid, and end of season are common) and it should not be assumed that asymmetries reported during pre-season would be the same during mid or end of season. Thus, information relating to potential changes over the course of a season may subsequently impact programming for athletes. Therefore, when assessing the effects of asymmetry on performance, measured changes over a longitudinal period should be included. In addition, where statistical analysis is concerned, authors should consider how ‘changes in asymmetry’ correspond to ‘changes in athletic performance’. This would provide an indication as to whether or not asymmetries are a concept that requires attention from a ‘performance reduction’ perspective or simply a by-product of playing sport over time (Hart et al. 2016).

A higher frequency of injuries are also commonly reported during the latter stages of matches for team sport athletes (Ekstrand et al. 2011; Price et al. 2004). Thus, quantifying how asymmetries respond to match-play or in a fatigued state, may further our understanding of the mechanisms of injury and performance loss during these crucial periods. To date, limited information exists examining the effects of fatigue on inter-limb asymmetries. Radzak et al. (2017) measured kinetic and kinematic asymmetries during gait in both rested and fatigued states. Fatigue was determined when rate of perceived exertion was reported ≥ 17. Subjects were then provided with a 3-minute active recovery before treadmill speed was increased to a velocity that was predicted to elicit 80% VO_{2max}. Small reductions (1-6%) in vertical stiffness and loading rate were reported whilst increases in knee internal rotation (14%) and knee stiffness (5.3%) were also noted in the fatigued state, with the authors noting that knee joint asymmetries in particular appeared to increase in a fatigued state (Radzak et al. 2017).

Hodges et al. (2011) used 17 healthy recreational adults to perform 5 sets of 8 repetitions during a back squat exercise at 90% of their previously determined 8RM. Bilateral vGRF asymmetries were calculated form twin force plates with inter-limb differences quantified for repetitions 1-2 and 7-8 within each set. Interestingly, average inter-limb asymmetries across all 5 sets was reported to be 4.3 ± 2.5% for repetitions 1-2 and 3.6 ± 2.3% for repetitions 7-8, representing no significant differences although it is interesting to note that asymmetries actually reduced as more repetitions were performed.

However, it should be acknowledged that fatigue was merely inferred from the chosen protocol, but unlikely to have taken any effect within the selected set parameters. Rather, and in line with previously reported studies using jump testing in soccer, practitioners may wish to quantify changes in asymmetry after a fatiguing protocol or competitive match-play. At present, there is a distinct lack of data pertaining to the presence of asymmetries under conditions of fatigue and their impact on sports performance; thus, warranting further investigation.

A final point to consider relates to the quantification of between-limb differences in asymmetric sports. As an example, the sport of Fencing is characterised by repeated bouts of attack by virtue of the 'Fencing lunge'. Athletes often experience large eccentric forces from the front limb (as it absorbs force from the lunging action) and higher propulsive forces from the rear limb during the 'push-off' action of the lunge (Turner et al. 2013). The nature of the sport dictates that Fencers will always compete with the same lead limb; thus, inter-limb asymmetries are likely to be present. However, to the authors' knowledge, no studies have aimed to quantify inter-limb asymmetries in such athletes and future research should look to report this information and assess its impact on sporting performance. In addition, a comparison between team sport athletes (where unilateral movement patterns occur, but may not necessarily be considered as 'asymmetric sports') would also further our understanding on this topic.

5.6 Conclusion

The cumulative body of literature indicates there is a high prevalence of asymmetry across a range of physical qualities and that inter-limb differences measured across a range of tasks have a negative association with physical and sport performance; however, findings are not always consistent. Asymmetries in strength would seem to negatively affect performance tasks including CODS, jumping, and sport-specific skills such as kicking accuracy; thus, minimising these differences would appear favourable. For jumping-based asymmetries, the evidence is less conclusive. Single leg vertical and horizontal jumps have shown suitable sensitivity in detecting asymmetries; however, associations with CODS performance are varied. In contrast, asymmetries during single leg tests of reactive strength have shown stronger relationships with reductions in CODS performance, whereby faster performers displayed smaller inter-limb asymmetries. Inconsistencies are also apparent during sport-specific actions, most notably in cycling and swimming. Additional asymmetry studies pertaining to dynamic balance, anthropometry, and sprinting have also shown mixed results, although there is currently a paucity of data using these measures. The findings of this systematic review emphasise the complexity of asymmetries and their relationships with measures of physical and sports performance; highlighting the need for further research.

CHAPTER 6: STUDY 1

6.0 Using unilateral strength, power and reactive strength tests to detect the magnitude and direction of asymmetry: A test-retest design.

6.1 Introduction

Inter-limb asymmetry refers to differences in the performance or function of one limb with respect to the other (Bishop et al. 2016; Keeley et al. 2011). Strength and jumping-based tests are often used to quantify these differences when assessing the physical characteristics of athletes (Bell et al. 2014; Ceroni et al. 2012; Newton et al. 2006), largely because these are considered fundamental physical qualities to enhance athletic performance. Strength testing methods to quantify asymmetry have included the back squat (Newton et al. 2006; Sato and Heise, 2012), isometric squat and IMTP (Dos'Santos et al. 2017a; Hart et al. 2012) or isokinetic dynamometry (Costa Silva et al. 2015; Ruas et al. 2015). Jump tests such as CMJ (Bell et al. 2014; Bishop et al. 2019a; Meylan et al. 2009) and DJ (Bishop et al. 2019b; Maloney et al. 2016; Maloney et al. 2017) are also commonly assessed to quantify asymmetry, most likely because of their similarity to sport-specific movement patterns, ease of implementation, and time-efficient nature.

When asymmetry is considered, more affordable versions of force platforms are available compared to 10-15 years ago; thus, assessments of between-limb differences using force-time diagnostics are now a practically viable option for a wide range of athletes (Bishop et al. 2017b; Lake et al. 2018b; Read et al. 2016). For example, when considering jump tests, previous research has highlighted the importance of additional metrics beyond jump height such as peak/mean force and propulsive/braking impulse (Cormack et al. 2008; Gathercole et al. 2015a; Young et al. 2011), because they allow some interpretation of jump strategy rather than outcome measures alone. However, limited literature exists in this capacity with respect to asymmetry; therefore, a more in-depth examination of unilateral tests which can be used to quantify inter-limb differences over more than a single test session is warranted (Bishop et al. 2017b; Read et al. 2016).

Regardless of the test selected, another consideration for asymmetry is how the data are reported. Typically, testing protocols encourage 2-3 trials (Turner et al. 2015), with some studies quantifying asymmetry from the best trial (Hart et al. 2012; Lockie et al. 2014) and others from the average of all trials performed (Bell et al. 2014; Maloney et al. 2017). To the authors' knowledge, no study has directly compared asymmetry scores when calculating the percentage difference between limbs from the best score and an average of all test trials. Given previous literature has shown the variable nature of asymmetry (Bishop et al. 2018c; Dos'Santos et al. 2017a; Maloney et al. 2016), it is plausible that these methods would result in notable differences in the magnitude of asymmetry. Thus, examining whether significant differences exist between test sessions and calculation methods (best versus average) would provide practitioners with meaningful information as to which method might be favorable for continued inter-limb asymmetry profiling.

Literature on this topic has also highlighted the importance of monitoring the 'direction of asymmetry' (Impellizzeri et al. 2007; Maloney 2018), and refers to the limb that produces the larger score (i.e., which limb may be dominant). Recent literature has shown that the direction of asymmetry may be just as variable as the magnitude (Bishop et al. 2018b; Dos'Santos et al. 2017b; Lake et al. 2018a). Bishop et al. (2018b) used the unilateral isometric squat, unilateral CMJ and unilateral broad jumps, to detect how consistently peak force and impulse favoured the same limb across tests using the Kappa coefficient statistic. With the exception of propulsive impulse, levels of agreement between the different jumps ranged from poor to fair (Kappa range = -0.34 to 0.32), indicating that the direction of asymmetry varied substantially between tests. Whilst useful, the aforementioned study reported the direction of asymmetry for a single test session only. Thus, further information regarding how consistent the direction of asymmetry is across more than a single test session is again, warranted.

Cumulatively, the available evidence indicates that further research is required to examine a broader range of metrics during unilateral tasks, determine if the best versus average asymmetry score is more reliable for test re-test comparison and, determine if there is consistency in the direction of asymmetry between sessions. Therefore, the aims of the present study were threefold: 1) to determine the test-retest reliability of unilateral strength and jumping-based tests that can be used to quantify asymmetries, 2) determine whether any significant differences exist for asymmetry between test sessions when calculating differences from the best trial and an average of all trials and, 3) determine how consistently asymmetries favour the same side between tests sessions.

6.2 Methods

6.2.1 Experimental Design

This study used a test-retest design enabling both within and between-session data to be quantified for three unilateral tests: the isometric squat, CMJ and DJ. Asymmetries were calculated from the best trial and as an average of all trials and test reliability computed thereafter. Systematic bias was quantified between test sessions to determine any significant changes in test scores and asymmetry values. Finally, Kappa Coefficients were used to determine the levels of agreement for the direction of asymmetry (Bishop et al. 2018b), showing whether the same limb scored higher between test sessions.

6.2.2 Participants

Twenty-eight recreational team sport athletes (age = 27.29 ± 4.6 years; mass = 80.72 ± 9.26 kg; height = 1.81 ± 0.06 m) volunteered to take part in this study. A minimum of 27 participants were determined from a priori power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) implementing statistical power of 0.8, a type 1 alpha level of 0.05 and a moderate ES of 0.5, which has been used in comparable literature (Dos'Santos et al. 2017b). Inclusion criteria required all participants to have a minimum of two year's resistance training experience, with any participant excluded from the study if they had experienced a lower body injury at the time of testing or in the preceding three months. Participants were required to provide written informed consent prior to commencement to demonstrate that they were willing and able to undertake all testing protocols. Ethical approval was granted from the London Sports Institute Research and Ethics committee at Middlesex University.

6.2.3 Procedures

Participants visited the laboratory three times: one for test familiarization and then for two data collection sessions. During both data collection sessions, participants performed three trials on each limb for the three unilateral tests on a single force platform (PASPORT force plate, PASCO Scientific, California, USA) sampling at 1000 Hz. Test order was randomized so as to minimize potential order effects and fatigue impacting one specific test. Seventy-two hours prior to data collection, a familiarization session was conducted, so as to reduce any potential learning effects during data collection sessions. Participants were provided with the relevant test instructions and the opportunity to practice each assessment until they reached a satisfactory level of technical competence, which was monitored throughout by an accredited strength and conditioning coach. A standardized dynamic warm up was conducted prior to each session consisting of dynamic stretches for the lower body (e.g., forward lunges, inchworms, lateral lunges, spidermans and bodyweight squats), in addition to three practice trials at approximately 60, 80, and 100% of perceived maximal effort for all tests. Three minutes of rest was provided after the final warm up trial before undertaking the first test and test sessions were separated by a minimum of 72 hours.

6.2.3.1 Unilateral Isometric Squat.

A custom built 'ISO rig' (Absolute Performance, Cardiff, UK) was used for this test protocol (Figures 6.1 and 6.2). Firstly, participants were instructed to step on to the centre of the force plate with their foot pointing forward. A goniometer was used to measure 140° of hip and knee flexion (Bishop et al. 2017b; Hart et al. 2012) for each participant, with full extension of the knee joint equalling 180°. The fulcrum of the goniometer was positioned on the lateral epicondyle of the femur. The stabilisation arm was lined up along the line of the fibula (in the direction of the lateral malleolus) and the movement arm was lined up with the femur (pointing towards the greater trochanter at the hip). The non-stance limb was required to hover next to the working limb, so as to try and keep the hips level during the isometric squat action; thus, aiding balance and stability. Once in position, participants were required to remain motionless for two seconds, without applying any upwards force (which was verified by manual detection of the force-time curve in real time). Each trial was then initiated by a "3, 2, 1, Go" countdown and participants were instructed to try and extend their knees and hips by driving up as "fast and hard as possible" (Dos'Santos et al. 2017a; Maffiuletti et al. 2016) against the bar for five seconds. Recorded metrics for each trial included peak force, RFD at 0.3s and impulse at 0.3s, which was chosen as the specified epoch for RFD and impulse based on comparable research using the unilateral isometric squats (Hart et al. 2012) and IMTP (Dos'Santos et al. 2017a). The first meaningful change in force was established when values surpassed ± five standard deviations (SD) of each participant's body mass, minus 30 milliseconds (Owen et al. 2014). Peak force was defined as the maximum force generated during the test. RFD was defined as the change in force divided by the change in time (0.3 s) (Maffiuletti et al. 2016) and impulse was defined as the net force multiplied by the time taken to produce it at 0.3 s; i.e., the area under the net force-time curve (Dos'Santos et al. 2017a).

Figures 6.1 and 6.2. Example positioning for the unilateral isometric squat protocol.

6.2.3.2 Unilateral Countermovement Jump.

Participants were instructed to step onto the centre of the force plate (foot pointing forward) with their designated test leg with hands placed on hips, which were required to remain in the same position for the duration of the test. Due to the portable nature of the force platform, weight plates were positioned on the ground, touching each side of the force platform to ensure no movement occurred throughout testing. The jump was initiated by performing a countermovement to a self-selected depth before accelerating vertically as fast as possible into the air. Specific test instructions were to "jump as high as you can". The test leg was required to remain fully extended throughout the flight phase of the jump before landing back onto the force plate as per the set up. The non-jumping leg was slightly flexed with the foot hovering at mid-shin level, and no additional swinging of this leg was allowed during trials. Each trial was separated by 60 seconds of rest. Recorded metrics included jump height, peak propulsive force and concentric impulse, with definitions for their quantification conducted in line with suggestions by Gathercole et al. (2015a), Chavda et al. (2018) and McMahon et al. (2018). Jump height was defined as the maximum height achieved calculated from the impulse-momentum method. Specifically, this was calculated as velocity at take-off squared divided by 2*9.81 ($Tov^2/2g$). Net peak force was defined as the maximum force output during the propulsive phase of the jump prior to take-off (Chavda et al. 2018). Concentric impulse was defined as the integral of force between the moment the system reached zero velocity until take-off (Chavda et al. 2018).

6.2.3.3 Unilateral Drop Jump.

Participants started by standing on an 18 cm box which was chosen as the height to drop from based on previous research (Maloney et al. 2016; Maloney et al. 2017). With hands fixed on hips, participants were required to step off the box with their designated test leg which subsequently landed on the centre of the force plate below. Upon landing, participants were instructed to "minimize ground contact time and jump as high as possible" in line with previous DJ research (Maloney et al. 2016; Maloney et al. 2017). Each trial was separated by a 60 second rest period and recorded metrics included jump height (calculated from the flight time method), GCT, quantified as the time spent on the floor during the amortization phase of the jump, and RSI, quantified using the equation flight time/ground contact time (Maloney et al. 2017).

6.2.4 Statistical Analysis

Initially all force-time data were exported to Microsoft Excel™, expressed as means and standard deviations (SD), and later transferred into SPSS (version 24.0; SPSS, Inc., Armonk, NY, USA) for additional analyses. Normality of the data was determined using the Shapiro-Wilk test. Within-session reliability was quantified using the CV, SEM and a 2-way random ICC (average measures) with absolute agreement inclusive of 95% confidence intervals (Weir, 2005). The CV was calculated via the formula: (SD[trials 1-3]/average[trials 1-3]*100) with values ≤ 10% suggested to be considered acceptable (Cormack et al. 2008). ICC values were interpreted in line with suggestions by Koo and Li, (2016) where scores > 0.9 = excellent, 0.75-0.9 = good, 0.5-0.75 = moderate, and < 0.5 = poor. The SEM was calculated using the formula: SD*√(1-ICC) (Atkinson and Neville, 1998). For between-session reliability, mean scores were used to calculate a CV and ICC value as previously described.

Inter-limb asymmetries were quantified as a percentage difference between limbs (from either best trials or an average of all trials on each side) using the formula: (100/(maximum value)*(minimum value)*–1+100), as proposed by Bishop et al. (2018d). When depicting inter-limb differences individually, the use of an 'IF function' in Microsoft Excel was added on the end of the formula: *IF(left<right,1,-1) (Bishop et al. 2018b), in order to show the direction of asymmetry, without altering the magnitude.

To determine systematic bias, paired samples Wilcoxon *t*-tests were conducted to quantify whether test or asymmetry scores were significantly different between sessions, with statistical significance set at $p < 0.05$. The magnitude of change was calculated between sessions for test and asymmetry data using Cohen's *d* ES with 95% confidence intervals using the formula: ($Mean_{S1}$ – $Mean_{S2}$)/SD_{pooled}, where S1 and S2 represent the respective test sessions. These were interpreted in line with Hopkins et al. (2009) where < 0.2 = trivial; 0.2-0.6 = small; 0.6-1.2 = moderate; 1.2-2.0 = large; 2.0-4.0 = very large; and > 4.0 = near perfect. Finally, Kappa coefficients were calculated to determine the levels of agreement for how consistently an asymmetry favoured the same side; thus, providing the direction of asymmetry. This method was chosen because the Kappa coefficient describes the proportion of agreement between two methods after any agreement by chance has been removed (Cohen, 1960). Kappa values were interpreted in line with suggestions from Viera and Garrett (2005), where ≤ 0 = poor, 0.01-0.20 = slight, 0.21-0.40 = fair, 0.41-0.60 = moderate, 0.61-0.80 = substantial and 0.81-0.99 = almost perfect.

6.3 Results

Within-session reliability data are presented in Table 6.1. The isometric squat showed excellent relative reliability during both test sessions (ICC = 0.96-0.98) but also the greatest variability of all tests (CV = 4.9-13.7%), although peak force showed low variability during both test sessions (CV ≤ 5.7%). The unilateral CMJ showed excellent reliability and acceptable variability in both test sessions (ICC = 0.93-0.98; CV ≤ 5.8%). The unilateral DJ showed excellent reliability and acceptable variability in both test sessions (ICC = 0.91-0.98; CV ≤ 8.1%). Between-session reliability data followed a similar trend to the within-session results. The isometric squat showed excellent reliability (ICC = 0.92-0.96) and the greatest variability of all tests (CV = 6.4-12.9%). The unilateral CMJ showed excellent reliability and acceptable variability for all metrics (ICC = 0.91-0.96; CV ≤ 6.3%). Finally, the unilateral DJ showed good to excellent reliability and slightly higher variability between sessions than the CMJ test (ICC = 0.81-0.92; CV ≤ 11.2%).

Descriptive data and inter-limb asymmetry scores are presented in Tables 6.2 and 6.3. Results from the paired samples Wilcoxon *t*-tests showed a significant difference in asymmetry was seen between test sessions for impulse during the isometric squat ($p = 0.04$) and GCT during the DJ ($p = 0.04$); however, this was only when calculating asymmetries from the best trial method. No other significant differences in asymmetry were present between sessions. Levels of agreement for asymmetry scores between test sessions were calculated using the Kappa coefficient and are shown in Table 6.4. Results showed levels of agreement between test sessions were fair to substantial for the isometric squat test (Kappa range = 0.29-0.64), moderate to substantial for the CMJ (Kappa range = 0.58-0.66) and fair to moderate for the DJ (Kappa range = 0.36-0.56). Given the changing nature of the direction of asymmetry for some participants between test sessions, individual asymmetry data are presented in Figures 6.3-6.8.

Table 6.1. Within and between-session reliability data using mean scores, for the unilateral isometric squat, unilateral CMJ and unilateral DJ tests.

Test/Metric	Test Session 1			Test Session 2			Between Sessions	
	ICC (95% CI)	*CV (%)*	*SEM*	*ICC (95% CI)*	*CV (%)*	*SEM*	*ICC (95% CI)*	*CV (%)*
Iso Squat:								
PF-L (N)	0.98 (0.96-0.99)	5.4	58.1	0.98 (0.97-0.99)	4.9	54.9	0.96 (0.92-0.98)	6.4
PF-R (N)	0.97 (0.95-0.99)	5.7	65.0	0.98 (0.96-0.99)	5.5	59.4	0.93 (0.85-0.97)	8.0
Imp-L (N·s)	0.96 (0.92-0.98)	13.7	13.9	0.96 (0.93-0.98)	10.1	11.9	0.95 (0.90-0.98)	8.9
Imp-R (N·s)	0.97 (0.94-0.99)	12.1	12.8	0.97 (0.93-0.98)	10.6	10.5	0.92 (0.83-0.96)	12.9
RFD-L (N/s^{-1})	0.97 (0.94-0.99)	9.2	181.8	0.96 (0.93-0.98)	8.1	181.3	0.96 (0.92-0.98)	7.1
RFD-R (N/s^{-1})	0.96 (0.93-0.98)	10.4	216.2	0.97 (0.94-0.98)	7.5	159.4	0.96 (0.91-0.98)	8.3
UCMJ:								
JH-L (m)	0.96 (0.93-0.98)	4.8	0.01	0.95 (0.91-0.98)	4.2	0.01	0.93 (0.86-0.97)	3.7
JH-R (m)	0.93 (0.86-0.96)	5.4	0.01	0.94 (0.90-0.97)	5.0	0.01	0.91 (0.81-0.96)	4.2
PF-L (N)	0.96 (0.93-0.98)	5.8	35.5	0.98 (0.96-0.99)	4.9	21.9	0.93 (0.86-0.97)	6.2
PF-R (N)	0.98 (0.95-0.99)	5.3	24.4	0.96 (0.93-0.98)	5.0	28.4	0.93 (0.84-0.97)	6.3
CON-L (N·s)	0.97 (0.95-0.99)	3.3	3.4	0.98 (0.96-0.99)	2.3	2.4	0.96 (0.91-0.98)	2.6
CON-R (N·s)	0.93 (0.87-0.97)	4.1	4.5	0.97 (0.94-0.98)	3.1	2.6	0.93 (0.86-0.97)	4.0
UDJ:								
JH-L (m)	0.96 (0.93-0.98)	7.5	0.01	0.98 (0.96-0.99)	7.1	0.01	0.83 (0.64-0.92)	10.1
JH-R (m)	0.96 (0.93-0.98)	8.1	0.01	0.97 (0.95-0.99)	6.8	0.01	0.89 (0.76-0.95)	11.2
RSI-L	0.95 (0.91-0.98)	4.9	0.04	0.98 (0.96-0.99)	4.0	0.03	0.85 (0.64-0.93)	6.7
RSI-R	0.97 (0.94-0.98)	4.7	0.03	0.96 (0.92-0.98)	5.9	0.04	0.92 (0.83-0.96)	5.1
GCT-L (s)	0.94 (0.89-0.97)	2.9	< 0.01	0.95 (0.91-0.98)	3.0	0.01	0.84 (0.65-0.92)	3.8
GCT-R (s)	0.91 (0.84-0.96)	3.9	0.01	0.93 (0.86-0.96)	4.3	0.01	0.81 (0.59-0.91)	4.7

ICC = intraclass correlation coefficient; CI = confidence intervals; CV = coefficient of variation; SEM = standard error of the measurement; Iso = isometric; PF = peak force; Imp = impulse at 0.3s; RFD = rate of force development at 0.3s; N = Newtons; N·s = Newton seconds; L = left; R = right; UCMJ = unilateral countermovement jump; JH = jump height; m = metres; CON = concentric impulse; UDJ = unilateral drop jump; RSI = reactive strength index; GCT = ground contact time.

Table 6.2. Mean test and asymmetry data ± SD, and Cohen's *d* effect sizes (95% confidence intervals) for test metrics reported from the best of three trials.

Test/Metric	Test Scores ± SD			Asymmetry ± SD		
	Session 1	*Session 2*	*Effect Size*	*Session 1*	*Session 2*	*Effect Size*
Iso Squat:						
PF-L (N)	1597.0 ± 438.9	1631.3 ± 394.2	0.08 (-0.44 to 0.61)	8.4 ± 6.8	8.9 ± 6.9	-0.07 (-0.45 to 0.60)
PF-R (N)	1595.1 ± 397.3	1643.2 ± 433.4	0.12 (-0.41 to 0.64)			
Imp-L (N·s)	199.5 ± 71.2	190.8 ± 64.0	-0.13 (-0.65 to 0.40)	15.5 ± 11.4	9.6 ± 7.8*	-0.60 (-1.14 to -0.07)
Imp-R (N·s)	192.9 ± 77.9	191.9 ± 64.0	-0.01 (-0.54 to 0.51)			
RFD-L (N/s^{-1})	3419.6 ± 1158.5	3399.5 ± 1005.1	-0.02 (-0.54 to 0.51)	10.7 ± 7.8	9.9 ± 5.4	-0.12 (-0.64 to 0.41)
RFD-R (N/s^{-1})	3447.1 ± 1144.9	3400.9 ± 1024.1	-0.04 (-0.57 to 0.48)			
UCMJ:						
JH-L (m)	0.21 ± 0.03	0.22 ± 0.03	0.33 (-0.19 to 0.86)	7.2 ± 6.1	7.1 ± 5.0	-0.02 (-0.54 to 0.51)
JH-R (m)	0.20 ± 0.03	0.21 ± 0.03	0.33 (-0.19 to 0.86)			
PF-L (N)	863.4 ± 204.0	847.0 ± 162.3	-0.09 (-0.61 to 0.44)	7.5 ± 5.1	6.6 ± 4.8	-0.18 (-0.71 to 0.34)
PF-R (N)	830.8 ± 181.5	818.6 ± 158.7	-0.07 (-0.60 to 0.45)			
CON-L (N·s)	152.0 ± 21.4	152.2 ± 16.8	0.01 (-0.51 to 0.53)	6.4 ± 6.0	5.3 ± 3.6	-0.22 (-0.75 to 0.30)
CON-R (N·s)	149.5 ± 20.0	147.9 ± 16.1	-0.09 (-0.61 to 0.44)			
UDJ:						
JH-L (m)	0.15 ± 0.03	0.14 ± 0.04	-0.28 (-0.81 to 0.24)	10.1 ± 8.7	10.7 ± 8.6	0.07 (-0.45 to 0.59)
JH-R (m)	0.14 ± 0.03	0.13 ± 0.04	-0.28 (-0.81 to 0.24)			
RSI-L	1.31 ± 0.17	1.23 ± 0.20	-0.43 (-0.96 to 0.10)	8.1 ± 4.8	7.3 ± 4.7	-0.17 (-0.69 to 0.36)
RSI-R	1.26 ± 0.20	1.23 ± 0.20	-0.15 (-0.67 to 0.37)			
GCT-L (s)	0.26 ± 0.02	0.27 ± 0.02	0.50 (-0.03 to 1.03)	3.8 ± 3.5	5.9 ± 4.3*	0.54 (0.00 to 1.07)
GCT-R (s)	0.26 ± 0.02	0.26 ± 0.03	0.00 (-0.52 to 0.52)			

* significantly different from asymmetry score in test session 1 ($p = 0.04$). Iso = isometric; PF = peak force; Imp = impulse at 0.3s; RFD = rate of force development at 0.3s; N = Newtons; N·s = Newton seconds; L = left; R = right; UCMJ = unilateral countermovement jump; JH = jump height; m = metres; CON = concentric impulse; UDJ = unilateral drop jump; RSI = reactive strength index; GCT = ground contact time.

Table 6.3. Mean test and asymmetry data ± SD, and Cohen's *d* effect sizes (95% confidence intervals) for test metrics reported when averaging data from three trials.

Test/Metric	Test Scores ± SD			Asymmetry ± SD		
	Session 1	*Session 2*	*Effect Size*	*Session 1*	*Session 2*	*Effect Size*
Iso Squat:						
PF-L (N)	1519.7 ± 414.8	1561.8 ± 392.3	0.10 (-0.42 to 0.63)	8.6 ± 5.9	9.0 ± 6.5	0.06 (-0.46 to 0.59)
PF-R (N)	1519.1 ± 382.4	1570.8 ± 424.6	0.13 (-0.40 to 0.65)			
Imp-L (N·s)	177.7 ± 69.3	174.5 ± 59.4	-0.05 (-0.57 to 0.47)	14.5 ± 11.3	10.9 ± 6.7	-0.39 (-0.92 to 0.14)
Imp-R (N·s)	174.4 ± 75.0	176.1 ± 61.6	0.02 (-0.50 to 0.55)			
RFD-L (N/s^{-1})	3156.7 ± 1069.3	3159.0 ± 906.7	0.00 (-0.52 to 0.53)	8.9 ± 8.8	9.0 ± 6.1	0.01 (-0.51 to 0.54)
RFD-R (N/s^{-1})	3147.7 ± 1081.1	3184.7 ± 937.4	0.04 (-0.49 to 0.56)			
UCMJ:						
JH-L (m)	0.20 ± 0.03	0.21 ± 0.03	0.33 (-0.19 to 0.86)	7.8 ± 5.9	7.6 ± 4.9	-0.04 (-0.56 to 0.49)
JH-R (m)	0.19 ± 0.03	0.20 ± 0.03	0.33 (-0.19 to 0.86)			
PF-L (N)	811.5 ± 177.6	807.7 ± 156.5	-0.02 (-0.55 to 0.50)	7.1 ± 4.5	6.6 ± 4.7	-0.11 (-0.63 to 0.42)
PF-R (N)	793.4 ± 174.0	779.6 ± 141.8	-0.09 (-0.61 to 0.44)			
CON-L (N·s)	147.1 ± 19.8	148.9 ± 16.8	0.10 (-0.43 to 0.62)	5.5 ± 4.3	5.4 ± 3.5	-0.03 (-0.55 to 0.50)
CON-R (N·s)	143.7 ± 17.4	143.5 ± 15.4	-0.01 (-0.54 to 0.51)			
UDJ:						
JH-L (m)	0.14 ± 0.03	0.13 ± 0.04	-0.28 (-0.81 to 0.24)	11.1 ± 6.9	10.8 ± 7.5	-0.04 (-0.57 to 0.48)
JH-R (m)	0.13 ± 0.03	0.13 ± 0.04	0.00 (-0.52 to 0.52)			
RSI-L	1.25 ± 0.18	1.19 ± 0.20	-0.32 (-0.84 to 0.21)	7.5 ± 5.1	7.4 ± 5.2	-0.02 (-0.54 to 0.50)
RSI-R	1.21 ± 0.20	1.17 ± 0.20	-0.20 (-0.73 to 0.33)			
GCT-L (s)	0.27 ± 0.02	0.27 ± 0.03	0.00 (-0.52 to 0.52)	3.6 ± 3.0	4.7 ± 3.8	0.32 (-0.21 to 0.85)
GCT-R (s)	0.27 ± 0.02	0.27 ± 0.03	0.00 (-0.52 to 0.52)			

Iso = isometric; PF = peak force; Imp = impulse at 0.3s; RFD = rate of force development at 0.3s; N = Newtons; N·s = Newton seconds; L = left; R = right; UCMJ = unilateral countermovement jump; JH = jump height; m = metres; CON = concentric impulse; UDJ = unilateral drop jump; RSI = reactive strength index; GCT = ground contact time.

Table 6.4. Kappa coefficients and descriptive levels of agreement showing how consistently asymmetry favours the same leg between test sessions from mean test scores, for the unilateral isometric squat, unilateral CMJ and unilateral DJ tests.

Test/Metric	**Kappa Coefficient**	**Descriptor**
Isometric Squat:		
Peak Force	0.64	Substantial
Impulse at 0.3s	0.29	Fair
RFD at 0.3s	0.50	Moderate
UCMJ:		
Jump Height	0.64	Substantial
Peak Force	0.66	Substantial
Concentric Impulse	0.58	Moderate
UDJ:		
Jump Height	0.36	Fair
Reactive Strength Index	0.56	Moderate
Ground Contact Time	0.42	Moderate

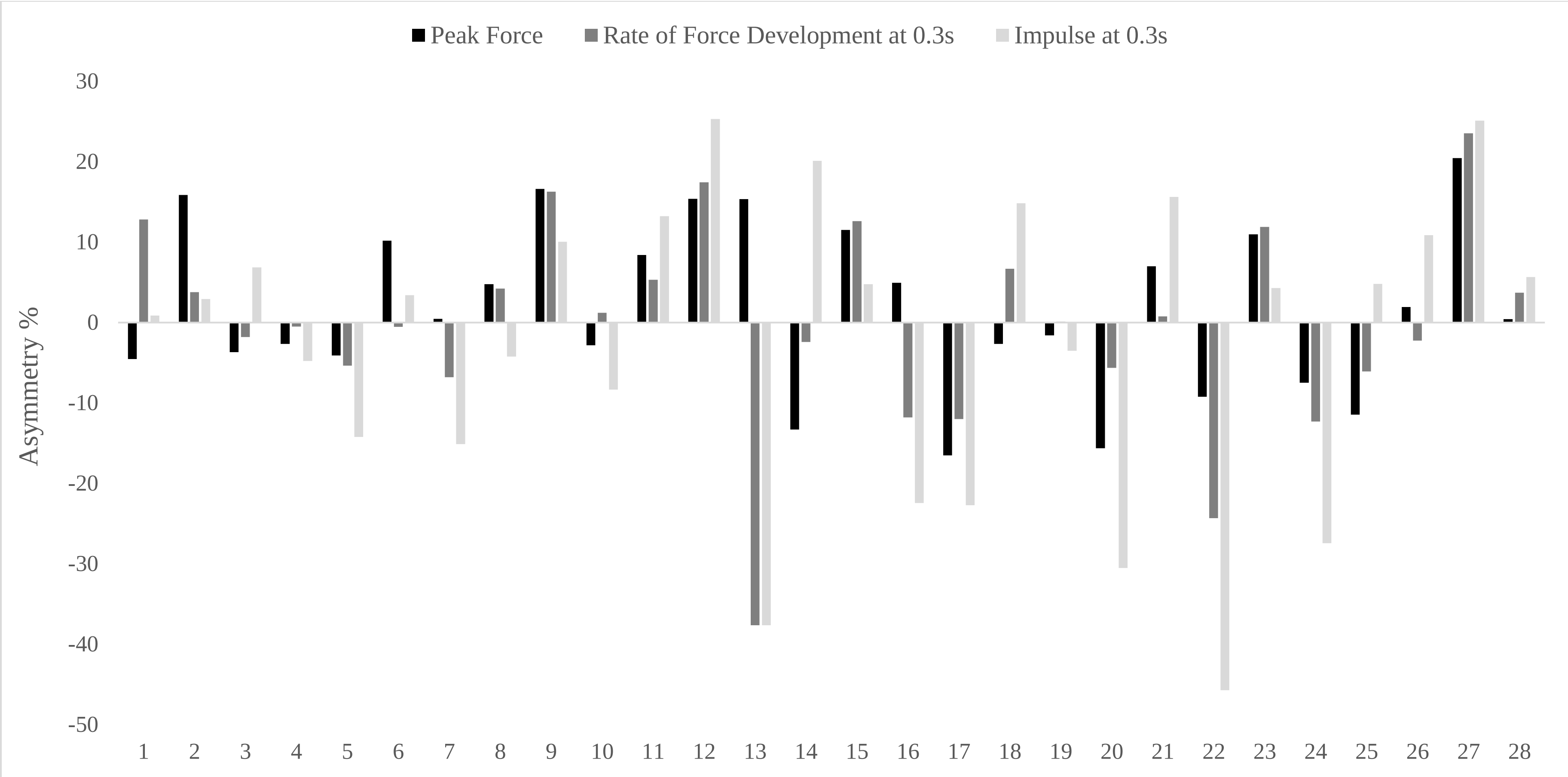


Figure 6.3. Individual asymmetry data for peak force, impulse and rate of force development from mean test scores, during the unilateral isometric squat test in test session one. Above 0 indicates larger score on right leg and below 0 indicates larger score on left leg.

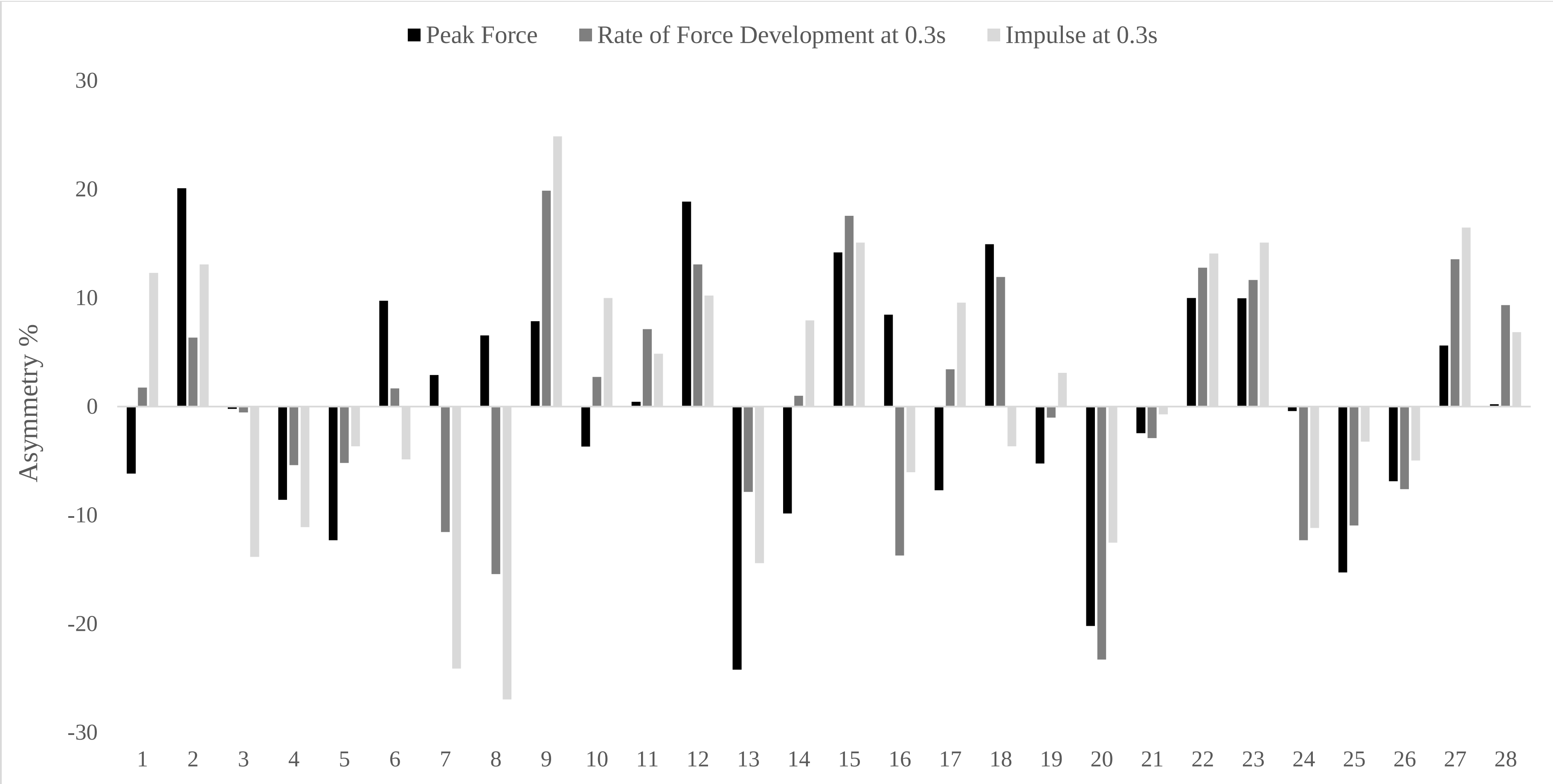


Figure 6.4. Individual asymmetry data for peak force, impulse and rate of force development from mean test scores, during the unilateral isometric squat test in test session two. Above 0 indicates larger score on right leg and below 0 indicates larger score on left leg.

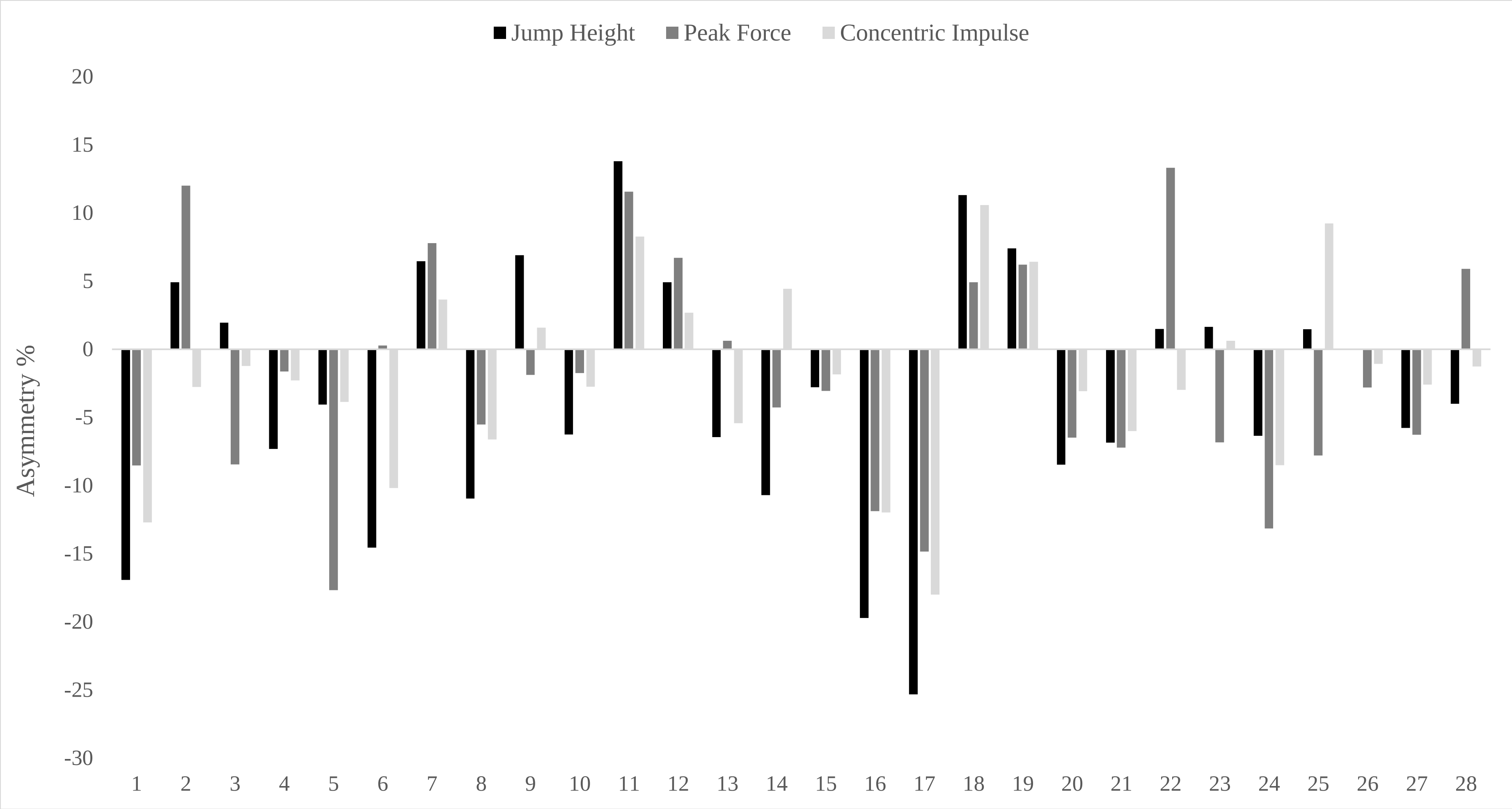


Figure 6.5. Individual asymmetry data for jump height, peak force and concentric impulse from mean test scores, during the unilateral CMJ test in test session one. Above 0 indicates larger score on right leg and below 0 indicates larger score on left leg.

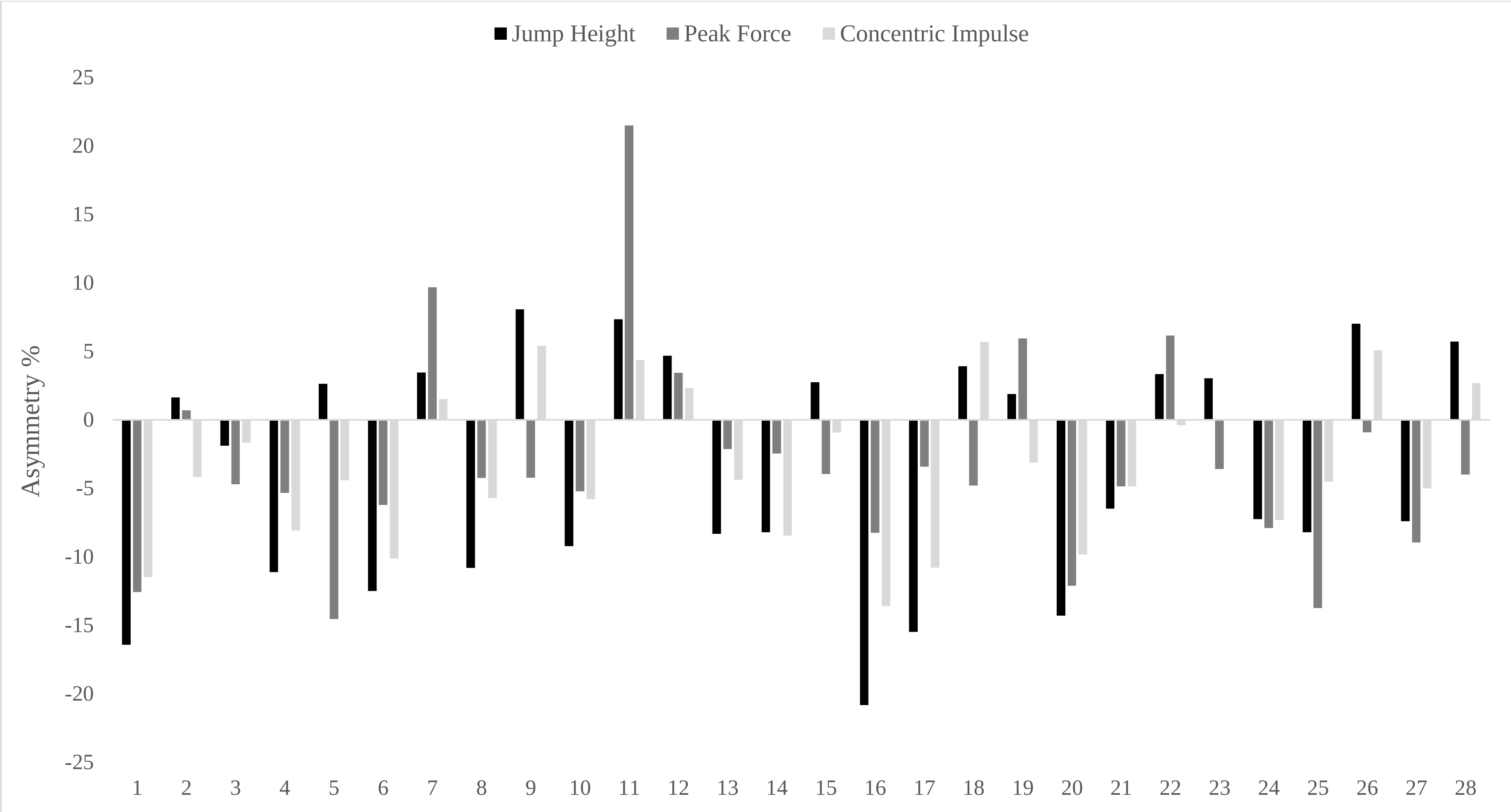


Figure 6.6. Individual asymmetry data for jump height, peak force and concentric impulse from mean test scores, during the unilateral CMJ test in test session two. Above 0 indicates larger score on right leg and below 0 indicates larger score on left leg.

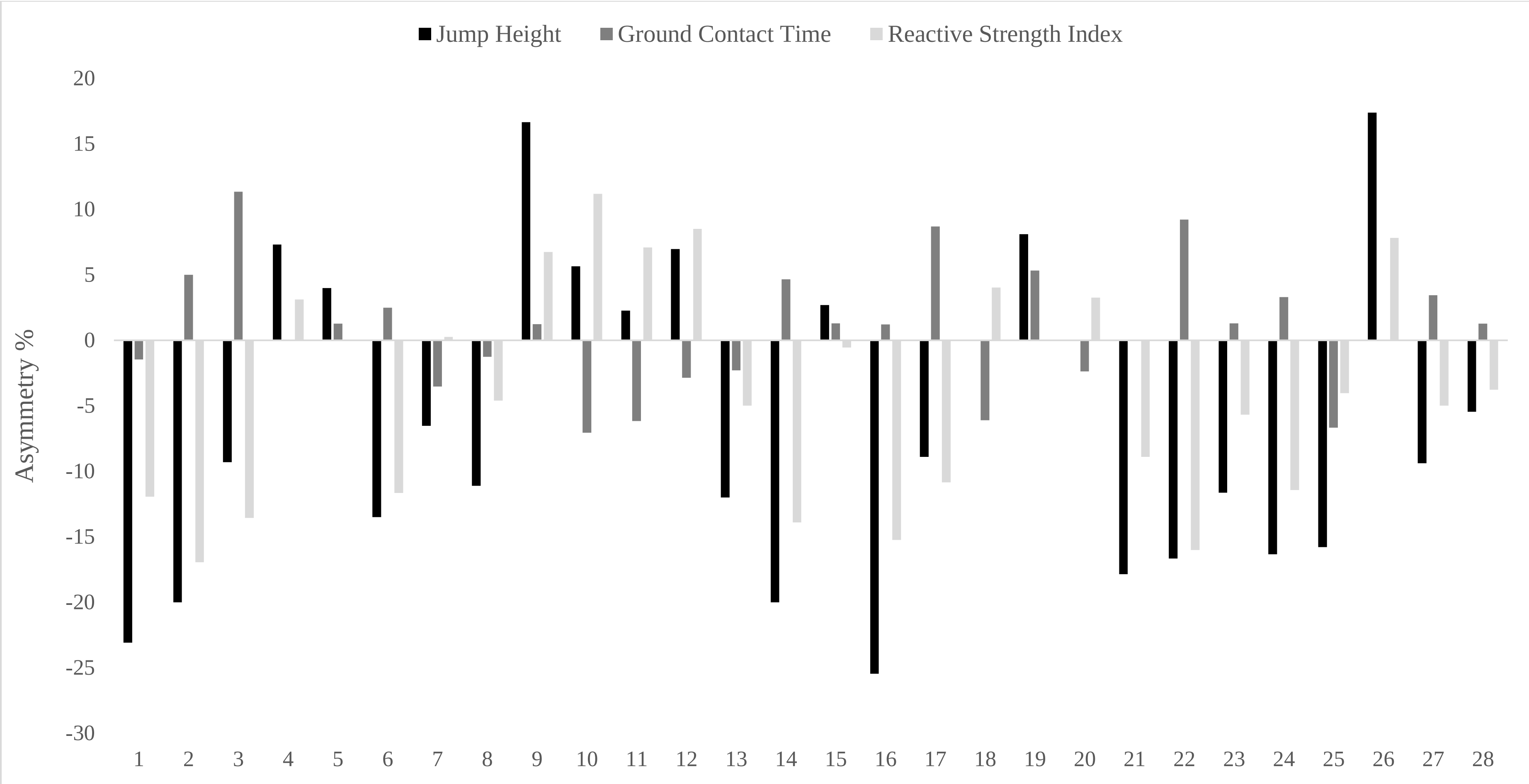


Figure 6.7. Individual asymmetry data for jump height, ground contact time and reactive strength index from mean test scores, during the unilateral DJ test in test session one. Above 0 indicates larger score on right leg and below 0 indicates larger score on left leg.

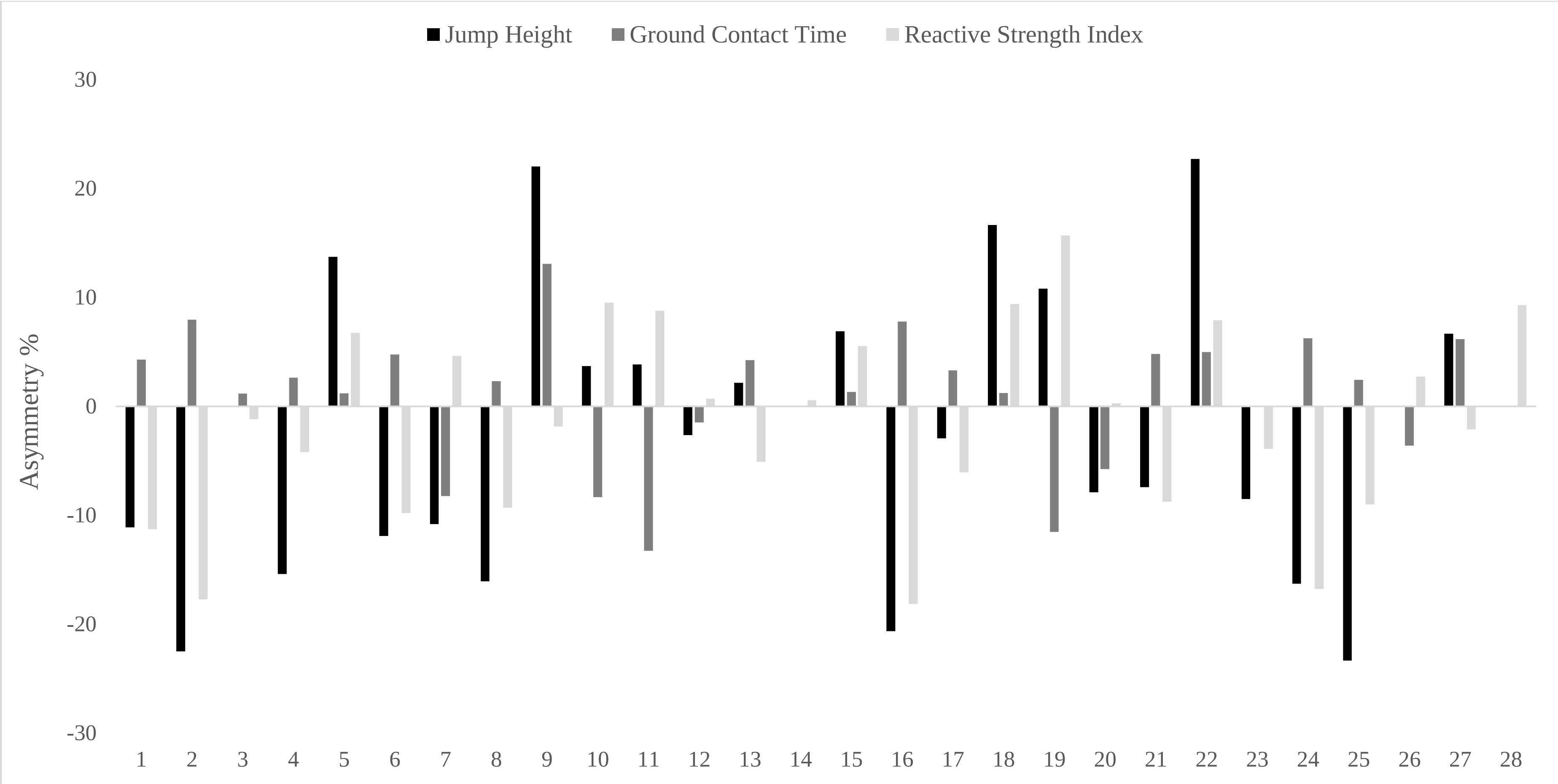


Figure 6.8. Individual asymmetry data for jump height, ground contact time and reactive strength index from mean test scores, during the unilateral DJ test in test session two. Above 0 indicates larger score on right leg and below 0 indicates larger score on left leg.

6.4 Discussion

The aims of the present study were threefold: 1) to determine the test-retest reliability of unilateral strength and jumping-based tests that can be used to quantify asymmetries, 2) determine whether any significant differences exist for asymmetry between test sessions when calculating differences from the best trial and an average of all trials and, 3) determine how consistently asymmetries favour the same side between tests sessions. Results showed moderate to excellent reliability for all tests both within and between sessions. A significant difference in asymmetry was found for impulse during the isometric squat (p = 0.04) and GCT during the DJ (p = 0.04) when calculating asymmetry from the best trial. No other significant differences in asymmetry were indicated. Kappa coefficients revealed fair to substantial levels of agreement for asymmetry between test sessions, with the strongest consistency shown for the unilateral CMJ.

Table 6.1 shows the within and between-session reliability data for each test based on mean scores. A similar trend was observed during both test sessions, with the greatest variability seen during the isometric squat. Impulse in particular showed CV values > 10% on both limbs during both test sessions, potentially indicating that practitioners should be cautious of using this metric if using the unilateral isometric squat. Given the lower variability reported for this metric during bilateral isometric strength assessments (Haff et al. 1997; Hart et al. 2012), this represents a novel finding when considering a unilateral version of this test. In addition, results are comparable with previous literature using the unilateral IMTP. Dos'Santos et al. (2017a) reported CV values of 10.5-11.6% for impulse in both professional rugby and collegiate athletes; thus, it would appear this metric may be subject to greater variability when assessed unilaterally. Furthermore, it is possible that greater familiarization is required in order to establish acceptable reliability for impulse during unilateral isometric strength assessments. Future research should aim to include additional testing sessions in an attempt to establish when variability has been reduced sufficiently (i.e., < 10%). That said, relative reliability was excellent for all isometric squat metrics, with peak force showing the strongest reliability throughout.

When considering the jump tests, within-session CV values were ≤ 8.1%, regardless of which test or metric was analysed. Between-session variability showed a similar pattern, although jump height reported slightly greater variability (10.1-11.2%) during the unilateral DJ on each leg. Relative reliability was excellent for all metrics during the unilateral CMJ, suggesting that jump height, peak force and concentric impulse are metrics with lower typical variability when quantifying unilateral vertical jump performance off a portable force platform. This serves as a useful finding for unilateral jump methods, given recent literature has validated the same portable force platform during bilateral jump testing (Lake et al. 2018b). The unilateral DJ showed excellent reliability for all metrics when quantified within-sessions; however, between-session reliability was reduced slightly (good to excellent) and with slightly higher variability for jump height. In summary, the unilateral CMJ showed the strongest within and between-session reliability, with the unilateral DJ showing slightly larger variability for jump height. The DJ is a more technically challenging and less innate task when compared to the CMJ (Maloney et al. 2016; Pedley et al. 2017); thus, it is likely that the lower reliability scores can be attributed to the more advanced nature of the jump. Consequently, test familiarization is a key consideration for practitioners, especially when using more advanced test methods such as the DJ.

Tables 6.2 and 6.3 show mean test scores and inter-limb asymmetry values (calculated from the best trial and from averaging test scores on both the left and right sides, respectively). Significant differences were evident between sessions for impulse asymmetry during the isometric squat ($p = 0.04$) and GCT during the DJ ($p = 0.04$), when calculated from the best trial (Table 6.2). It is suggested that this is not necessarily a positive finding, given that our study used a test-retest design and no training intervention had been undertaken to warrant a change in asymmetry score. Furthermore, given that impulse also showed the greatest CV in all tests, this further reiterates that practitioners may wish to be mindful of using this metric (when testing unilaterally) to quantify changes in inter-limb asymmetry, following periods of training due its more variable nature. Understanding that asymmetry is a ratio number, which can only be calculated once scores from both limbs are attained, is an important factor which can help to explain this. For example, asymmetry naturally inherits the associated error from both left and right limbs, which is likely to be a key factor in its variable nature (Bishop et al. 2018b; Bishop et al. 2019b). Consequently, practitioners are advised to calculate asymmetry as an average of all trials, in an attempt to account for the natural variability seen during testing. This is supported in part by Lake et al. (2018a) who investigated whether the peak and mean force methods of calculating asymmetry agreed during a bilateral CMJ. Levels of agreement between methods were assessed using the Kappa coefficient and ranged from 0.67-0.72, representing 'substantial' levels of agreement. Whilst this may indicate a positive outcome, the authors proposed that given these values were not near perfect (i.e., Kappa values at or close to 1), that the two methods of quantifying asymmetry should not be used interchangeably. Thus, an average of all trials may help to capture some of the inconsistency seen across trials (noting that if using unilateral test methods, the best score could be trial 1 on the left limb, but trial 3 on the right limb).

Table 6.4 shows the Kappa coefficients and accompanying descriptors for how consistently asymmetry favoured the same leg between test sessions, for each metric. The Kappa coefficient describes the proportion of agreement between two methods after any agreement by chance has been removed (Cohen, 1960). Levels of agreement were fair to substantial (0.29-0.64) for the isometric squat, moderate to substantial (0.58-0.66) for the

CMJ, and fair to moderate (0.36-0.56) for the DJ. Furthermore, it is interesting to note that greater levels of agreement appear to be associated with improved test reliability, noting that the unilateral CMJ showed the lowest CV values both within and between test sessions. Collectively, these data indicate that the direction of asymmetry (i.e., how consistently the same leg scores higher between test sessions) varies considerably. Thus, it is suggested that individual data analysis is a key consideration for practitioners when monitoring inter-limb asymmetry (see Figures 6.3-6.8). For example, when viewing Figures 6.5 and 6.6, it is clear to see that subject 1 is left limb dominant for all metrics during the unilateral CMJ, in both test sessions. However, subject 18 is right limb dominant for peak force in test session 1 (asymmetry = 4.92%), but left limb dominant for peak force in test session 2 (asymmetry = -4.80%). Thus, if practitioners do not monitor the direction of asymmetry at an individual level, assumptions are being made about the consistency of the magnitude, with no interpretation regarding limb dominance. This example seems especially relevant given that the magnitude of asymmetry can be considered quite small in each test session (< 5%); however, the change in limb dominance results in an 'asymmetry shift' of ~10%. Despite recent literature highlighting poor levels of agreement for the same metric across tests (Bishop et al. 2018b), to the authors' knowledge, this is the first study to report levels of agreement for the direction of asymmetry over more than a single test session. Thus, direct comparisons with previous research are not possible and requires further investigation using longitudinal study designs. However, these data would indicate that the direction of asymmetry tends to exhibit improved levels of agreement for tests with better reliability.

6.5 Conclusion

In summary, the magnitude of asymmetry appears to show significant differences between test sessions for the isometric squat when computing data from the best trial, but not from an average of all trials. Given no training intervention was undertaken and no significant differences were found between test sessions when computing asymmetry from the average of all trials, it is suggested that the average method might be considered the most appropriate for calculating inter-limb differences. The direction of asymmetry appears highly variable; thus, individual data analysis is a strong consideration for practitioners and monitoring the direction of asymmetry may be more important than purely the magnitude when the purpose is to measure changes over time. Thus, the remaining studies in this thesis will always calculate asymmetry as an average of all trials collected and use the Kappa coefficient statistic to determine consistency in limb dominance throughout a competitive soccer season. In addition, owing to the time-efficient nature of jump testing and the remainder of studies being performed in a professional soccer club environment, only the unilateral CMJ and unilateral DJ tests were carried forward to examine asymmetry.

CHAPTER 7: STUDY 2

7.0 Seasonal variation and longitudinal associations between jumping asymmetries, speed and change of direction speed performance in elite academy soccer players.

7.1 Introduction

Soccer is a high intensity, intermittent team sport that requires the development of multiple physical qualities for optimal performance. Time-motion analysis data has shown the prevalence of these sporting actions, which enables practitioners to prioritise the development of key physical parameters that are likely to impact player performance. For example, Nedelac et al. (2014) highlighted that professional soccer players may jump up to 15 times in a competitive match. Taylor et al. (2017) reported that repeated high intensity actions such as acceleration, deceleration and sprinting can occur up to 168 times in matches. In addition, it has been suggested that CODS may be one of the most important physical qualities in soccer (Turner and Stewart, 2014), which is supported by Bangsbo (1992) who showed that soccer players can change direction between 1200-1400 times during matches. Thus, enhanced jumping, sprinting and CODS performance are undoubtedly key factors in the athletic development of soccer players.

Jump tests have been a common tool to monitor physical performance in soccer athletes (Casajus, 2001; Haugen, 2018); however, longitudinal tracking of jump performance throughout a season has been less frequently investigated. Casajus (2001) used jump height during the CMJ and SJ tests to report seasonal variation in 15 professional soccer players, although data were only collected at two time points (September and February). Results showed no significant changes in jump height in either test. In contrast, the CMJ was used by Haugen (2018) to assess seasonal variation in vertical jump performance in 44 Norwegian professional soccer players. Results showed mean jump height (in cm) of 37.4

± 4.0 for pre-season, 38.1 ± 4.0 in-season, and 38.6 ± 3.9 in the off-season, with significant differences evident between pre-season and off-season. Such data is useful for practitioners as it may help them understand specific demands players face at different stages of the season. For example, players often experience heightened training volumes during pre-season (Faude et al. 2013), increased fixture density during mid-season (Carling et al. 2012), with the effects of cumulated loading potentially driving sport-specific adaptations by the end of the season (Ostojic, 2003). In addition, it appears that bilateral jump tests are commonly used to track changes in vertical jump performance over time (Casajus, 2001; Claudino et al. 2016; Haugen, 2018), with limited data available to examine longitudinal changes in unilateral modalities. Furthermore, the aforementioned studies only tracked jump height; thus, a more in-depth analysis of jump strategy is warranted longitudinally using unilateral tests.

Recent research has investigated the prevalence of asymmetry from unilateral jump tests and reported correlations with measures of athletic performance (Bishop et al. 2018c; Bishop et al. 2019b; Dos'Santos et al. 2017b; Lockie et al. 2014; Maloney et al. 2017). However, these studies have only reported associations between asymmetry and performance scores at a single time point. Previous literature has highlighted that longitudinal data pertaining to asymmetry is missing (Bishop et al. 2018e) and with its task-specific and variable nature (Bishop et al. 2018a; Dos'Santos et al. 2017a; Lockie et al. 2014; Maloney et al. 2017), longitudinal tracking is justified to aid our understanding of its usability as part of the monitoring process.

An additional consideration for practitioners is how changes in asymmetry might impact changes in athletic performance tasks. Seasonal changes in tasks such as maximal sprinting have been shown in professional soccer athletes, with players typically getting faster as the season progresses (Haugen, 2018). However, given that longitudinal data for asymmetry is missing (Bishop et al. 2018e) and numerous studies have only investigated associations with reduced speed and CODS performance at a single time point (Bishop et al. 2018c; Bishop et al. 2019b; Dos'Santos et al. 2017b; Lockie et al. 2014; Maloney et al. 2017), it stands to reason that the interaction between changes in asymmetry and athletic performance tasks are also unknown. This would assist practitioners in understanding whether a true link exists between inter-limb asymmetry and surrogate measures of athletic performance which are commonly used to monitor physical performance.

Therefore, this study had four key aims: 1) determine the relationship between jump asymmetries and athletic performance tasks at a range of different time points in a competitive soccer season, 2) determine the relationship between changes in asymmetry and changes in athletic performance tasks, 3) provide seasonal variation data for unilateral jump, speed and CODS tasks and, 4) provide seasonal variation for the magnitude and direction of asymmetry during unilateral jump tasks.

7.2 Methods

7.2.1 Experimental Design

This study used a repeated measures design recording data at three time points during the course of a soccer season. Unilateral CMJ, unilateral DJ, 5, 10, 30 m and 505 tests were collected during pre-season (July), mid-season (January) and end-season (May) in elite academy male soccer players. All testing was conducted on two separate days with test sessions separated by 48 hours at each time point, in an attempt to minimize fatigue impacting any single test. Day 1 consisted of the unilateral CMJ and unilateral DJ tests and day 2 consisted of the 30 m (inclusive of 5 and 10 m splits) and 505 tests, which was agreed with the club. Players performed a standardized warm up procedure starting with dynamic stretches and the same procedures were adhered to at all time points. Specifically, this consisted of a single set of 10 repetitions of multiplanar lunges, inchworms, spidermans and bodyweight squats, followed by three practice trials of each test at 60, 80 and 100% of perceived maximal effort. Three minutes of rest was provided between the last practice trial and the start of the first test and 60-seconds of rest was provided between trials during the data collection process, with all testing performed in a randomized order on each day.

7.2.2 Participants

Eighteen elite under-23 academy male soccer players (age: 19.0 ± 2.2 years; height: 1.80 ± 0.07 m; body mass: 73.3 ± 9.0 kg) from a Category 3 academy of a professional soccer club volunteered to participate in this study. All players had a minimum of two years structured strength and conditioning training experience and a minimum of six years' competitive soccer experience at the academy level. Players were required to be injury-free at the time testing and in the preceding four weeks prior to each test session. For subjects over the age of 18, written informed consent was provided and for subjects under 18, written parental consent was obtained in addition to subject ascent, and each player was also cleared to participate in testing by the club's medical department. Ethical approval was provided by the London Sport Institute Research and Ethics committee at Middlesex University, London, UK.

7.2.3 Procedures

7.2.3.1 Unilateral Countermovement Jump and Unilateral Drop Jump

The same procedures for these two tests were adhered to as per the methods section in Chapter 6, with the same jump metrics collected at all time points throughout the season. For the unilateral CMJ, metrics included jump height, peak force and concentric impulse. For the unilateral DJ, metrics included jump height, GCT and RSI.

7.2.3.2 30m Sprint

Dual beam electronic timing gates (Brower Timing Systems, Utah, USA) were positioned at 0, 5, 10 and 30 m, at a height of 1 m, enabling athlete's acceleration and top speed ability to be measured. Athletes started the test in a staggered 2-point stance with toes positioned 30 cm behind the start line so as to not break the beam of the timing gates prior to the initiation of the test. When ready, subjects sprinted through the timing gates allowing time to be recorded to the nearest hundredth of a second. Three trials were performed on a grass soccer pitch in football boots, with an average of all trials used for further analysis.

7.2.3.3 505 Change of Direction Speed test

A distance of 15 m was measured out with dual beam electronic timing gates (Brower Timing Systems, Utah, USA) positioned at the 10 m mark. The 15 m point was marked out clearly by an existing white line on the pitch, to ensure that players had an obvious sight as they approached the turning point. Players sprinted 15 m and then performed a 180° turn off both the right and left legs, with a total of two trials completed on each leg. The time started when players broke the electronic beam at the 10 m mark and after turning 180°, subsequently sprinted back through the timing gates to complete a recorded distance of 10 m. Trials were only deemed successful if the players' foot fully crossed the line during the turn. Both trials were averaged on each limb for subsequent data analysis.

7.2.4 Statistical Analysis

All data were initially recorded as means and SD in Microsoft Excel and later transferred to SPSS (version 25.0; SPSS, Inc., Armonk, NY, USA). All data was checked for normality using the Shapiro-Wilk test. Raw test scores showed normal distribution, but asymmetry scores were not normally distributed. Within-session reliability of test measures was computed at each time point using an average measures two-way random ICC with absolute agreement and 95% confidence intervals, and the CV. Interpretation of ICC values was in accordance with previous research by Koo and Li (2016) where values > 0.9 = excellent, 0.75-0.9 = good, 0.5-0.75 = moderate, and < 0.5 = poor. The CV was calculated via the formula: (SD[trials 1–3]/average[trials 1–3]*100) with values ≤ 10% suggested to be considered acceptable (Cormack et al. 2008).

A repeated measures ANOVA was conducted to determine differences between time points for all test scores, with statistical significance set at $p < 0.05$. The magnitude of change was calculated between time points using Cohen's *d* ES with 95% confidence intervals using the formula: $(Mean_{T1} – Mean_{T2})/SD_{pooled}$, where T1 and T2 represent the respective time points in question (e.g., pre, mid or end-season). These were interpreted in line with Hopkins et al. (2009) where < 0.2 = trivial; 0.2-0.6 = small; 0.6-1.2 = moderate; 1.2-2.0 = large; 2.0-4.0 = very large; and > 4.0 = near perfect.

Spearman's rank order correlations (ρ) were conducted twice. Firstly, to establish the relationship between inter-limb asymmetries and fitness test scores at each individual time point. Secondly, to establish the relationship between changes in asymmetry (as a percentage) and changes in athletic performance tasks (as raw scores) between time points. Bonferroni corrections were applied to all correlations to account for multiple comparisons and the familywise type I error rate, resulting in statistical significance being set at $p < 0.008$. Values were interpreted in line with suggestions from Hopkins et al. (2009) where 0-0.10 = trivial, 0.11-0.30 = small, 0.31-0.50 = moderate, 0.51-0.70 = large, 0.71-0.90 = very large and 0.91-1.0 = nearly perfect.

A median split analysis was performed at each time point creating high and low asymmetry groups for each separate jump metric, to determine whether players with larger between-limb differences performed slower during the speed and CODS tasks. This was assessed between groups with Mann-Whitney U tests, with statistical significance set at $p < 0.05$, and Cohen's *d* ES were used to determine differences between high and low asymmetry groups.

Finally, inter-limb asymmetries were quantified using the percentage difference method and the IF function used determine the direction of asymmetry, as outlined in chapter 6. Kappa coefficients were calculated to determine the levels of agreement for how consistently an asymmetry favoured the same side (direction of asymmetry) when comparing the different time points measured and were interpreted in line with the suggested scale from chapter 6.

7.3 Results

Reliability data are presented for each time point in Table 7.1. All tests showed acceptable variability (< 10%) with the exception of jump height on the right leg during the unilateral CMJ in pre-season, which showed a slightly elevated CV of 10.96%. Relative reliability ranged from good to excellent for all metrics at each time point.

Descriptive data and accompanying effect sizes are presented in Table 7.2 for all tests at each time point. For the unilateral CMJ, significant reductions in jump height and concentric impulse were evident on both limbs, and for peak force on the left limb. When considering ES data for all metrics, small to moderate changes were evident between pre and mid-season (ES range = -0.45 to -1.08), trivial to small changes between pre and end-season (ES range = -0.01 to 0.24) and small to large changes between mid and end-season (ES range = 0.56 to 1.52). For the unilateral DJ, there was a clear trend for GCT to reduce as the season progressed, with statistical significance reached on both limbs at the end of the season compared to pre-season. RSI also improved as the season progressed, with statistical significance reached again at the end of the season and with greater improvements on the left leg. Jump height showed no meaningful changes throughout the season. When considering ES data for all metrics, trivial to moderate changes were evident between pre and mid-season (ES range = -0.73 to 0.39), trivial to moderate changes between pre and end-season (ES range = -1.10 to 0.86) and trivial to small changes between mid and end-season (ES range = -0.57 to 0.49). For linear speed tests, no significant changes were evident, with trivial to small changes evident throughout the season (ES range = -0.53 to 0.38). Finally, for CODS, players got faster as the season progressed, with statistical significance reached at the end of the season compared to pre-season on the right leg and compared to both pre and mid-season on the left leg. This represented moderate reductions in total time from pre to end of season (ES range = -0.81 to -1.08) and mid to end of season (ES range = -0.63 to -0.73).

Mean inter-limb asymmetry data are presented for each time point in Table 7.3. Trivial to small non-linear changes were shown throughout the season (ES range = -0.60 to 0.55). Kappa coefficients and accompanying descriptors for how consistently asymmetry favoured the same limb between time points are presented in Table 7.4. For both tests, agreement ranged from poor to substantial (CMJ = -0.06 to 0.77) and (DJ = -0.10 to 0.78), highlighting the variable nature in the direction of asymmetry throughout the soccer season. Individual asymmetry scores have also been presented for each time point for the unilateral CMJ (Figures 7.1-7.3) and unilateral DJ (Figures 7.4-7.6) tests, indicating pronounced within-participant variability.

Table 7.1. Within-session reliability data for test measures throughout the season.

Test/Metric	Pre-season		Mid-season		End-season	
	CV (%)	*ICC (95% CI)*	*CV (%)*	*ICC (95% CI)*	*CV (%)*	*ICC (95% CI)*
UCMJ:						
Jump height-L (m)	9.28	0.94 (0.88-0.98)	5.34	0.97 (0.94-0.99)	7.90	0.93 (0.85-0.97)
Jump height-R (m)	10.96	0.86 (0.68-0.94)	4.27	0.97 (0.93-0.99)	9.63	0.80 (0.57-0.92)
Peak force-L (N)	8.75	0.89 (0.77-0.96)	4.16	0.92 (0.81-0.97)	9.48	0.92 (0.82-0.97)
Peak force-R (N)	8.94	0.90 (0.79-0.96)	3.80	0.96 (0.92-0.99)	9.50	0.93 (0.86-0.97)
CON impulse-L (N·s)	7.48	0.95 (0.90-0.98)	4.22	0.97 (0.94-0.99)	6.55	0.88 (0.73-0.95)
CON impulse-R (N·s)	9.24	0.92 (0.82-0.97)	4.78	0.94 (0.87-0.98)	7.82	0.75 (0.49-0.90)
UDJ:						
Jump height-L (m)	5.32	0.96 (0.92-0.99)	5.70	0.98 (0.96-0.99)	6.38	0.97 (0.94-0.99)
Jump height-R (m)	6.05	0.97 (0.93-0.99)	6.00	0.96 (0.92-0.99)	7.30	0.93 (0.84-0.97)
GCT-L (s)	5.91	0.90 (0.77-0.96)	5.13	0.84 (0.65-0.94)	4.79	0.93 (0.85-0.97)
GCT-R (s)	5.13	0.95 (0.89-0.98)	6.45	0.86 (0.69-0.94)	5.10	0.91 (0.80-0.96)
RSI-L	6.43	0.95 (0.88-0.98)	5.12	0.97 (0.93-0.99)	4.95	0.96 (0.92-0.99)
RSI-R	6.55	0.97 (0.92-0.99)	6.62	0.95 (0.90-0.98)	6.38	0.88 (0.74-0.95)
Linear Speed:						
5m (s)	5.74	0.72 (0.37-0.89)	4.54	0.87 (0.71-0.95)	5.06	0.88 (0.73-0.95)
10m (s)	3.50	0.79 (0.51-0.92)	3.88	0.63 (0.18-0.85)	3.68	0.87 (0.71-0.95)
30m (s)	1.80	0.89 (0.70-0.96)	1.72	0.93 (0.84-0.97)	2.31	0.94 (0.87-0.98)
CODS:						
505-L (s)	1.52	0.94 (0.82-0.98)	1.05	0.97 (0.91-0.99)	1.80	0.81 (0.50-0.93)
505-R (s)	1.07	0.97 (0.93-0.99)	0.93	0.98 (0.94-0.99)	1.80	0.88 (0.69-0.96)

CV = coefficient of variation; ICC = intraclass correlation coefficient; CI = confidence intervals; UCMJ = unilateral countermovement jump; L = left; R = right; m = metres; N = Newtons; CON = concentric; N·s = Newton seconds; UDJ = unilateral drop jump; GCT = ground contact time; s = seconds; RSI = reactive strength index; CODS = change of direction speed.

Table 7.2. Mean fitness test scores ± standard deviations (SD) for pre, mid and end of season, and effect size data (*d*) between time points.

Test/Metric	**Mean ± SD** *(Pre-season)*	**Mean ± SD** *(Mid-season)*	**Mean ± SD** *(End-season)*	**Effect Size** *(Pre-Mid)*	**Effect Size** *(Pre-End)*	**Effect Size** *(Mid-End)*
UCMJ:						
Jump height-L (m)	0.17 ± 0.04	0.15 ± 0.03[a,c]	0.17 ± 0.03	-0.57 (-1.23 to 0.10)	0.00 (-0.65 to 0.65)	0.67 (0.00 to 1.34)
Jump height-R (m)	0.17 ± 0.03	0.15 ± 0.02[b,c]	0.17 ± 0.02	-0.78 (-1.46 to -0.11)	0.00 (-0.65 to 0.65)	1.00 (0.31 to 1.69)
Peak force-L (N)	802.6 ± 149.1	712.4 ± 66.9[a,c]	823.5 ± 170.0	-0.78 (-1.46 to -0.10)	0.13 (-0.52 to 0.78)	0.86 (0.18 to 1.54)
Peak force-R (N)	757.8 ± 161.6	698.3 ± 94.8	784.0 ± 193.7	-0.45 (-1.11 to 0.21)	0.15 (-0.51 to 0.80)	0.56 (-0.10 to 1.23)
CON-impulse-L (N·s)	118.8 ± 27.2	101.6 ± 17.1[b,d]	124.0 ± 14.8	-0.76 (-1.43 to -0.08)	0.24 (-0.42 to 0.89)	1.40 (0.67 to 2.13)
CON-impulse-R (N·s)	121.6 ± 23.4	100.4 ± 14.7[b,d]	121.4 ± 12.8	-1.08 (-1.78 to -0.39)	-0.01 (-0.66 to 0.64)	1.52 (0.78 to 2.27)
UDJ:						
Jump height-L (m)	0.21 ± 0.04	0.21 ± 0.05	0.22 ± 0.05	0.00 (-0.65 to 0.65)	0.22 (-0.43 to 0.88)	0.20 (-0.45 to 0.85)
Jump height-R (m)	0.21 ± 0.04	0.21 ± 0.04	0.21 ± 0.04	0.00 (-0.65 to 0.65)	0.00 (-0.65 to 0.65)	0.00 (-0.65 to 0.65)
GCT-L (s)	0.33 ± 0.05	0.30 ± 0.03	0.28 ± 0.04[b,e]	-0.73 (-1.40 to -0.05)	-1.10 (-1.81 to -0.40)	-0.57 (-1.23 to 0.10)
GCT-R (s)	0.33 ± 0.05	0.31 ± 0.04	0.29 ± 0.03[b]	-0.44 (-1.10 to 0.22)	-0.97 (-1.66 to -0.28)	-0.57 (-1.23 to 0.10)
RSI-L	1.28 ± 0.23	1.37 ± 0.23	1.49 ± 0.26[b,e]	0.39 (-0.27 to 1.05)	0.86 (0.17 to 1.54)	0.49 (-0.17 to 1.15)
RSI-R	1.29 ± 0.28	1.36 ± 0.26	1.45 ± 0.17[b]	0.26 (-0.40 to 0.92)	0.69 (0.02 to 1.36)	0.41 (-0.25 to 1.07)
Linear Speed:						
5m (s)	1.07 ± 0.08	1.09 ± 0.09	1.04 ± 0.10	0.23 (-0.42 to 0.89)	-0.33 (-0.99 to 0.33)	-0.53 (-1.19 to 0.14)
10m (s)	1.76 ± 0.09	1.77 ± 0.08	1.78 ± 0.12	0.12 (-0.54 to 0.77)	0.19 (-0.47 to 0.84)	0.10 (-0.56 to 0.75)
30m (s)	4.15 ± 0.15	4.17 ± 0.17	4.23 ± 0.26	0.12 (-0.53 to 0.78)	0.38 (-0.28 to 1.04)	0.27 (-0.38 to 0.93)
CODS:						
505-L (s)	2.34 ± 0.12	2.30 ± 0.11	2.23 ± 0.08[b,e]	-0.35 (-1.01 to 0.31)	-1.08 (-1.78 to -0.38)	-0.73 (-1.40 to -0.05)
505-R (s)	2.32 ± 0.12	2.30 ± 0.12	2.23 ± 0.10[b]	-0.17 (-0.82 to 0.49)	-0.81 (-1.49 to -0.13)	-0.63 (-1.30 to 0.04)

[a] = significantly different from pre-season ($p < 0.05$); [b] = significantly different from pre-season ($p < 0.01$); [c] = significantly different from end-season ($p < 0.05$); [d] = significantly different from end-season ($p < 0.01$); [e] = significantly different from mid-season ($p < 0.05$).

UCMJ = unilateral countermovement jump; L = left; R = right; m = metres; N·s = Newton seconds; UDJ = unilateral drop jump; RSI = reactive strength index; s = seconds; CODS = change of direction speed.

Table 7.3. Mean inter-limb asymmetry ± SD and effect size (95% confidence intervals) data between pre, mid and end-season.

Test/Metric	**Asymmetry %** *(Pre-season)*	**Asymmetry %** *(Mid-season)*	**Asymmetry %** *(End-season)*	**Effect Size** *(Pre to Mid)*	**Effect Size** *(Pre to End)*	**Effect Size** *(Mid to End)*
UCMJ:						
Jump height	11.19 ± 9.58	8.61 ± 6.99	8.93 ± 6.83	-0.31 (-0.96 to 0.35)	-0.27 (-0.93 to 0.38)	0.05 (-0.61 to 0.70)
Peak force	10.49 ± 8.50	6.22 ± 5.38	9.54 ± 6.63	-0.60 (-1.27 to 0.07)	-0.12 (-0.78 to 0.53)	0.55 (-0.12 to 1.22)
CON impulse	9.14 ± 7.35	8.13 ± 6.07	6.34 ± 5.41	-0.15 (-0.80 to 0.50)	-0.43 (-1.09 to 0.23)	-0.31 (-0.97 to 0.35)
UDJ:						
Jump height	8.42 ± 6.61	10.13 ± 9.15	10.42 ± 8.57	0.21 (-0.44 to 0.87)	0.26 (-0.39 to 0.92)	0.03 (-0.62 to 0.69)
GCT	6.38 ± 3.66	6.96 ± 5.44	6.10 ± 3.63	0.13 (-0.53 to 0.78)	-0.08 (-0.73 to 0.58)	-0.19 (-0.84 to 0.47)
RSI	8.27 ± 6.18	10.80 ± 6.14	9.49 ± 8.05	0.41 (-0.25 to 1.07)	0.17 (-0.48 to 0.82)	-0.18 (-0.84 to 0.47)

UCMJ = unilateral countermovement jump; UDJ = unilateral drop jump; GCT = ground contact time; RSI = reactive strength index.

Table 7.4. Kappa coefficients and accompanying descriptors for levels of agreement describing how consistently asymmetry favoured the same side across pre, mid and end-season.

Test/Metric	**Pre to Mid** *Kappa (Descriptor)*	**Pre to End** *Kappa (Descriptor)*	**Mid to End** *Kappa (Descriptor)*
UCMJ:			
Jump height	0.52 (Moderate)	0.35 (Fair)	0.77 (Substantial)
Peak force	0.51 (Moderate)	0.51 (Moderate)	0.45 (Moderate)
Concentric impulse	0.07 (Slight)	-0.06 (Poor)	0.33 (Fair)
UDJ:			
Jump height	0.20 (Slight)	-0.10 (Poor)	0.68 (Substantial)
Ground contact time	0.32 (Fair)	0.07 (Slight)	0.30 (Fair)
Reactive strength index	0.78 (Substantial)	0.22 (Fair)	0.22 (Fair)

UCMJ = unilateral countermovement jump; UDJ = unilateral drop jump.

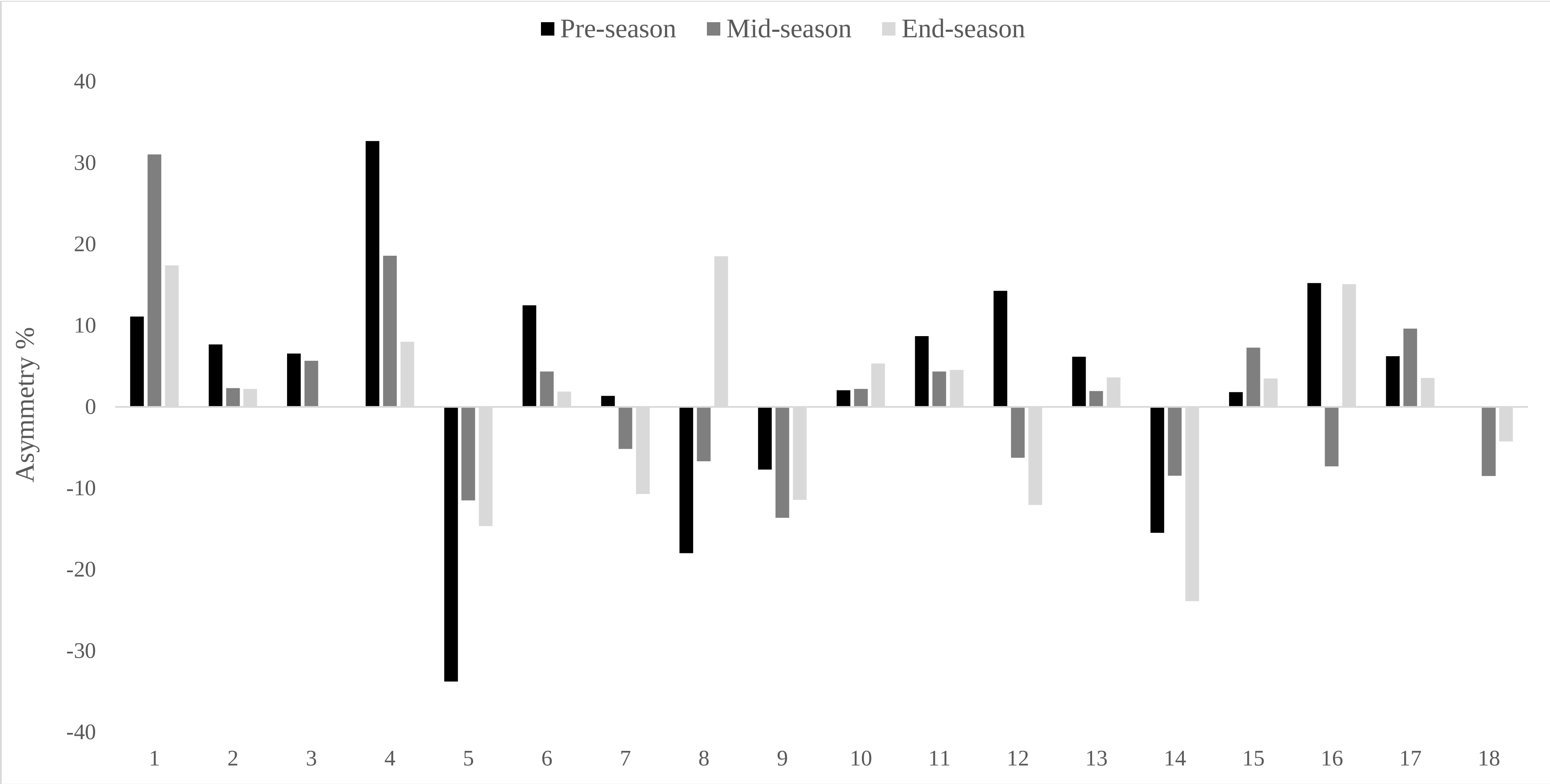


Figure 7.1. Individual asymmetry data for jump height during the unilateral CMJ. N.B: above 0 means asymmetry favours the right leg; below 0 means asymmetry favours the left leg.

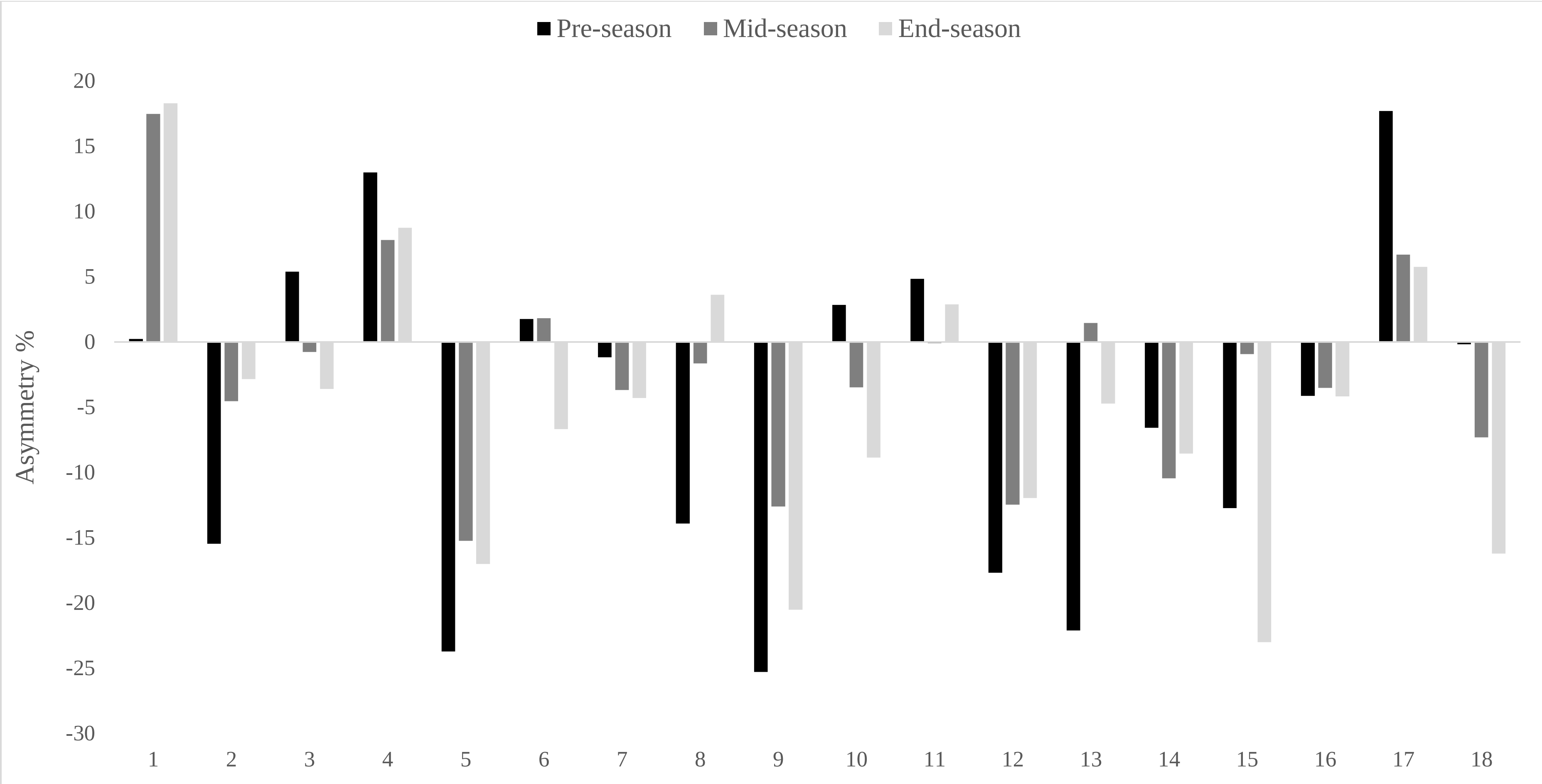


Figure 7.2. Individual asymmetry data for peak force during the unilateral CMJ. N.B: above 0 means asymmetry favours the right leg; below 0 means asymmetry favours the left leg.

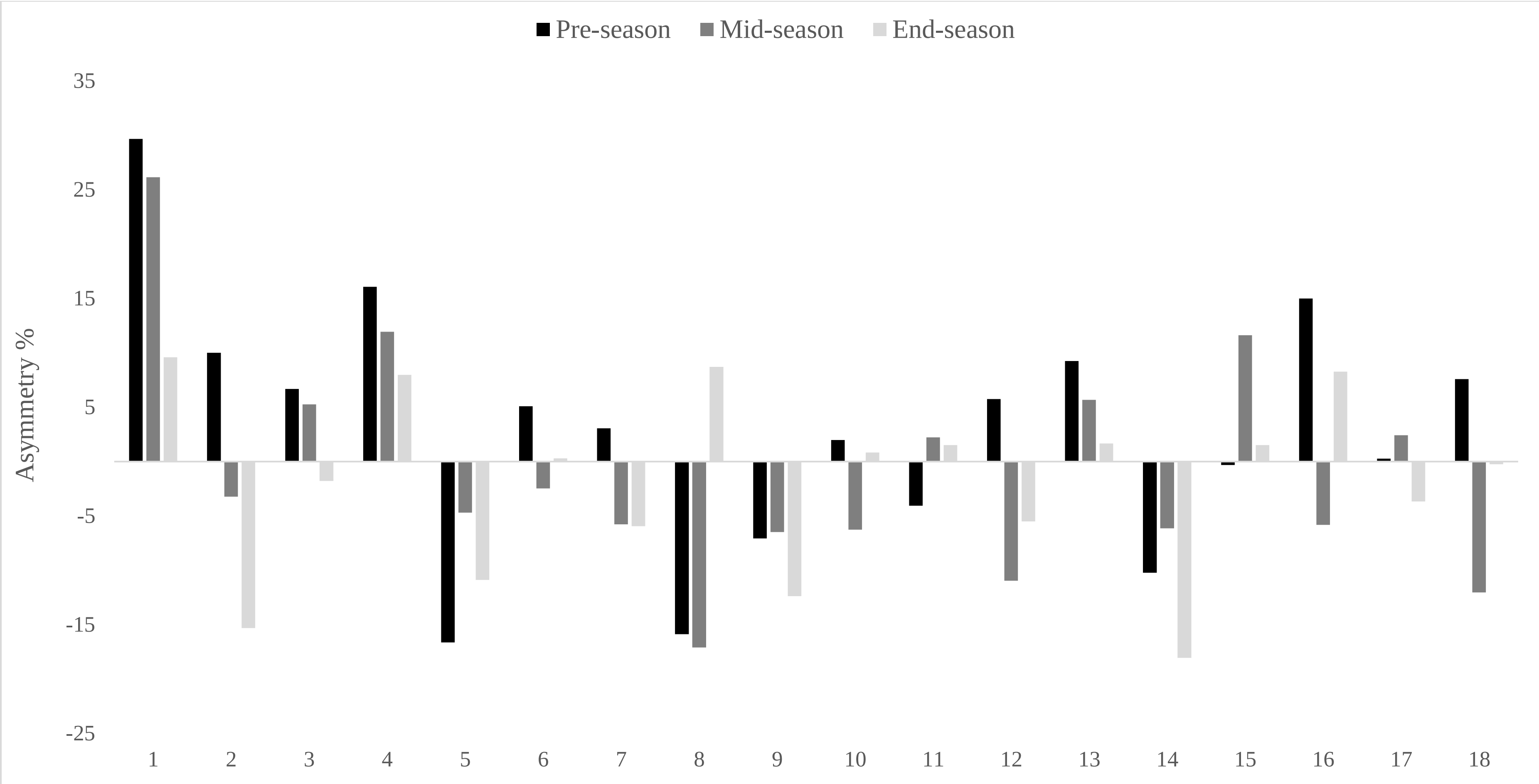


Figure 7.3. Individual asymmetry data for concentric impulse during the unilateral CMJ. N.B: above 0 means asymmetry favours the right leg; below 0 means asymmetry favours the left leg.

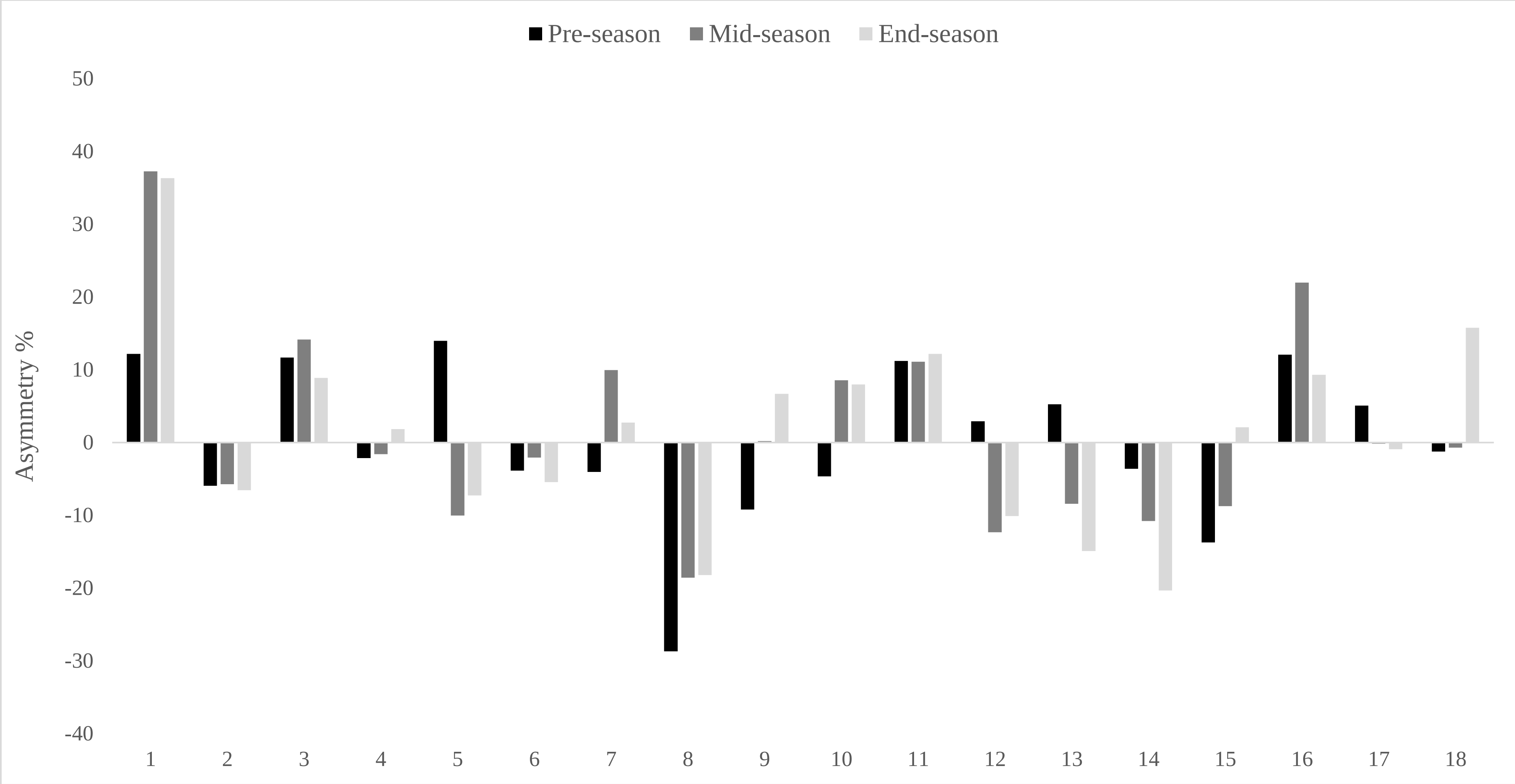


Figure 7.4. Individual asymmetry data for jump height during the unilateral DJ. N.B: above 0 means asymmetry favours the right leg; below 0 means asymmetry favours the left leg.

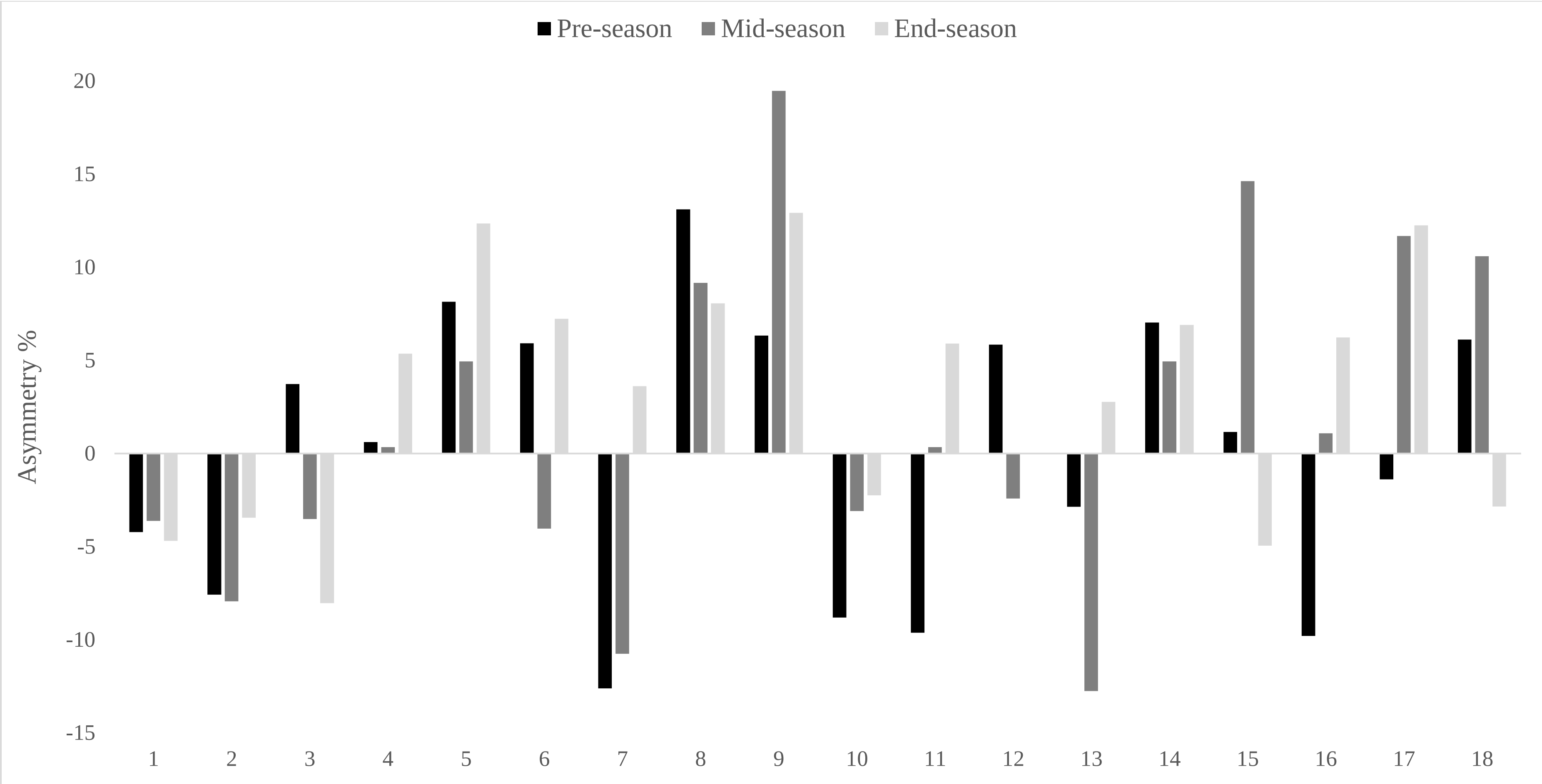


Figure 7.5. Individual asymmetry data for ground contact time during the unilateral DJ. N.B: above 0 means asymmetry favours the right leg; below 0 means asymmetry favours the left leg.

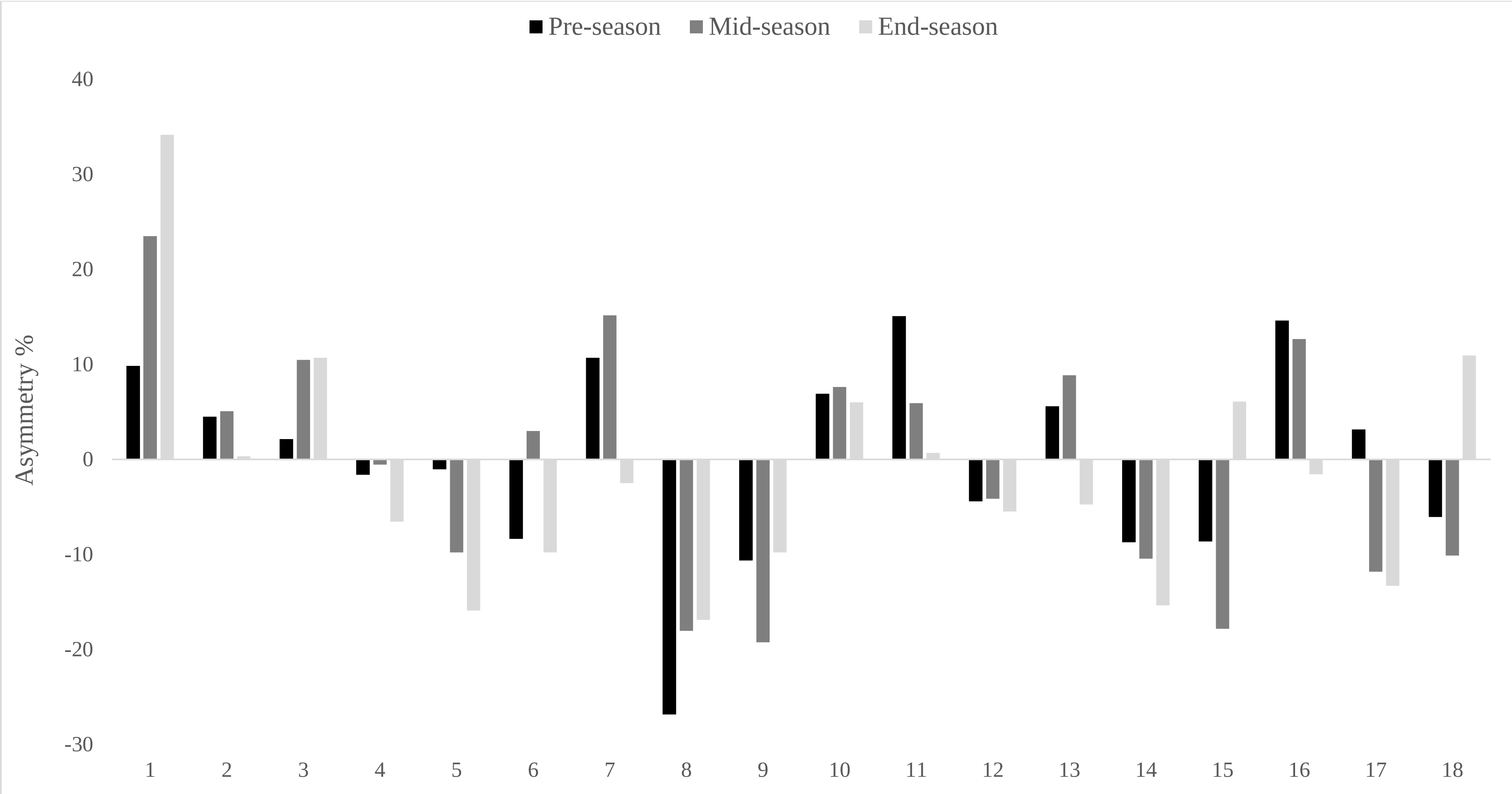


Figure 7.6. Individual asymmetry data for reactive strength index during the unilateral DJ. N.B: above 0 means asymmetry favours the right leg; below 0 means asymmetry favours the left leg.

Table 7.5 shows all correlations between jump asymmetries and speed and CODS tests at each time point. No significant relationships were present at the pre or mid-season time points (ρ = -0.32 to 0.37). However, at the end of season, significant large relationships were found between DJ height asymmetry and 5 m (ρ = 0.63 [CI = 0.23-0.85]; p = 0.005), 10 m (ρ = 0.62; [CI = 0.22-0.84]; p = 0.006) and 505 on the right limb (ρ = 0.65; [CI = 0.26-0.86]; p = 0.003).

Table 7.6 shows relationships between changes in asymmetry and changes in performance tasks. No significant relationships were evident (ρ = -0.44 to 0.56). Kappa coefficients showing levels of agreement between changes in asymmetry and changes in performance tasks are shown in Table 7.7 and showed very high variation across the season. For unilateral CMJ metrics, Kappa values ranged from poor to substantial (-0.56 to 0.64), when determining levels of agreement with performance changes throughout the season. For the unilateral DJ, Kappa values ranged from poor to moderate (-0.62 to 0.44), when determining levels of agreement with performance changes throughout the season.

Tables 7.8-7.10 show results when using the median split to create high and low asymmetry groups for pre, mid and end-season respectively. At all time points, significant differences in asymmetry were found between groups for all jump metrics ($p < 0.01$). For performance tests, significant differences were found at the end-season time point between groups when using DJ height asymmetry for 10 m ($p < 0.05$; d = -1.15), 505 left ($p < 0.05$; d = -0.96) and 505 right ($p < 0.01$; d = -1.40). No other significant differences in speed or CODS were present between groups.

Table 7.5. Spearman's ρ correlations between jump asymmetry data and performance at all time points.

Asymmetry Test/Metric	5 m	10 m	30 m	505 (left)	505 (right)
Pre-season UCMJ:					
Jump height	0.33	0.25	0.18	-0.11	0.06
Peak force	0.10	0.10	0.16	0.15	0.18
CON impulse	0.36	0.27	0.24	0.03	0.12
Pre-season UDJ:					
Jump height	0.14	0.10	0.14	-0.04	0.12
GCT	-0.28	-0.31	-0.32	0.31	0.08
RSI	-0.06	-0.09	0.01	0.30	0.03
Mid-season UCMJ:					
Jump height	0.20	0.03	0.37	-0.15	-0.19
Peak force	0.35	0.27	0.36	0.11	-0.09
CON impulse	-0.02	0.01	0.32	-0.09	0.13
Mid-season UDJ:					
Jump height	-0.10	0.16	-0.01	0.11	0.21
GCT	-0.08	-0.25	-0.07	-0.04	-0.01
RSI	0.04	-0.08	0.18	0.11	0.20
End-season UCMJ:					
Jump height	0.53	0.44	0.44	0.35	0.27
Peak force	0.02	0.10	0.37	0.21	0.09
CON impulse	0.34	0.29	0.15	0.01	-0.13
End-season UDJ:					
Jump height	0.63**	0.62**	0.42	0.35	0.65**
GCT	-0.24	-0.20	-0.14	-0.08	-0.40
RSI	-0.03	-0.02	0.15	0.02	0.04

** = significant at $p < 0.008$.

UCMJ = unilateral countermovement jump; CON = concentric; UDJ = unilateral drop jump; GCT = ground contact time; RSI = reactive strength index.

Table 7.6. Spearman's ρ correlations between the change in asymmetry and the change in performance scores at all time points.

Asymmetry Test/Metric	Δ 5 m	Δ 10 m	Δ 30 m	Δ 505 (left)	Δ 505 (right)
Pre-season UCMJ:					
Δ Jump height	0.18	0.01	0.21	0.08	0.28
Δ Peak force	-0.13	-0.06	0.19	0.15	0.10
Δ CON impulse	0.18	0.01	-0.33	0.11	0.34
Pre-season UDJ:					
Δ Jump height	-0.16	-0.22	0.19	0.13	-0.02
Δ GCT	0.25	0.11	-0.01	0.01	0.10
Δ RSI	0.02	0.08	0.23	0.24	0.11
Mid-season UCMJ:					
Δ Jump height	0.30	0.20	0.32	0.21	0.22
Δ Peak force	-0.03	-0.03	-0.10	0.56	0.31
Δ CON impulse	0.21	0.21	0.20	-0.06	-0.33
Mid-season UDJ:					
Δ Jump height	0.28	0.36	0.21	-0.12	0.16
Δ GCT	-0.44	-0.36	-0.09	0.07	0.08
Δ RSI	-0.14	-0.15	-0.04	0.12	0.20
End-season UCMJ:					
Δ Jump height	0.31	0.37	0.31	-0.18	-0.24
Δ Peak force	-0.12	-0.11	0.23	0.34	0.12
Δ CON impulse	0.03	0.04	0.06	-0.25	-0.25
End-season UDJ:					
Δ Jump height	0.29	0.49	0.41	-0.12	0.24
Δ GCT	0.07	0.13	-0.38	-0.13	-0.04
Δ RSI	0.27	0.23	-0.09	0.02	0.42

UCMJ = unilateral countermovement jump; CON = concentric; UDJ = unilateral drop jump; GCT = ground contact time; RSI = reactive strength index.

Table 7.7. Kappa coefficients and descriptive levels of agreement for the changes in asymmetry during both jump tests and changes in performance between time points.

Asymmetry Metric	5 m	10 m	30 m	505 (left)	505 (right)
UCMJ Jump Height:					
Pre-Mid	0.28 (Fair)	0.36 (Fair)	0.07 (Slight)	0.16 (Slight)	0.40 (Fair)
Pre-End	0.30 (Fair)	0.12 (Slight)	0.46 (Moderate)	0.16 (Slight)	0.30 (Fair)
Mid-End	0.44 (Moderate)	0.56 (Moderate)	0.33 (Fair)	-0.44 (Poor)	-0.56 (Poor)
UCMJ Peak Force:					
Pre-Mid	-0.20 (Poor)	0.20 (Slight)	0.00 (Poor)	-0.18 (Poor)	-0.01 (Poor)
Pre-End	0.07 (Slight)	-0.31 (Poor)	0.03 (Slight)	0.40 (Fair)	0.30 (Fair)
Mid-End	-0.02 (Poor)	-0.09 (Poor)	0.22 (Fair)	0.15 (Slight)	-0.22 (Poor)
UCMJ CON Impulse:					
Pre-Mid	0.28 (Fair)	0.36 (Fair)	-0.14 (Poor)	0.26 (Fair)	0.64 (Substantial)
Pre-End	-0.01 (Poor)	-0.07 (Poor)	0.07 (Slight)	0.28 (Fair)	-0.01 (Poor)
Mid-End	0.11 (Slight)	-0.40 (Poor)	-0.11 (Poor)	-0.39 (Poor)	-0.17 (Poor)
UDJ Jump Height:					
Pre-Mid	-0.07 (Poor)	-0.19 (Poor)	-0.07 (Poor)	-0.06 (Poor)	-0.16 (Poor)
Pre-End	0.44 (Moderate)	0.44 (Moderate)	0.33 (Fair)	-0.33 (Poor)	-0.22 (Poor)
Mid-End	0.00 (Poor)	0.11 (Slight)	0.11 (Slight)	0.00 (Poor)	0.33 (Fair)
UDJ GCT:					
Pre-Mid	0.40 (Fair)	0.07 (Slight)	0.20 (Slight)	0.09 (Slight)	0.25 (Fair)
Pre-End	-0.62 (Poor)	-0.53 (Poor)	-0.19 (Poor)	-0.09 (Poor)	0.07 (Slight)
Mid-End	0.22 (Fair)	-0.33 (Poor)	-0.22 (Poor)	0.00 (Poor)	0.11 (Slight)
UDJ RSI:					
Pre-Mid	0.25 (Fair)	0.16 (Slight)	0.25 (Fair)	0.13 (Slight)	0.00 (Poor)
Pre-End	-0.33 (Poor)	-0.33 (Poor)	-0.33 (Poor)	-0.33 (Poor)	0.00 (Poor)
Mid-End	0.00 (Poor)	-0.11 (Poor)	-0.33 (Poor)	0.22 (Fair)	0.33 (Fair)

UCMJ = unilateral countermovement jump; CON = concentric; UDJ = unilateral drop jump; GCT = ground contact time; RSI = reactive strength index.

Table 7.8. Mean inter-limb asymmetry, performance test scores ± standard deviations and Cohen's *d* effect sizes (95% confidence intervals) between high and low asymmetry groups during pre-season.

Jump Test/Metric	Asymmetry %	5m (s)	10m (s)	30m (s)	505-L (s)	505-R (s)
UCMJ Jump Height:						
High asymmetry	17.97 ± 9.06	1.10 ± 0.08	1.79 ± 0.10	4.19 ± 0.07	2.33 ± 0.10	2.33 ± 0.12
Low asymmetry	4.40 ± 3.03**	1.05 ± 0.06	1.74 ± 0.08	4.12 ± 0.12	2.34 ± 0.14	2.32 ± 0.13
Effect size (*d*)	-2.01 (-3.14 to -0.88)	-0.71 (-1.66 to 0.25)	-0.55 (-1.49 to 0.39)	-0.48 (-1.41 to 0.46)	0.08 (-0.84 to 1.01)	-0.08 (-1.00 to 0.84)
UCMJ Peak Force:						
High asymmetry	17.96 ± 4.73	1.07 ± 0.05	1.76 ± 0.06	4.17 ± 0.11	2.33 ± 0.14	2.33 ± 0.10
Low asymmetry	3.02 ± 2.34**	1.08 ± 0.10	1.77 ± 0.12	4.13 ± 0.19	2.34 ± 0.09	2.33 ± 0.14
Effect size (*d*)	-4.00 (-5.61 to -2.40)	0.13 (-0.80 to 1.05)	0.11 (-0.82 to 1.03)	-0.26 (-1.19 to 0.67)	0.08 (-0.84 to 1.01)	0.00 (-0.92 to 0.92)
UCMJ CON Impulse:						
High asymmetry	14.48 ± 6.64	1.09 ± 0.10	1.78 ± 0.11	4.18 ± 0.18	2.34 ± 0.10	2.31 ± 0.09
Low asymmetry	3.81 ± 2.57**	1.05 ± 0.05	1.75 ± 0.07	4.12 ± 0.11	2.34 ± 0.14	2.34 ± 0.15
Effect size (*d*)	-2.12 (-3.27 to -0.96)	-0.51 (-1.44 to 0.43)	-0.33 (-1.26 to 0.60)	-0.40 (-1.34 to 0.53)	0.00 (-0.92 to 0.92)	0.24 (-0.68 to 1.17)
UDJ Jump Height:						
High asymmetry	13.20 ± 6.31	1.09 ± 0.09	1.79 ± 0.10	4.17 ± 0.16	2.34 ± 0.12	2.35 ± 0.11
Low asymmetry	3.65 ± 1.34**	1.05 ± 0.06	1.74 ± 0.08	4.13 ± 0.14	2.33 ± 0.12	2.31 ± 0.13
Effect size (*d*)	-2.09 (-3.24 to -0.94)	-0.52 (-1.46 to 0.42)	-0.55 (-1.49 to 0.39)	-0.27 (-1.19 to 0.66)	-0.08 (-1.01 to 0.84)	-0.33 (-1.26 to 0.60)
UDJ GCT:						
High asymmetry	9.23 ± 2.35	1.06 ± 0.06	1.74 ± 0.07	4.10 ± 0.13	2.37 ± 0.11	2.35 ± 0.13
Low asymmetry	3.54 ± 2.17**	1.09 ± 0.09	1.79 ± 0.11	4.20 ± 0.16	2.31 ± 0.12	2.31 ± 0.11
Effect size (*d*)	-2.52 (-3.75 to -1.28)	0.39 (-0.54 to 1.33)	0.54 (-0.40 to 1.48)	0.69 (-0.26 to 1.64)	-0.52 (-1.46 to 0.42)	-0.33 (-1.26 to 0.60)
UDJ RSI:						
High asymmetry	12.60 ± 5.88	1.08 ± 0.10	1.77 ± 0.12	4.15 ± 0.19	2.33 ± 0.12	2.32 ± 0.13
Low asymmetry	3.94 ± 2.07**	1.07 ± 0.05	1.76 ± 0.07	4.16 ± 0.11	2.34 ± 0.12	2.34 ± 0.12
Effect size (*d*)	-1.96 (-3.09 to -0.84)	-0.13 (-1.05 to 0.80)	-0.10 (-1.03 to 0.82)	0.06 (-0.86 to 0.99)	0.08 (-0.84 to 1.01)	0.16 (-0.77 to 1.09)

** significantly different between groups ($p < 0.01$).

UCMJ = unilateral countermovement jump; CON = concentric; UDJ = unilateral drop jump; GCT = ground contact time; RSI = reactive strength index.

Table 7.9. Mean inter-limb asymmetry, performance test scores ± standard deviations and Cohen's *d* effect sizes (95% confidence intervals) between high and low asymmetry groups during mid-season.

Jump Test/Metric	Asymmetry %	5m (s)	10m (s)	30m (s)	505-L (s)	505-R (s)
UCMJ Jump Height:						
High asymmetry	12.88 ± 7.72	1.12 ± 0.10	1.78 ± 0.11	4.24 ± 0.20	2.29 ± 0.10	2.28 ± 0.09
Low asymmetry	4.33 ± 1.79**	1.06 ± 0.08	1.76 ± 0.05	4.11 ± 0.13	2.32 ± 0.13	2.33 ± 0.15
Effect size (*d*)	-1.53 (-2.58 to -0.48)	-0.66 (-1.61 to 0.29)	-0.23 (-1.16 to 0.69)	-0.77 (-1.73 to 0.19)	0.26 (-0.67 to 1.19)	0.40 (-0.53 to 1.34)
UCMJ Peak Force:						
High asymmetry	10.51 ± 4.29	1.11 ± 0.08	1.79 ± 0.10	4.22 ± 0.18	2.29 ± 0.10	2.28 ± 0.10
Low asymmetry	1.93 ± 1.32**	1.06 ± 0.10	1.75 ± 0.04	4.13 ± 0.17	2.32 ± 0.13	2.33 ± 0.14
Effect size (*d*)	-2.70 (-3.98 to -1.43)	-0.55 (-1.49 to 0.39)	-0.53 (-1.46 to 0.41)	-0.51 (-1.45 to 0.43)	0.26 (-0.67 to 1.19)	0.41 (-0.52 to 1.34)
UCMJ CON Impulse:						
High asymmetry	12.08 ± 6.37	1.09 ± 0.08	1.77 ± 0.11	4.21 ± 0.18	2.31 ± 0.10	2.32 ± 0.12
Low asymmetry	4.17 ± 1.56**	1.09 ± 0.11	1.76 ± 0.04	4.14 ± 0.17	2.30 ± 0.13	2.29 ± 0.13
Effect size (*d*)	-1.71 (-2.78 to -0.63)	0.00 (-0.92 to 0.92)	-0.12 (-1.05 to 0.80)	-0.40 (-1.33 to 0.53)	-0.09 (-1.01 to 0.84)	-0.24 (-1.17 to 0.69)
UDJ Jump Height:						
High asymmetry	16.24 ± 8.91	1.07 ± 0.12	1.78 ± 0.10	4.17 ± 0.23	2.32 ± 0.08	2.32 ± 0.11
Low asymmetry	4.02 ± 3.80**	1.10 ± 0.06	1.76 ± 0.06	4.18 ± 0.10	2.28 ± 0.14	2.28 ± 0.13
Effect size (*d*)	-1.78 (-2.88 to -0.69)	0.32 (-0.61 to 1.25)	-0.24 (-1.17 to 0.68)	0.06 (-0.87 to 0.98)	-0.35 (-1.28 to 0.58)	-0.33 (-1.26 to 0.60)
UDJ GCT:						
High asymmetry	11.33 ± 4.14	1.08 ± 0.08	1.74 ± 0.07	4.13 ± 0.15	2.30 ± 0.12	2.29 ± 0.10
Low asymmetry	2.60 ± 1.66**	1.10 ± 0.10	1.80 ± 0.09	4.22 ± 0.19	2.30 ± 0.11	2.31 ± 0.15
Effect size (*d*)	-2.77 (-4.06 to -1.48)	0.22 (-0.71 to 1.15)	0.74 (-0.21 to 1.70)	0.53 (-0.41 to 1.47)	0.00 (-0.92 to 0.92)	0.16 (-0.77 to 1.08)
UDJ RSI:						
High asymmetry	15.47 ± 4.50	1.09 ± 0.13	1.77 ± 0.10	4.19 ± 0.24	2.30 ± 0.10	2.29 ± 0.09
Low asymmetry	6.12 ± 3.27**	1.09 ± 0.04	1.77 ± 0.05	4.16 ± 0.08	2.30 ± 0.13	2.31 ± 0.15
Effect size (*d*)	-2.38 (-3.58 to -1.17)	0.00 (-0.92 to 0.92)	0.00 (-0.92 to 0.92)	-0.17 (-1.09 to 0.76)	0.00 (-0.92 to 0.92)	0.16 (-0.76 to 1.09)

** significantly different between groups ($p < 0.01$).

UCMJ = unilateral countermovement jump; CON = concentric; UDJ = unilateral drop jump; GCT = ground contact time; RSI = reactive strength index.

Table 7.10. Mean inter-limb asymmetry, performance test scores ± standard deviations and Cohen's *d* effect sizes (95% confidence intervals) between high and low asymmetry groups during end-season.

Jump Test/Metric	Asymmetry %	5m (s)	10m (s)	30m (s)	505-L (s)	505-R (s)
UCMJ Jump Height:						
High asymmetry	14.64 ± 4.80	1.07 ± 0.08	1.80 ± 0.12	4.24 ± 0.22	2.25 ± 0.09	2.23 ± 0.11
Low asymmetry	3.22 ± 1.62**	1.01 ± 0.11	1.76 ± 0.12	4.21 ± 0.30	2.21 ± 0.07	2.24 ± 0.10
Effect size (*d*)	-3.19 (-4.58 to -1.80)	-0.62 (-1.57 to 0.32)	-0.33 (-1.26 to 0.60)	-0.11 (-1.04 to 0.81)	-0.50 (-1.43 to 0.44)	0.10 (-0.83 to 1.02)
UCMJ Peak Force:						
High asymmetry	14.80 ± 5.46	1.06 ± 0.09	1.81 ± 0.11	4.32 ± 0.20	2.24 ± 0.09	2.24 ± 0.09
Low asymmetry	4.29 ± 1.27**	1.01 ± 0.10	1.75 ± 0.13	4.13 ± 0.28	2.22 ± 0.08	2.23 ± 0.12
Effect size (*d*)	-2.65 (-3.92 to -1.39)	-0.53 (-1.47 to 0.41)	-0.50 (-1.44 to 0.44)	-0.78 (-1.74 to 0.18)	-0.23 (-1.16 to 0.69)	-0.09 (-1.02 to 0.83)
UCMJ CON Impulse:						
High asymmetry	10.79 ± 3.86	1.07 ± 0.08	1.78 ± 0.11	4.23 ± 0.22	2.23 ± 0.10	2.23 ± 0.11
Low asymmetry	1.89 ± 1.70**	1.01 ± 0.11	1.77 ± 0.13	4.22 ± 0.30	2.23 ± 0.06	2.25 ± 0.10
Effect size (*d*)	-2.98 (-4.33 to -1.64)	-0.62 (-1.57 to 0.32)	-0.08 (-1.01 to 0.84)	-0.04 (-0.96 to 0.89)	0.00 (-0.92 to 0.92)	0.19 (-0.74 to 1.12)
UDJ Jump Height:						
High asymmetry	16.22 ± 8.54	1.07 ± 0.11	1.84 ± 0.13	4.27 ± 0.26	2.26 ± 0.05	2.30 ± 0.11
Low asymmetry	4.61 ± 2.70**	1.00 ± 0.07	1.72 ± 0.07*	4.18 ± 0.26	2.19 ± 0.09*	2.18 ± 0.05**
Effect size (*d*)	-1.83 (-2.93 to -0.73)	-0.76 (-1.72 to 0.20)	-1.15 (-2.15 to -0.15)	-0.35 (-1.28 to 0.58)	-0.96 (-1.94 to 0.01)	-1.40 (-2.44 to -0.37)
UDJ GCT:						
High asymmetry	8.88 ± 2.82	1.02 ± 0.10	1.77 ± 0.12	4.17 ± 0.20	2.22 ± 0.09	2.21 ± 0.08
Low asymmetry	3.33 ± 1.64**	1.05 ± 0.10	1.78 ± 0.13	4.28 ± 0.31	2.23 ± 0.07	2.26 ± 0.12
Effect size (*d*)	-2.41 (-3.62 to -1.19)	0.30 (-0.63 to 1.23)	0.08 (-0.84 to 1.00)	0.42 (-0.51 to 1.36)	0.12 (-0.80 to 1.05)	0.49 (-0.45 to 1.43)
UDJ RSI:						
High asymmetry	15.20 ± 7.62	1.03 ± 0.11	1.77 ± 0.12	4.20 ± 0.24	2.23 ± 0.09	2.24 ± 0.12
Low asymmetry	3.77 ± 2.49**	1.05 ± 0.08	1.79 ± 0.13	4.25 ± 0.29	2.22 ± 0.07	2.23 ± 0.10
Effect size (*d*)	-2.02 (-3.15 to -0.88)	0.21 (-0.72 to 1.13)	0.16 (-0.77 to 1.09)	0.19 (-0.74 to 1.11)	-0.12 (-1.05 to 0.80)	-0.09 (-1.01 to 0.83)

** significantly different between groups ($p < 0.01$); * significantly different between groups ($p < 0.05$).
UCMJ = unilateral countermovement jump; CON = concentric; UDJ = unilateral drop jump; GCT = ground contact time; RSI = reactive strength index.

7.4 Discussion

The aims of the present study were: 1) determine the relationship between jump asymmetries and athletic performance tasks at a range of different time points in a competitive soccer season, 2) determine the relationship between changes in asymmetry and changes in athletic performance tasks, 3) provide seasonal variation data for unilateral jump, speed and CODS tasks and, 4) provide seasonal variation for the magnitude and direction of asymmetry during unilateral jump tasks.

Results showed that when assessing relationships, significant correlations between asymmetry and measures of athletic performance were evident, but only at the end-season time point. However, when determining relationships between changes in asymmetry and changes in performance tasks, no meaningful associations were found, with large variation in levels of agreement. Finally, the median split analysis revealed that significant differences existed between high and low asymmetry groups for all asymmetry variables at all time points, but only 10 m and 505 performance at the end-season time point when using DJ height asymmetry to split the group.

When considering seasonal variation, significant reductions in unilateral CMJ performance at mid-season with performance improving at the end-season time point. For the unilateral DJ, minimal change was evident for jump height; however, GCT showed small to moderate improvements across the season, which had a similar effect on changes in RSI. The magnitude of asymmetry remained consistent throughout the season, showing no significant changes. However, the direction of asymmetry varied considerably with slight to substantial levels of agreement for both jump tests throughout the season and this in part has likely contributed to the lack of significant findings when examining associations with sprint and CODS performance.

To the authors' knowledge, this is the first study to monitor the association between asymmetry and measures of athletic performance over the course of a season in team sport athletes. Significant large associations between DJ height asymmetry and 5 m (ρ = 0.63; p < 0.008), 10 m (ρ = 0.62; p < 0.008) and 505 right (ρ = 0.65; p < 0.008) were evident at the end of season. Of note, all significant correlations are positive indicating that larger asymmetries in DJ height are associated with slower acceleration, speed and CODS performance. However, given that no significant relationships were evident during pre and mid-season, it can be concluded that the association between asymmetry and performance does not track over time in elite academy soccer players. Whilst challenging to fully explain, previous literature has shown that between-limb differences are highly task-specific (Bishop et al. 2018c; Bishop et al. 2019d; Dos'Santos et al. 2017b; Lockie et al. 2014; Maloney et al. 2016); thus, the varying nature of asymmetry is almost certainly one of the key factors in the lack of consistency in results. This is supported by viewing Tables 7.8-7.10, which show the SD is often quite large relative to the mean for the asymmetry scores, in both the high and low asymmetry groups. Furthermore, Figures 7.1-7.6 show that the individual asymmetry scores are also highly variable, regardless of test, metric or time point throughout the season.

To further comprehend how asymmetry interacts with athletic performance tasks, the change in asymmetry and performance was also monitored throughout the season and no significant associations were found. Given the high degree of variability seen in asymmetry across the season (i.e., some players increased and some players decreased), this provided both positive and negative changes in asymmetry at each time point. Furthermore, with no consistent trend as to how this occurred, it is perhaps not surprising that significant relationships were not evident. The Kappa coefficient was also used to determine levels of agreement between changes in asymmetry and changes in performance tests. Collectively, results showed limited levels of agreement, with only CMJ concentric impulse showing substantial agreement (Kappa = 0.64) between changes in asymmetry and changes in 505 on the right limb in the first half of the season. As such, these data further support the notion that changes in asymmetry are largely unrelated to changes in performance and may well be a natural consequence of competing throughout a soccer season (Hart et al. 2016). However, it is worth noting that total time was the metric used for the speed and CODS tests and similar to the jump tests used in the present study. It is plausible that a more in-depth analysis of the strategy used to perform these speed/CODS tasks is required in order to understand the interaction between asymmetry and performance tasks. As such, metrics such as contact time and stiffness (for linear speed) and entry/exit velocity (for CODS) could be viable options for practitioners to consider in future investigations.

To further examine if greater asymmetry was associated with reductions in athletic performance tasks, the present study also used a median split analysis, splitting the sample into high and low asymmetry groups. Given the nature of how groups were formed, it is unsurprising that significant differences in asymmetry were seen between groups at all time points. In addition, at the end of the season, the low asymmetry group were significantly faster at 10 m and 505 on both limbs, but only when splitting groups via DJ height asymmetry. The lack of significant differences in performance tests between groups (when splitting via all other asymmetry metrics) is likely explained by the small sample size and must be considered as a limitation to this investigation. In addition, given the median split analysis was used 18 times in the present study (6 times at each time point), and significant differences in speed and CODS were only found between groups once, this provides further support that asymmetry and athletic performance measures are most likely independent of each other. Further to this, even when moderate effects were observed between groups (e.g., Table 7.9, at mid-season for 30 m times, when splitting via CMJ height asymmetry; ES = -

0.77), the confidence intervals show that the range of differences could be anything from large reductions to trivial increases (-1.73 to 0.19). This further supports the notion that asymmetry and athletic performance are most likely not related when assessed over time and should be interpreted on an individual basis (Bishop et al. 2018b; Bishop et al. 2019c; Bishop et al. 2019d).

The inconsistencies in asymmetry shown by players across the different time-points can at least in part provide an explanation as to the lack of associations with performance. However, seasonal variation in jump performance may also help to explain this which was evident for both the unilateral CMJ and unilateral DJ tests (Table 7.2). For the unilateral CMJ, small to moderate reductions in jump height (ES = -0.57 to -0.78) and peak force (ES = -0.45 to -0.78) were seen from pre to mid-season, whilst concentric impulse showed moderate reductions (ES = -0.76 to -1.08). Changes from pre to end-season were trivial to small across all metrics (ES = -0.01 to 0.24). However, when reporting changes from mid to end-season, moderate increases were seen for jump height (ES = 0.67 to 1.00), small to moderate increases for peak force (ES = 0.56 to 0.86) and large increases for concentric impulse (ES = 1.40 to 1.52). Although challenging to fully explain, previous literature has indicated that fixture density is often greatest during the middle of a soccer season (Carling et al. 2012), something which may have affected the sample in this investigation. For example, players were required to play 4 matches in 11 days over the Christmas and New Year period, just prior to mid-season testing in January. This may in part explain why jump performance showed notable reductions at the mid-season time point for the unilateral CMJ. However, practitioners should take particular caution when interpreting data from pre to end-season, given the inherent variability shown in the confidence intervals. For example, changes between these time points showed moderate negative or positive changes (see

Table 7.2); thus, it is advised that practitioners examine these changes in performance on an individual level before relying on the mean data to inform subsequent decision-making.

Interestingly, the DJ showed a different trend. Jump height was not sensitive enough to show any meaningful changes throughout the season (ES = 0.00 to 0.22). However, players showed small to moderate reductions in GCT from pre to mid-season (ES = -0.44 to -0.73), and moderate reductions from pre to end-season (ES = -0.97 to -1.10), indicating a change in jump strategy during this test. Equally, the confidence intervals highlight that reductions in GCT were small to large on an individual level from the first to the last time point. In turn, noting that RSI is a consequence of both jump height and GCT, it stands to reason that this metric also showed a similar (albeit reduced) trend, with small improvements from pre to mid-season (ES = 0.26 to 0.39) and moderate improvements from mid to end-season (ES = 0.69 to 0.86). These data indicate that players were "stiffer" when performing the DJ as the season progressed, highlighting the importance of monitoring jump strategy, as well as outcome measures, such as jump height. It is also plausible that there was a greater learning effect for the DJ test as the season progressed, which seems plausible given the DJ is likely to be a more technically demanding task than the CMJ (Pedley et al. 2017), especially when performed unilaterally (Maloney et al. 2016). Therefore, it is suggested that the inclusion of both vertical and reactive strength jump tests highlight different changes in jump performance throughout the season, suggesting that both may have their place in profiling elite academy soccer players' unilateral jump performance.

Meaningful variations in performance were also evident for the 505 test, but not linear speed. The 505 showed a similar trend to the DJ test, with performance improving as the season progressed, and peaking at end of season testing. This is again, somewhat challenging to fully explain. However, previous research has suggested an increased requirement for technical competence and enhanced motor control when changing direction, in comparison to straight line running (Sheppard and Young, 2006; Young et al. 2002; Young and Farrow, 2006). Furthermore, given the previously stated importance of agility and CODS in soccer (Bangsbo, 1992; Chaouachi et al. 2012; McFarland et al. 2016; Tous-Fajardo et al. 2016; Turner, 2011), it is plausible that as the season progressed, players became more “match fit” and the increased exposure to changing direction stimulated improved performance as the season progressed.

Mean inter-limb asymmetry values (Table 7.3) showed relatively consistent scores with between-limb differences for the unilateral CMJ ranging from 6.22-11.19%, which represented trivial to small changes (ES = -0.60 to 0.55). For the unilateral DJ, mean asymmetry values ranged from 6.10-10.80%, again representing trivial to small changes (ES = -0.19 to 0.41). However, caution should be applied when interpreting these data and concluding that inter-limb asymmetry is consistent throughout a soccer season. Firstly, Table 7.3 shows the high SD for each metric when using the mean asymmetry score and may explain why only trivial to small changes were evident between time points. Owing to the variable nature of asymmetry, Bishop et al. (2018b) suggested that an individual approach to assessing asymmetry is likely needed in order to establish meaningful data. For example, in Figure 7.1, subjects 4 and 5 exhibited large asymmetries in jump height during pre-season (32.7 and -33.8%, respectively). In contrast, subjects 7 and 15 showed very small imbalances (1.4 and 1.8%, respectively). Thus, with such large variation in the group, it does not seem surprising that asymmetry values remained consistent throughout the season, when interpreted as a group mean score. Therefore, and in line with recent suggestions, a more individual approach to data interpretation is likely needed (Bishop et al. 2018b; Bishop et al. 2019b).

Recent literature has suggested investigating the direction of asymmetry in an attempt to establish how consistently asymmetry favours the same limb during either tests (Bishop et al. 2018b) or time points (Bishop et al. 2019e). In the present study, this was done via the use of the Kappa coefficient statistic, which determines the proportion of agreement once any agreement by chance has been removed (Cohen, 1960). Thus, this method of analysis represents a robust method of detecting the direction of asymmetry on an individual level and to the authors' knowledge, has not been done longitudinally for this topic (Bishop et al. 2019e).

Results showed that the direction of asymmetry is metric-specific and variable within each jump test (Table 7.4). During the unilateral CMJ, jump height showed substantial levels of agreement (Kappa = 0.77) when comparing asymmetry data from mid to end-season, but only fair levels of agreement (Kappa = 0.35) from pre to end-season. In contrast, peak force showed moderate levels of agreement (Kappa = 0.45 to 0.51) throughout the season, whereas concentric impulse was much more variable and showed poor to fair levels of agreement throughout the season (Kappa = -0.06 to 0.33). These data show that strategy-based metrics (e.g., impulse) exhibits substantial variation in asymmetry in comparison to metrics such as jump height or peak force; thus, may be too inconsistent to use when profiling existing side-to-side differences, which represents a novel finding on the topic of inter-limb asymmetry.

The unilateral DJ showed similar variation when assessing the direction of asymmetry. Substantial levels of agreement were shown for jump height when comparing mid to end-season (Kappa = 0.68) and RSI when comparing pre to mid-season (Kappa = 0.78). However, all other time points showed poor to fair levels of agreement for the direction of asymmetry, further highlighting the variable nature of this concept in healthy soccer players and the need to interpret asymmetry data from an individual perspective (Bishop et al. 2018b; Bishop et al. 2019b), as shown by Figures 7.1-7.6. To provide another example, in Figure 7.4, athlete 5 starts the season right limb dominant with an asymmetry of 14%, but then measures left limb dominant (10%) by mid-season, resulting in a 24% shift in the imbalance. Thus, such examples may require practitioners to determine whether such large shifts in asymmetry are merely a consequence of repeated soccer match-play or part of a potential risk factor for future injury occurrence.

Despite the novelty of reporting asymmetry longitudinally, there is one key limitation to the present investigation which should be acknowledged. Firstly, training or competition load data was not available throughout; thus, understanding why such variations occurred in the direction of asymmetry is challenging. Soccer athletes frequently perform high-intensity actions unilaterally such as jumping, sprinting and changing direction (Taylor et al. 2017) and given the positional differences associated with soccer, it is unlikely that these actions will occur in an equal amount on each limb. In addition, limb dominance is likely to change depending on the task in question (Dos'Santos et al. 2019a). Thus, the only way to establish why the existing variability in the direction of asymmetry exists, is to interpret such data in conjunction with training or competition loads and should be considered in future research on the topic of asymmetries.

7.5 Conclusion

These findings indicate that when assessing relationships between asymmetry and performance, although significant large associations were found between jumping asymmetries and speed and CODS performance, this only occurs at individual time points and these relationships are often changeable. When considered longitudinally, asymmetry appears to be largely independent from measures of athletic performance, likely due to their inconsistency in agreement between test sessions. Therefore, the practice of measuring asymmetry during jump testing using commonly applied metrics for the purposes of monitoring associations with speed and CODS cannot be recommended. Furthermore, given the longitudinal findings in the present study, it is hard to suggest that asymmetry should be reduced through the use of targeted training programs in the hope that it may indirectly enhance speed or CODS performance.

In addition, unilateral CMJ, unilateral DJ and 505 tests showed non-linear changes in performance at different stages throughout the season and represent useful methods for monitoring unilateral jump and CODS performance in elite academy soccer players. When assessing asymmetry, group mean values appear consistent when calculating the magnitude alone; however, the direction of asymmetry shows that substantial variation exists at an individual level. When profiling inter-limb differences, practitioners are advised to undertake individual analysis with their athletes and use the Kappa coefficient to determine how consistently asymmetry favours the same limb over time, noting that the mean value alone disguises this inherent change in imbalance.

CHAPTER 8: STUDY 3

8.0 Effects of soccer match-play on unilateral jumping and inter-limb asymmetry: A repeated measures design.

8.1 Introduction

Soccer is a high-intensity, intermittent sport that requires players to sprint, jump, kick and change direction on multiple occasions in response to different stimuli (Turner and Stewart, 2014). Time-motion analysis data has shown that elite soccer players cover distances on average of 10-11 km in matches (Rampinini et al. 2007). Matches can also include up to 168 high intensity actions (Taylor et al. 2017), 1200-1400 changes of direction (Bangsbo, 1992), and up to 15 jumps per match (Nedelac et al. 2014). Given that many of these actions occur unilaterally, the development of inter-limb asymmetries are to be expected, which is supported by previous research (Hart et al., 2016).

Jump testing has been a commonly used method to monitor neuromuscular fatigue in soccer players (Malone et al. 2015; Taylor et al. 2012; Thorpe et al. 2015). Studies often employ simulated soccer protocols rather than competitive matches to determine acute responses (Harper et al. 2016; Thomas et al. 2017). Jump height (from the unilateral CMJ) and RSI (from the bilateral DJ) performance have both been shown to significantly decline immediately post fatigue protocols (Bishop et al. 2019a; Oliver et al. 2008). However, given many movement patterns in soccer occur unilaterally (e.g., cutting, sprinting, kicking) the use of single leg jump tests would also provide an ecologically valid method of assessment and allow practitioners to calculate asymmetry which provides an indication of between-limb differences in performance capacity.

To the authors' knowledge, only one study has investigated how both single leg jump performance and inter-limb asymmetry responds to competitive soccer match-play.

Bromley et al. (2018) performed unilateral CMJ pre, post, 24, 48 and 72 hours after a single competitive soccer match in 14 academy soccer players. Significant reductions ($p < 0.05$) in peak force, eccentric and concentric impulse, and peak landing force were evident on both limbs across the temporal recovery period, but not jump height. Furthermore, when compared to baseline, effect size data showed changes in asymmetry ranging from trivial to very large for peak force (ES range: 0.12-2.80) and eccentric impulse (ES range: 0.01-3.15), trivial to large for peak landing force (ES range: 0.01-1.38), and trivial to moderate for concentric impulse (ES range: 0.30-1.02), with the largest changes seen either post or 24 hours' post-match. This suggests that both single leg jump performance and between-limb asymmetries may be sensitive to change after competitive soccer match-play (Bromley et al. 2018).

Despite the usefulness of this information, no minimum cut-off requirement in 'time played' was specified for players, and a total of 14 participants were counted in the analysis, indicating the goalkeeper and substitutes were included. In addition, results were not interpreted considering the external workloads performed and were obtained from a single match which does not account for the high game-to-game variability in actions such as high speed running and total distance (Gregson et al. 2010). Cumulatively, these limitations reduce our understanding of how single leg jump performance and asymmetry acutely respond to game demands, and what potential associations exist between asymmetry and commonly reported within-game metrics (Nedelac et al. 2014). Thus, a repeated measures design would provide a more meaningful understanding of the interaction between single leg jumping, inter-limb asymmetry and soccer match-play.

Therefore, the primary aim of the present study was to determine the acute effects of soccer match-play on unilateral jump performance and inter-limb asymmetries. Our second aim was to examine associations between asymmetry and commonly reported external load variables collected during competition. It was hypothesised that reductions in unilateral jump performance and increases in inter-limb asymmetry would be evident acutely following games, and significant relationships between asymmetry and GPS data would also be evident.

8.2 Methods

8.2.1 Experimental Design

This study used a repeated measures design throughout the 2018-2019 soccer season, investigating the effects of five competitive soccer matches on unilateral jump performance and inter-limb asymmetries in a single team of elite male academy soccer players. Players performed unilateral CMJ and unilateral DJ on match days two hours before kick-off and then repeated both jump tests approximately 10 minutes' post-match. All tests were conducted in the club's gymnasium, under the same testing conditions. GPS data were also collected during each game. Players were only included in the data analysis for each match if they were an 'outfield' player, and played a minimum of 60 minutes (Abbott et al. 2018; Clifford et al. 2018).

8.2.2 Participants

Eighteen elite under-18 academy soccer players (age: 16.89 ± 0.32 years; height: 1.79 ± 0.04 m; body mass: 74.12 ± 5.07 kg) from a Category 2 academy of a professional soccer club in the English Championship volunteered to participate in the present study. All players were familiar with procedures having conducted these as part of routine fitness testing at the club in the previous two years, and were free from injury each time they were tested and in the preceding two weeks before each game. Parental consent, participant ascent, and clearance from the clubs medical staff were obtained prior to testing. Ethical approval was granted by the London Sport Institute Research and Ethics committee at Middlesex University, London, UK.

8.2.3 Procedures

All testing protocols were replicated for each match throughout this study. Players performed a standardized warm up which included 5-minutes on a stationary bike at a self-selected speed, followed by a range of dynamic stretches. Specifically, a single set of 10 repetitions of multiplanar lunges, inchworms, spidermans and bodyweight squats were performed, followed by three practice trials of each jump test (on each leg) at 60, 80 and 100% of perceived maximal effort in an attempt to minimize individual differences in technique for each player. Three minutes of rest was provided between the last practice trial and the start of the first jump test and 30-seconds of rest was provided between trials during the data collection process, with all testing performed in a randomized order. Post-match testing, players removed their shin guards and replaced their football boots with the same footwear used during pre-match testing. No warm up procedures were repeated during post-match testing.

8.2.3.1 Unilateral Countermovement Jump and Unilateral Drop Jump

The same procedures for these two tests were adhered to as per the methods section in Chapter 4, with the same jump metrics collected at all time points throughout the season. For the unilateral CMJ, metrics included jump height, peak force and concentric impulse. For the unilateral DJ, metrics included jump height, GCT and RSI.

8.2.3.2 Global Positioning System (GPS) data

GPS data was obtained using Catapult OptimEye X4 units (OptimEye X4, Firmware 6.70, Catapult Innovations) operating at 10 Hz for each match. For each player, units were positioned inside wearable garments, positioned between the scapulae underneath the soccer shirt. Recorded metrics from the software included total distance (m), explosive distance (m) defined as the combined high-intensity accelerations and decelerations covered at > 3 $m \cdot s^{-2}$ (Russell et al. 2016), high speed running (HSR – m) defined as the individual percentage of maximum velocity ranging from 60-90%, and player load, defined as the cumulative high-intensity actions recorded throughout the match as a resultant of the accelerometer data (Boyd et al. 2013). Individual thresholds for HSR were defined from the maximal velocity obtained during three previously recorded maximal effort 40 m sprints. All metrics were also made 'relative' and quantified in m per minute ($m \cdot min^{-1}$), with the exception of player load.

8.2.4 Statistical Analysis

All data were initially recorded as means and SD in Microsoft Excel and later transferred to SPSS (version 25.0; SPSS, Inc., Armonk, NY, USA). Normality of the data was assessed using a Shapiro-Wilk test. Within-session reliability of test measures was computed pre and post-match using an average measures two-way random ICC with absolute agreement and 95% confidence intervals, and the CV. Interpretation of ICC values was in accordance with previous research by Koo and Li (2016), where values > 0.9 = excellent, 0.75-0.9 = good, 0.5-0.75 = moderate, and < 0.5 = poor. CV values ≤ 10% were suggested to be considered acceptable (Cormack et al. 2008).

Paired samples Wilcoxon *t*-tests were conducted to determine whether unilateral test or asymmetry scores were significantly different between pre and post-match, with statistical significance set at $p < 0.05$. The magnitude of change was also calculated between pre and post-match using Cohen's *d* ES: $(Mean_{pre} – Mean_{post})/SD_{pooled}$. These were interpreted in line with Hopkins et al. (2009) where < 0.2 = trivial; 0.2-0.6 = small; 0.6-1.2 = moderate; 1.2-2.0 = large; 2.0-4.0 = very large; and > 4.0 = near perfect.

A repeated measures ANOVA was conducted to determine if any significant differences in GPS variables were observed between matches and the CV was used to calculate between-game variability, as per previous suggestions (Gregson et al. 2010). Spearman's ρ correlations were conducted to determine the relationship between post-match asymmetry and the change in asymmetry (from pre to post) with GPS variables. Bonferroni corrections were applied to all correlations to account for multiple comparisons and the familywise type I error rate, resulting in statistical significance being set at $p < 0.008$.

Inter-limb asymmetries were quantified using the percentage difference method and the IF function used determine the direction of asymmetry, as outlined in chapter 6. Previous research has highlighted the importance of reporting asymmetry in conjunction with test variability so that practitioners can determine what is considered 'real' (Exell et al. 2012). Thus, players reporting a change in asymmetry greater than the pre-match CV, were also identified as showing a real change. Finally, Kappa coefficients were calculated to determine the levels of agreement for how consistently an asymmetry favoured the same side (between pre and post matches) when comparing the different time points measured and were interpreted in line with the suggested scale from chapter 6.

8.3 Results

Owing to the repeated measures design in the present study, the starting team was rarely the same for all five matches; thus, 18 players were included. Only a single player competed in all 5 matches, five players competed in 4 matches, five players in 3 matches, three players in 2 matches and four players in 1 match. Table 8.1 shows mean pre and post-match jump scores and test reliability data pooled for all five games. The unilateral CMJ showed good to excellent reliability (ICC: 0.84-0.95) and acceptable variability (CV ≤ 7.58%), and for the unilateral DJ, test reliability was also good to excellent (ICC: 0.68-0.93) with acceptable variability across all matches (CV ≤ 6.71%).

For the unilateral CMJ, significant reductions in jump height ($p < 0.01$; ES: -0.67; 13.3% reduction) and concentric impulse ($p < 0.01$; ES: -0.68 to -0.69; 10.8-11.2% reduction) were seen on both limbs post-match, but not peak force (ES: -0.05 to -0.13; 1.1-3.1% reduction). For the unilateral DJ, significant reductions in jump height ($p < 0.01$; ES: -0.57; 8.7% reduction) and RSI ($p < 0.01$; ES: -0.39 to -0.58; 4.4-7.5% reduction) were shown on both limbs post-match, but not GCT which showed no change.

Table 8.2 shows mean GPS data. No significant differences were evident between matches and high variability was seen between games with a CV range of 9.7-33.0% for all metrics. Table 8.3 shows Spearman's correlations between post-match asymmetry/the change in asymmetry (from pre to post match) and GPS based metrics. A significant correlation was shown for post-match RSI asymmetry and relative HSR ($\rho = 0.44$; 95% CI = 0.19-0.64; $p < 0.008$). No other significant correlations were present. Table 8.4 shows Kappa coefficients and descriptors for each game indicating how consistently asymmetry favoured the same limb between pre and post-match. For the unilateral CMJ, levels of agreement for jump height were poor to moderate (Kappa: -0.20 to 0.60), fair to substantial for peak force (Kappa: 0.23 to 0.62), and poor to moderate for concentric impulse (Kappa: -0.54 to 0.40). For the unilateral DJ, jump height showed fair to substantial levels of agreement (Kappa: 0.21 to 0.62), slight to moderate for RSI (Kappa: 0.14 to 0.60) and poor to moderate for GCT (Kappa: -0.36 to 0.55).

Owing to the individual and variable nature of asymmetry, mean pre and post asymmetry data and individual player responses are shown in Figures 8.1-8.6. Players showing a change in asymmetry (between pre and post-match) greater than the pre-match CV values, have been signified by a dashed line and varied substantially between matches. Out of 10 players in any given match, real changes in asymmetry ranged from: 1-6 (CMJ height), 3-8 (peak force), 2-6 (concentric impulse), 3-7 (DJ height), 3-6 (RSI) and 1-4 (GCT).

Table 8.1. Mean scores ± standard deviations (SD), effect sizes, coefficient of variation (CV) and intraclass correlation coefficient (ICC) data for pre and post-game jump testing (data pooled from 5 games).

Test/Metric	Mean ± SD			CV (%)		ICC (95% CI)	
	Pre	*Post*	*Effect Size (95% CI)*	*Pre*	*Post*	*Pre*	*Post*
UCMJ:							
Jump height-L (m)	0.15 ± 0.03	0.13 ± 0.03*	-0.67 (-1.07 to -0.26)	5.66	5.79	0.93 (0.87-0.96)	0.95 (0.92-0.97)
Jump height-R (m)	0.15 ± 0.03	0.13 ± 0.03*	-0.67 (-1.07 to -0.26)	7.44	7.58	0.92 (0.84-0.95)	0.91 (0.85-0.95)
Peak force-L (N)	740.4 ± 184.8	717.3 ± 162.5	-0.13 (-0.53 to 0.26)	7.04	6.30	0.92 (0.86-0.96)	0.92 (0.86-0.96)
Peak force-R (N)	718.5 ± 177.9	710.3 ± 172.3	-0.05 (-0.44 to 0.35)	5.85	6.28	0.95 (0.90-0.97)	0.95 (0.91-0.97)
CON imp-L (N·s)	113.1 ± 20.4	100.4 ± 16.3*	-0.69 (-1.09 to -0.28)	5.36	4.60	0.94 (0.89-0.96)	0.93 (0.88-0.96)
CON imp-R (N·s)	112.1 ± 19.5	100.0 ± 15.8*	-0.68 (-1.09 to -0.28)	5.24	7.01	0.94 (0.84-0.97)	0.84 (0.72-0.91)
UDJ:							
Jump height-L (m)	0.23 ± 0.03	0.21 ± 0.04*	-0.57 (-0.97 to -0.17)	4.17	5.39	0.93 (0.87-0.96)	0.92 (0.86-0.95)
Jump height-R (m)	0.23 ± 0.03	0.21 ± 0.04*	-0.57 (-0.97 to -0.17)	4.12	6.14	0.90 (0.82-0.94)	0.91 (0.84-0.95)
RSI-L	1.37 ± 0.15	1.31 ± 0.16*	-0.39 (-0.78 to 0.01)	4.22	5.63	0.88 (0.78-0.93)	0.83 (0.70-0.90)
RSI-R	1.33 ± 0.15	1.23 ± 0.19*	-0.58 (-0.98 to -0.18)	4.81	6.71	0.84 (0.72-0.91)	0.81 (0.67-0.89)
GCT-L (s)	0.32 ± 0.03	0.32 ± 0.03	0.00 (-0.39 to 0.39)	4.82	4.44	0.74 (0.53-0.85)	0.81 (0.67-0.89)
GCT-R (s)	0.33 ± 0.03	0.33 ± 0.04	0.00 (-0.39 to 0.39)	5.29	4.77	0.68 (0.44-0.82)	0.81 (0.67-0.89)

* significant at $p < 0.01$.

CI = confidence intervals; UCMJ = unilateral countermovement jump; UDJ = unilateral drop jump; L = left; R = right; m = metres; N = Newtons; CON = concentric; N·s = Newton seconds; RSI = reactive strength index.

Table 8.2. Mean global positioning system (GPS) data for each recorded game (data shown in metres and metres per minute).

GPS Metric	CV (%)	Game 1	Game 2	Game 3	Game 4	Game 5
Distance (m)	14.1	10045.3 ± 1245.0	9717.7 ± 1819.1	9937.8 ± 1848.2	9439.0 ± 1225.9	9376.5 ± 1034.4
Distance ($m\cdot min^{-1}$)	9.7	117.0 ± 6.6	114.7 ± 19.2	112.5 ± 14.3	108.4 ± 8.0	107.8 ± 6.3
Exp. distance (m)	23.8	334.9 ± 71.2	323.2 ± 65.7	289.1 ± 71.3	298.8 ± 95.0	258.7 ± 56.4
Exp. distance ($m\cdot min^{-1}$)	21.3	4.0 ± 0.9	3.9 ± 0.8	3.3 ± 0.7	3.4 ± 1.0	3.0 ± 0.7
HSR (m)	33.0	785.7 ± 192.2	695.4 ± 240.6	743.0 ± 243.9	661.6 ± 269.8	656.6 ± 225.3
HSR ($m\cdot min^{-1}$)	29.2	9.2 ± 1.9	8.2 ± 2.5	8.5 ± 2.5	7.6 ± 2.8	7.6 ± 2.6
Player load	16.7	922.5 ± 161.0	989.5 ± 209.1	994.9 ± 138.8	887.6 ± 170.0	897.2 ± 140.2

Exp. = explosive; HSR = high speed running.

Table 8.3. Spearman's ρ correlations between post-game/change in asymmetry and GPS-based metrics (data pooled from 5 games).

Asymmetry Variable	Minutes	Distance (m)	Distance ($m \cdot min^{-1}$)	Exp. Distance (m)	Exp. Distance ($m \cdot min^{-1}$)	HSR (m)	HSR ($m \cdot min^{-1}$)	Player Load
UCMJ:								
Jump height	-0.05	-0.01	-0.08	-0.03	0.02	0.04	0.06	-0.07
Δ Jump height	*-0.05*	*-0.06*	*-0.12*	*-0.04*	*0.02*	*0.02*	*0.02*	*-0.05*
Peak force	0.15	0.17	0.10	0.01	0.02	0.16	0.11	-0.01
Δ Peak force	*0.10*	*-0.02*	*-0.05*	*-0.10*	*-0.08*	*0.01*	*-0.01*	*-0.06*
CON impulse	0.12	0.21	0.13	0.02	0.03	0.09	0.06	0.04
Δ CON impulse	*-0.07*	*0.01*	*0.04*	*-0.18*	*-0.08*	*-0.07*	*-0.05*	*0.02*
UDJ:								
Jump height	-0.04	0.07	0.11	0.23	0.25	0.17	0.19	0.05
Δ Jump height	*0.04*	*0.12*	*0.16*	*0.07*	*0.04*	*0.12*	*0.13*	*0.21*
RSI	-0.10	0.14	0.21	0.29	0.34	0.35	0.44*	0.02
Δ RSI	*-0.01*	*-0.09*	*-0.01*	*0.05*	*0.06*	*0.15*	*0.19*	*-0.10*
GCT	-0.17	0.07	0.18	-0.11	-0.03	-0.03	0.10	0.05
Δ GCT	*-0.02*	*-0.10*	*-0.09*	*-0.07*	*-0.06*	*-0.08*	*-0.05*	*-0.06*

* significant at $p < 0.008$.

Exp. = explosive; HSR = high speed running; m = metres; $m \cdot min^{-1}$ = metres per minute; UCMJ = unilateral countermovement jump; CON = concentric; UDJ = unilateral drop jump; Δ = change in; RSI = reactive strength index.

Table 8.4. Kappa coefficients and descriptive levels of agreement for the direction of asymmetry (data pooled from 5 games and shown for each individual game).

Asymmetry Variable	All Matches	Game 1	Game 2	Game 3	Game 4	Game 5
UCMJ:						
Jump height	0.25 (Fair)	0.23 (Fair)	0.60 (Moderate)	-0.20 (Poor)	0.20 (Slight)	0.40 (Fair)
Peak force	0.47 (Moderate)	0.60 (Moderate)	0.62 (Substantial)	0.38 (Fair)	0.23 (Fair)	0.40 (Fair)
CON impulse	-0.13 (Poor)	-0.54 (Poor)	0.00 (Poor)	-0.36 (Poor)	0.00 (Poor)	0.40 (Fair)
UDJ:						
Jump height	0.46 (Moderate)	0.35 (Fair)	0.60 (Moderate)	0.21 (Fair)	0.62 (Substantial)	0.40 (Fair)
RSI	0.40 (Fair)	0.14 (Slight)	0.38 (Fair)	0.60 (Moderate)	0.40 (Fair)	0.55 (Moderate)
GCT	0.09 (Slight)	0.00 (Poor)	-0.36 (Poor)	0.55 (Moderate)	0.35 (Fair)	0.21 (Fair)

UCMJ = unilateral countermovement jump; CON = concentric; UDJ = unilateral drop jump; RSI = reactive strength index; GCT = ground contact time.

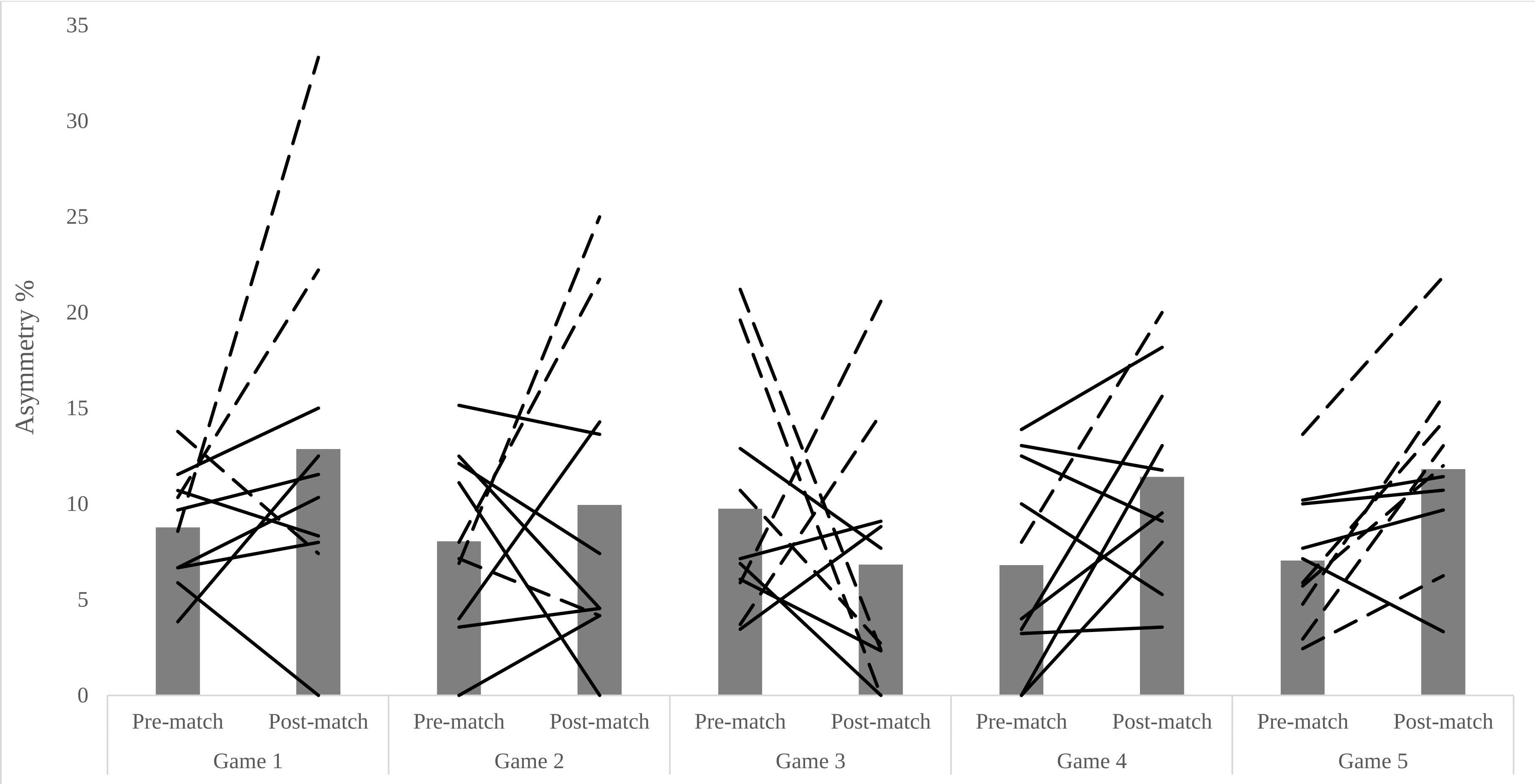


Figure 8.1. Mean and individual inter-limb asymmetry data for jump height during the unilateral CMJ test across 5 games. Dashed lines indicate a change in asymmetry greater than the pre-match coefficient of variation.

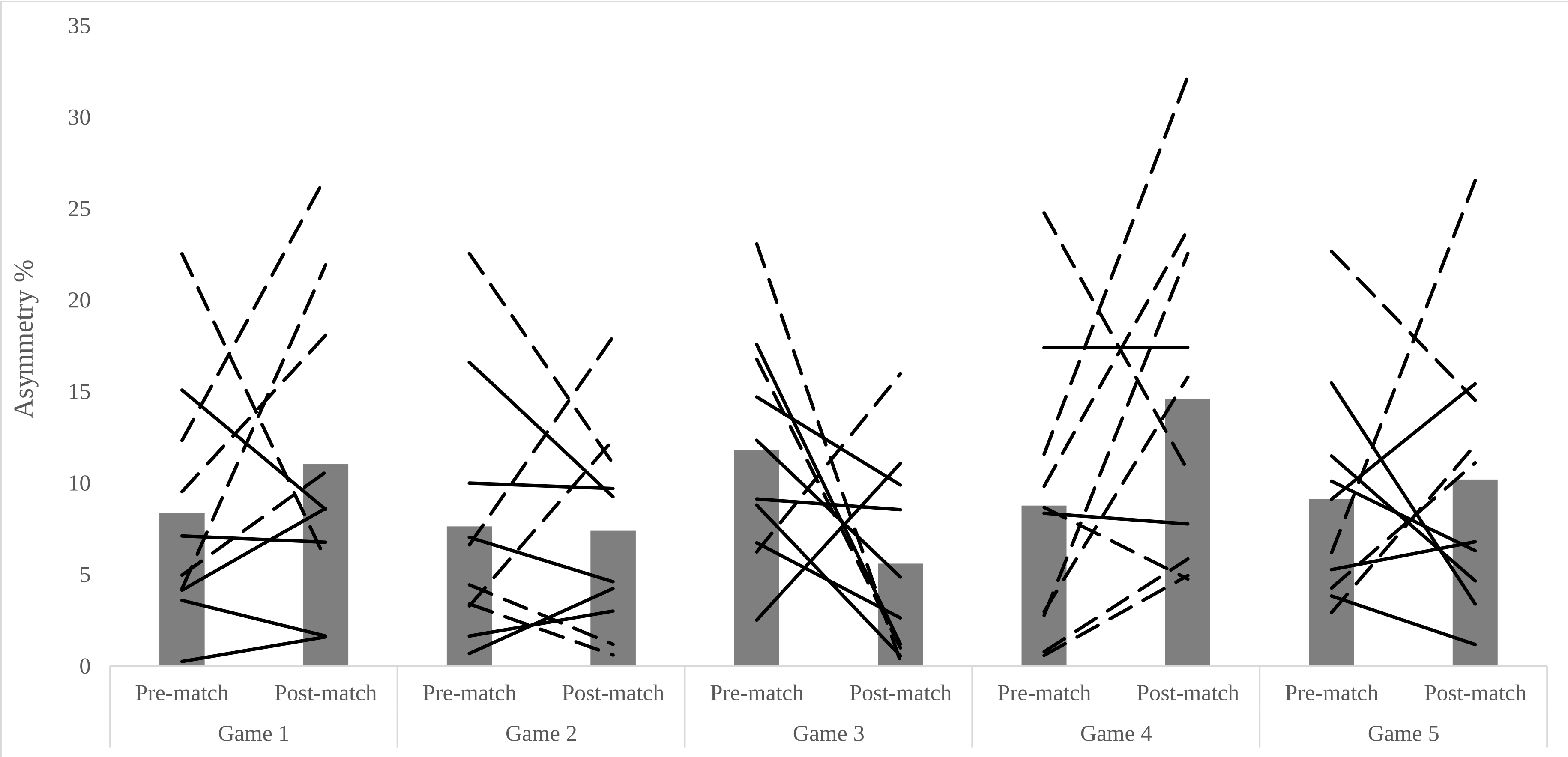


Figure 8.2. Mean and individual inter-limb asymmetry data for peak force during the unilateral CMJ test across 5 games. Dashed lines indicate a change in asymmetry greater than the pre-match coefficient of variation.

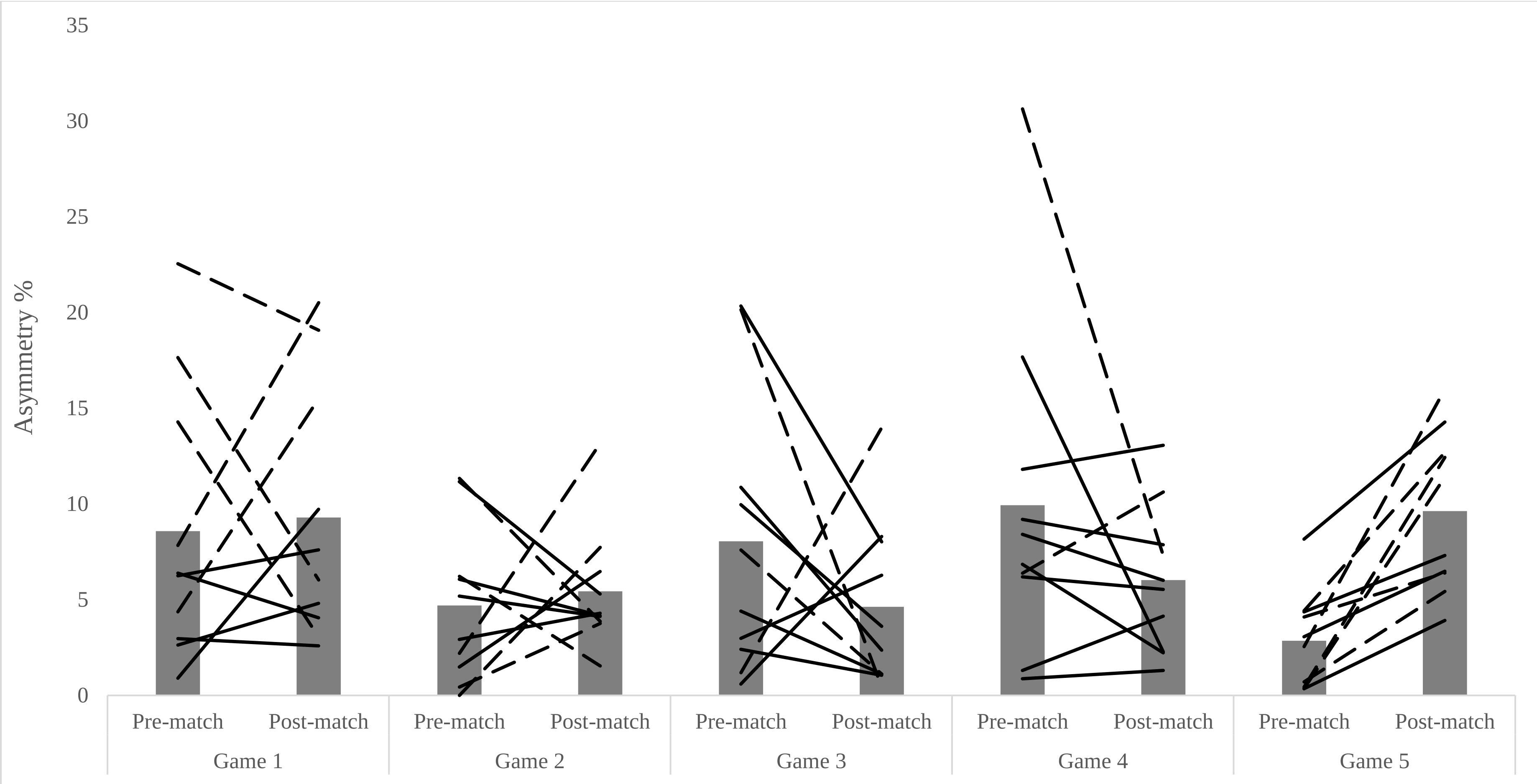


Figure 8.3. Mean and individual inter-limb asymmetry data for concentric impulse during the unilateral CMJ test across 5 games. Dashed lines indicate a change in asymmetry greater than the pre-match coefficient of variation.

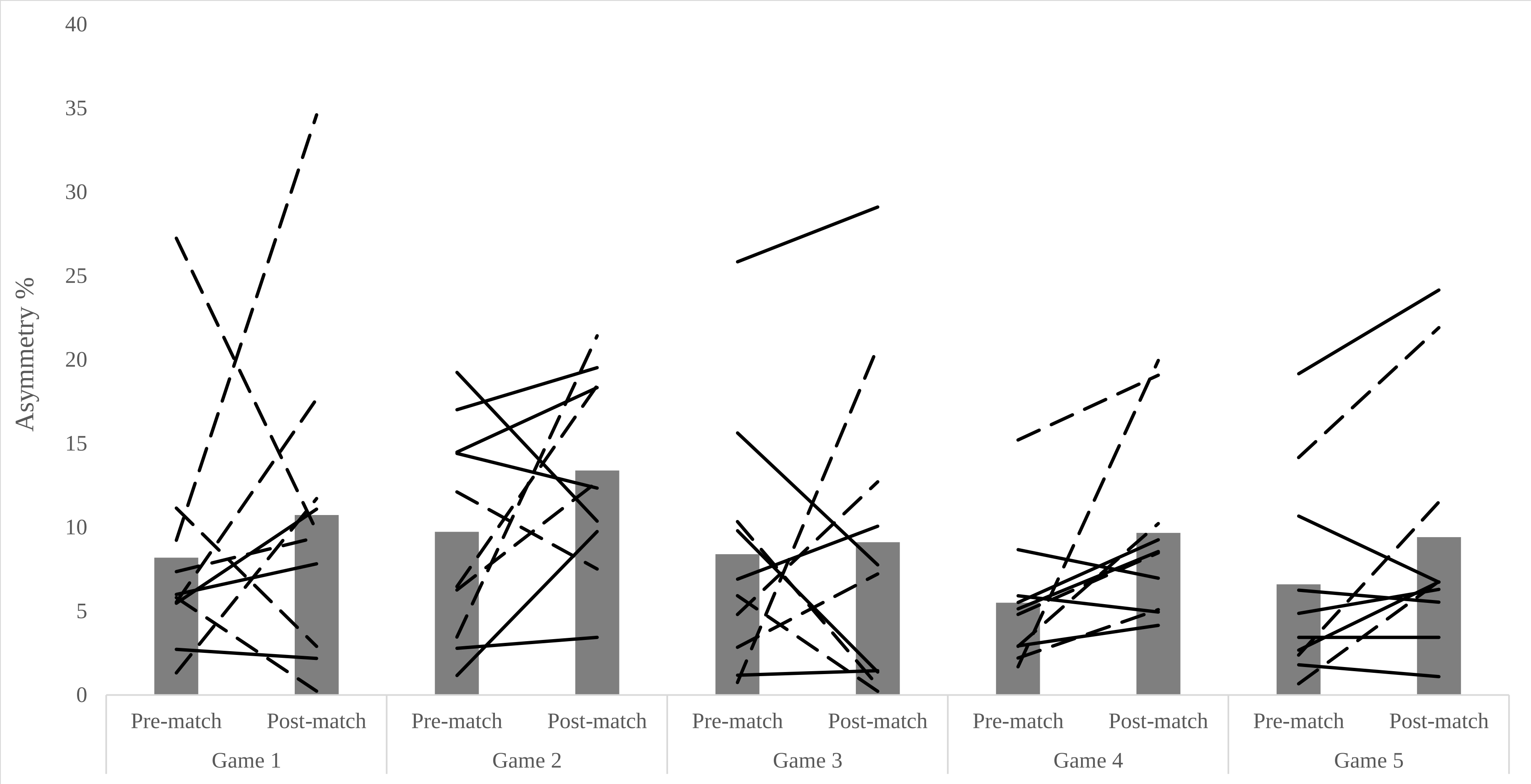


Figure 8.4. Mean and individual inter-limb asymmetry data for jump height during the unilateral DJ test across 5 games. Dashed lines indicate a change in asymmetry greater than the pre-match coefficient of variation.

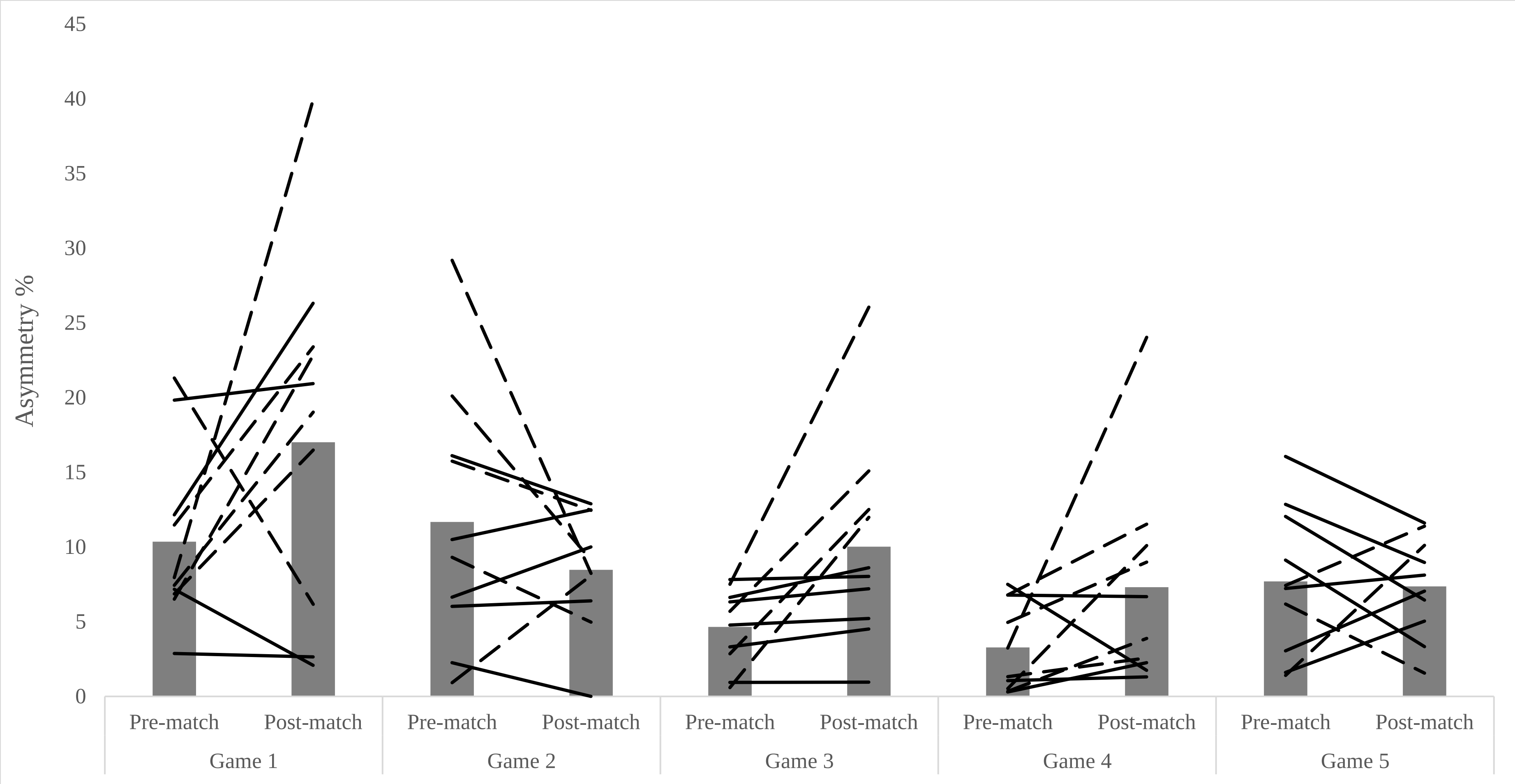


Figure 8.5. Mean and individual inter-limb asymmetry data for reactive strength index during the unilateral DJ test across 5 games. Dashed lines indicate a change in asymmetry greater than the pre-match coefficient of variation.

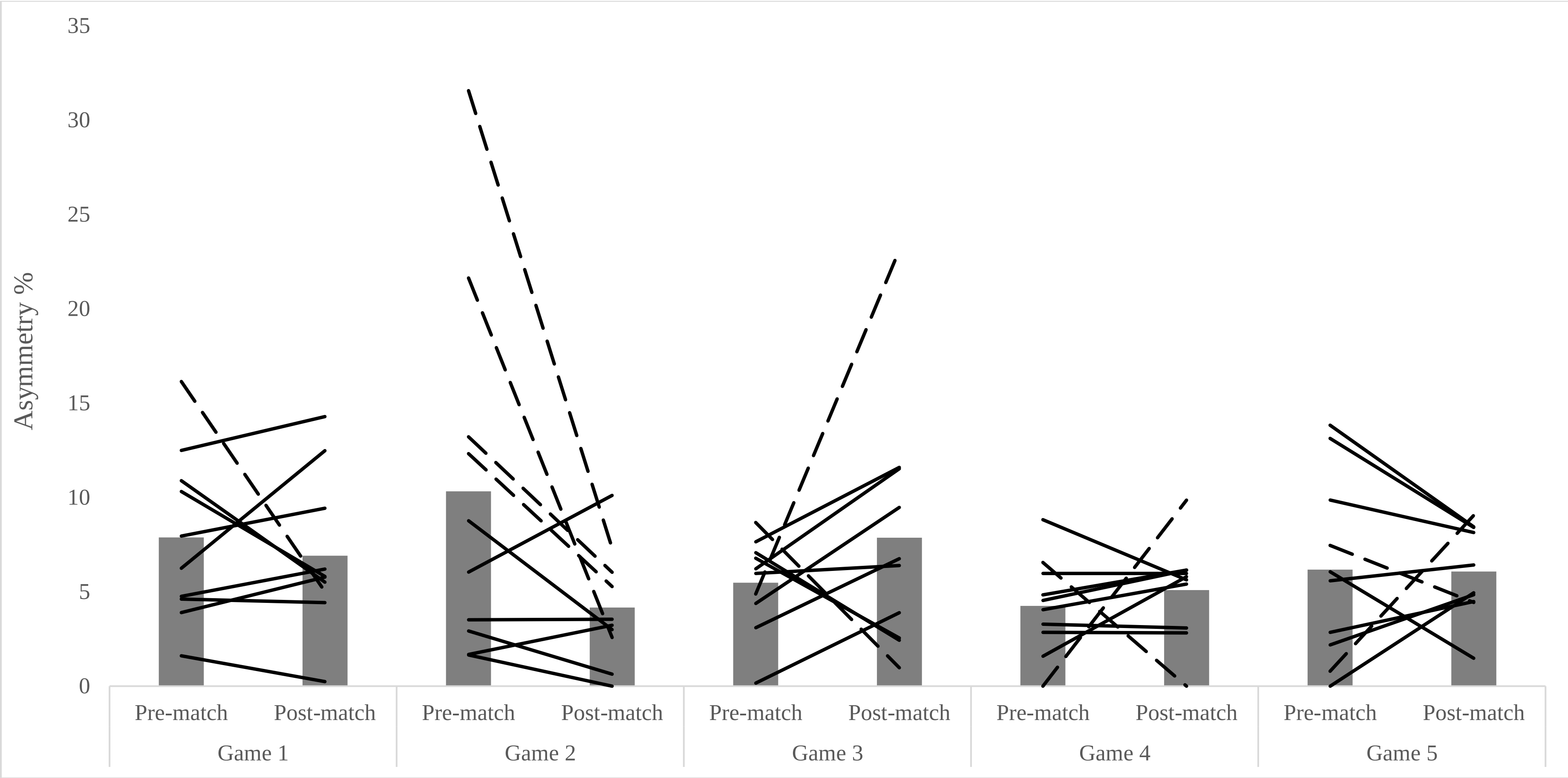


Figure 8.6. Mean and individual inter-limb asymmetry data for ground contact time during the unilateral DJ test across 5 games. Dashed lines indicate a change in asymmetry greater than the pre-match coefficient of variation.

8.4 Discussion

The primary aim of this study was to determine the acute effects of soccer match-play on unilateral jump performance and inter-limb asymmetries. The second aim was to examine associations between asymmetry and external load variables collected during competition. Results showed significant reductions in unilateral CMJ height and concentric impulse, and unilateral DJ height and RSI. No significant group changes in asymmetry were displayed during each match. However, individual responses were highly variable, with some players showing changes greater than the test variability although these were inconsistent across the different games and test metrics. Finally, a significant moderate relationship was evident between post-match RSI asymmetry and relative HSR. No other significant correlations were evident between asymmetry and GPS metrics.

The findings of the present study show that unilateral jump performance is negatively affected by competitive soccer match-play. This seems logical given that competition has previously been shown to produce an acute fatigue response (Ascensao et al. 2008; Ispirlidis et al. 2008; Nedelac et al. 2014). These findings are in part supported by Bromley et al. (2018) who showed that unilateral CMJ peak force and concentric impulse were impaired post-match in elite academy soccer players. However, Bromley et al. (2018) showed that unilateral CMJ height was not sensitive enough to detect meaningful changes post-match, which is in contrast to the results of the present study. Further to this, the present study did not find meaningful changes in peak force, but did for jump height and concentric impulse. Although challenging to fully explain, previous research has shown that impulse, rather than peak force, is a key determinant of jump height (Ruddock et al. 2015). Thus, it stands to reason that significant reductions in both jump height and concentric impulse were evident. Further to this, although reductions in peak force were trivial, confidence intervals showed that changes ranged from small reductions to small increases (-0.53 to 0.35), indicating that group level responses are highly variable, due to the inherent differences shown for respective individuals. These data denote a meaningful representation of the variable nature of acute responses shown in unilateral jump performance after competitive matches.

The unilateral DJ also showed meaningful reductions in performance for jump height and RSI on both limbs post-match and confidence intervals also showed that individual changes ranged from moderate reductions to trivial increases (-0.98 to 0.01). To the authors' knowledge, this is the first study to use the unilateral DJ to detect changes in jump performance post-match in elite academy soccer players. Oliver et al. (2008) reported that the bilateral DJ was more sensitive than the CMJ and SJ tests in its ability to detect reductions in performance after a 42-minute treadmill protocol designed to simulate the movement intensities in soccer. All three tests showed significant reductions in jump height, but the DJ also showed significant increases in impact ground reaction force. This suggested a reduced ability to attenuate forces on landing which could be attributed to the significant reduction in muscle activity also observed from the EMG measurements of the vastus lateralis, biceps femoris, gastrocnemius and soleus muscles during this test. However, Oliver et al. (2008) used a single fatiguing protocol, while the present study used a repeated measures design. Furthermore, given our findings did show significant reductions in jump height and concentric impulse (unilateral CMJ) and jump height and RSI (unilateral DJ), both tests can be considered useful when aiming to detect acute changes in unilateral jump performance across competitive soccer matches, which also represents a novel finding.

Despite reductions in jump performance, no significant changes in asymmetry were noted for any metric. This is likely due to the high between-subject variability as shown by the varied individual player response, and low agreement between pre/post-match limb dominance. Previous research has suggested that asymmetry should be reported on an individual basis (Bishop et al. 2018b; Bishop et al. 2019d) and relative to test variability (Exell et al. 2012). On the group level, there was a trend of increased CMJ and DJ height asymmetry, with mean increases shown in 4 out of 5 (Figure 8.1) and 5 out of 5 (Figure 8.4) matches, respectively. All other test metrics showed mixed results, with no consistent pattern. Individual responses were highly variable, with some players showing very large increases post-match, whilst others actually reduced the imbalance compared to pre-game testing. However, no consistent pattern or frequency of how many participants showed changes greater than the test variability was seen across each test and metric reported. From an applied perspective, this makes it challenging to suggest that monitoring asymmetry post soccer competition is advantageous for practitioners.

The direction of asymmetry (left or right dominance) was also determined in the present study to quantify how consistently asymmetry favoured the same limb between pre and post-match. Unilateral CMJ peak force showed the greatest consistency in limb dominance with fair to substantial levels of agreement. Intuitively, this makes sense because it was the only CMJ metric not to show significant changes in jump performance (Table 8.1). Thus, with less change in scores evident in comparison to jump height and concentric impulse, it seems logical that limb dominance was also more consistent for peak force. However, with impulse being a key determinant of jump height (Ruddock et al. 2015), it could be argued that despite greater consistency, monitoring peak force alone during jumping tests may not provide meaningful information for coaches. DJ height asymmetry also showed fair to substantial levels of agreement, and greater consistency than RSI. However, it is worth noting that for both tests, substantial changes in the direction of asymmetry were evident pre to post-match, being ‘poor’ for multiple metrics in multiple matches (Table 8.4). These data reinforce the concept of asymmetry being highly variable across tasks, metrics, and in response to soccer match play, with no consistent pattern present. Thus, with the observed inconsistencies as to which limb is dominant across the different test metrics and matches analyzed, caution should be applied if coaches wish to monitor jumping asymmetry on the group or individual level pre and post-soccer competition.

Likely as a consequence of the varied response in asymmetry seen pre to post-match, the only significant relationship with external load variables measured during the game was between post-match RSI asymmetry and relative HSR (ρ = 0.44). The correlation was positive, indicating that larger post-match asymmetries in RSI are associated with increased distance covered at high speeds. It is plausible that HSR is more closely associated with RSI asymmetries because both of these metrics are based on time (i.e., athletes need to perform these tasks as fast as possible). This also may serve as a potential reason why associations were not found with the unilateral CMJ which is a slower movement when compared to the unilateral DJ, although further research is needed to fully corroborate this theory. However, it is important to remember that the strength of this significant relationship is only moderate, and agreement in the direction of asymmetry pre to post-match for RSI was only 'fair' across all matches (Kappa = 0.40). As for the change in asymmetry, both jump tests showed no significant relationships with GPS data, most likely due to individual player variation for both asymmetry and in-game soccer actions. Therefore, it seems plausible to suggest that the change in asymmetry is largely independent of in-game soccer movement patterns such as distance covered, explosive distance and HSR. Thus, to inform player readiness, these data indicate that unilateral jump metrics are more appropriate than asymmetry, which is likely too variable to inform the ongoing monitoring process.

8.5 Conclusion

The present study shows that the majority of unilateral jump metrics commonly measured during both the unilateral CMJ and unilateral DJ tests are sensitive to change post-match in elite academy soccer players. In contrast, inter-limb asymmetry showed no significant changes, and performance was highly variable between pre and post-competition on both the group and individual level. Thus, practitioners can confidently use unilateral jump testing to detect acute changes following soccer match-play, but should be cautious in their use of inter-limb asymmetry owing to its highly variable nature.

CHAPTER 9:

9.0 Conclusions, Practical Applications and Directions for Future Research

9.1. Overall Summary

The purpose of this thesis was to monitor inter-limb asymmetry longitudinally and establish the long-term associations between asymmetry measured during different jumping tests and surrogate measures of athletic performance in elite academy soccer players. The findings from this thesis provide new insights into the topic of inter-limb asymmetry and demonstrate an original and significant contribution to the literature, which coaches and academics can use to guide future practice and research.

9.2. Key Findings

9.2.1. Literature Review

The literature review demonstrated that when choosing tests, it is important to remember that between-limb asymmetry is a product of having separate data for each limb, and is subsequently calculated thereafter. Thus, test reliability (especially for unilateral tests where movement variability is likely to be greater than their bilateral counterparts) remains a key factor in utilising protocols which are likely to exhibit usable data. Given the nature of team sports often reacting to an opponents' movement patterns, equal loading on each limb is highly unlikely; thus, the prevalence and development of inter-limb asymmetry should be expected. For soccer athletes, existing needs analysis data highlights that movement proficiency and multiple physical qualities should be developed in order to optimise physical performance. Key attributes include sprinting, changing direction and jumping; thus, these represent appropriate athletic characteristics to test in this population. In addition, unilateral movement patterns are common in soccer and where jumping is concerned, the vertical direction is the most prevalent. Therefore, unilateral CMJ and unilateral DJ tests represent appropriate methods of jump assessment for soccer athletes and enable both lower body power and reactive strength to be assessed (as well as inter-limb asymmetry); both of which have been deemed important physical qualities in soccer.

Secondly, numerous formulas have been used to calculate asymmetry and given the variation in how they are comprised, the selected method can alter the asymmetry outcome. Subsequently, this thesis proposes that asymmetry is merely a percentage difference, and should be calculated accordingly. In addition, there are fundamental differences in how asymmetry should be calculated when establishing the percentage difference from bilateral and unilateral test measures. Specifically, it is suggested that when calculating asymmetry from a bilateral task, the between-limb difference should be interpreted relative to the sum or total output. Given that both limbs interact together, this seems like a valid suggestion. However, for unilateral tests, no contribution exists from the opposing limb; thus, the total output is merely what is produced on that one, working limb. Therefore, the notion of quantifying a percentage difference in line with fundamental mathematical principles (i.e., fractions) should be adhered to when using unilateral test methods. Future research should consider applying the appropriate formulas identified to ensure heightened accuracy and standardization to aid comparisons between future studies.

Thirdly, there are additional factors which can impact asymmetry in soccer athletes; namely seasonal variation and fatigue/match-play. When considering seasonal variation during jump tests, previous literature has highlighted significant differences in jump performance do occur throughout the season. This may be attributed to a variety of factors, such as: physical adaptations, cumulative fatigue, test scheduling, player motivation, etc. However, nearly all aforementioned studies have been conducted using bilateral jump tests, with a distinct lack of literature using unilateral tests in this regard. Given the prevalence of unilateral movement patterns in soccer, the use of unilateral jump tests to monitor seasonal variations are warranted. When considering fatigue, numerous studies have investigated the response of jump tests to both competition and simulation protocols. Both indicate that meaningful reductions do occur during the recovery period, with the largest often seen immediately post-activity. When considering competition specifically, the nature of such studies often employ small samples, given that in a sport such as soccer, only 11 players can compete at any one time, per team. Not all studies investigated how jump tests respond over multiple matches; thus, the final study represents a meaningful interpretation of how unilateral jump tests and asymmetry respond to competitive soccer match-play. Understanding this, would enable practitioners to determine whether asymmetry can be included as part of the ongoing monitoring process during recovery periods.

After an extensive literature search and over 16,000 articles found across eight search terms, only 18 articles were included in the final analysis of a systematic review which examined the association between inter-limb asymmetry from a variety of test protocols and measures of physical or sporting performance. When considered collectively, 12 out of 18 (67%) showed some association with reduced physical or sporting performance. Collectively, this provides an impression that asymmetry may be something that practitioners should investigate. However, notable limitations were acknowledged which have helped to formulate the experimental investigations in the current thesis.

All studies included in the final analysis are from a single time point using a correlational design, with authors often not specifying what time of year test protocols were conducted. Given we know seasonal variation to be a confounding factor in jump testing (and therefore, asymmetry), specifying such information appears highly relevant. In addition, although the collective information from this systematic review suggests there may be an association between larger asymmetries and reduced physical or sporting performance, longitudinal investigations have not been conducted and are warranted in order to determine the consistency of these relationships. Further to this, and given that no longitudinal data exists, it stands to reason that studies have not investigated whether changes in asymmetry correspond to changes in surrogate measures of athletic performance. This would provide greater context for practitioners as to whether targeted training interventions are needed for the reduction of inter-limb differences.

9.2.2. Chapter 6 (Study 1)

The aims of this study were to: 1) determine the test-retest reliability of unilateral strength, power, and reactive strength tests that can be used to quantify inter-limb asymmetries, 2) determine whether any significant differences in asymmetry were present between test sessions and, 3) determine how consistently asymmetry favoured the same side between test sessions.

For the first aim, all tests showed good to excellent relative reliability within and between-sessions, with absolute reliability slightly higher than 10% for impulse during the isometric squat, both within and between-sessions. For the second aim, significant differences in asymmetry were evident between test sessions, when quantified from the best trial method in both the isometric squat (impulse) and unilateral DJ (GCT). This was not viewed as a positive finding seeing as no training intervention was completed to impact the subsequent asymmetry outcome. In contrast, no significant differences were evident in any test or metric when asymmetry was computed as an average of all three trials. Thus, it is suggested that calculating asymmetry from an average of all trials is favourable over the best trial method, as this enables some of the variability to be captured that is evident between trials. For the third aim, the Kappa coefficient showed that the direction of asymmetry is also highly variable and metric dependent, with lower levels of agreement for less reliable metrics (e.g., impulse during the isometric squat). Collectively, the unilateral CMJ showed the greatest consistency between test sessions for the reported metrics, which also aligns to this test also showing the best reliability. The findings from this study show that both the unilateral CMJ and unilateral DJ tests can be considered reliable tests which can be used to quantify asymmetry, and were subsequently carried forward for the remainder of empirical investigations. In addition, the direction of asymmetry is highly variable and offers practitioners greater context regarding the consistency of existing side-to-side differences, than the magnitude of asymmetry alone.

9.2.3. Chapter 7 (Study 2)

The aims of this study were to: 1) determine the relationship between jump asymmetries and athletic performance tasks at a range of different time points in a competitive soccer season, 2) determine the relationship between changes in asymmetry and changes in athletic performance tasks, 3) provide seasonal variation data for unilateral jump, speed and CODS tasks and, 4) provide seasonal variation for the magnitude and direction of asymmetry during unilateral jump tasks.

Despite numerous studies showing associations with reduced athletic performance, all investigations to date have been published for a single time point. The results from this study show that any existing relationships between asymmetry and speed or CODS performance do not track consistently over time. The varying nature of asymmetry is undoubtedly a factor here to explain the lack of findings, and it appears that asymmetry and athletic performance tasks are largely independent of each other. This was reinforced by the second aim, which aimed to establish whether changes in asymmetry were associated with changes in speed or CODS performance. No meaningful relationships or levels of agreement were evident (ρ range = -0.44 to 0.56; Kappa range = -0.44 to 0.64), which indicated that as asymmetry increases, there is no clear association with speed or CODS performance. This further highlights the independent nature of asymmetry in relation to surrogate measures of athletic performance.

The unilateral CMJ and unilateral DJ tests showed significant changes throughout the season, but did not follow the same trend. The unilateral CMJ showed significant reductions in all metrics at mid-season, whereas the unilateral DJ showed progressive improvements in GCT and RSI as the season progressed, with statistical significance reached at the end of the season. Given both tests showed significant changes in jump performance, both can be considered viable options for practitioners wanting to select unilateral jump tests for seasonal monitoring. The 505 test also showed a similar trend to the unilateral DJ test, progressively improving over time, with statistical significance also reached at the end of the season. Given the previously reported high volume of changes of direction that soccer players perform in competition, it seems unsurprising that performance for this physical characteristic improved as the season progressed. In contrast, linear speed showed no meaningful changes throughout the season.

When monitoring asymmetry, the group mean value showed no significant differences throughout the season, which gives the impression of consistent scores over time. However, the SD value is always very high when compared to the mean; thus, we know there is inherent variability each time we calculate asymmetry. Monitoring the direction of asymmetry was able to account for this associated within-group variability. This was represented by Kappa coefficients ranging from poor to substantial during both jump tests (unilateral CMJ Kappa range = -0.06 to 0.77; unilateral DJ Kappa range = -0.10 to 0.78). Given the group mean value appears to mask the inherent variability that accompanies asymmetry, it is suggested that an individual approach to data analysis and monitoring the direction of imbalance is needed in order to establish a meaningful understanding of asymmetry. Despite the novelty of this data, the seasonal variation was not recorded in line with training or competition load data. Thus, helped to guide the third empirical investigation.

9.2.4. Chapter 8 (Study 3)

The aims of this study were to: 1) determine the effects of soccer match-play on unilateral jump performance and inter-limb asymmetries and, 2) examine associations between asymmetry and commonly reported external load variables collected during repeated soccer match-play. This was completed to investigate the efficacy of unilateral jump testing to detect changes post-competition, whilst simultaneously investigating whether asymmetry could be used as part of the post-match monitoring process.

This study showed unilateral jump performance in both the CMJ and DJ tests are detrimentally affected immediately post soccer match-play. In contrast, at the group level, no significant changes in asymmetry were evident post-match, likely due to the highly variable individual responses shown in each match. For the second aim, RSI asymmetry showed a significant moderate relationship with relative HSR. However, this was the only asymmetry metric to report significant associations with external load metrics and no significant relationships were reported between changes in asymmetry and external load data. Therefore, unilateral jump testing can confidently be used to detect acute changes in jump performance. In contrast, given existing side-to-side differences showed little consistency in response to soccer match-play, practitioners should be cautious prioritising the collection of data for the purpose of monitoring inter-limb asymmetry.

9.3. Practical Applications

The findings from this thesis show that unilateral strength, power and reactive strength tests can all be used to quantify inter-limb asymmetry; however, the unilateral CMJ displays lower variability in comparison to unilateral isometric squat and DJ tests. When monitoring asymmetry over time, recording the direction of asymmetry will help determine whether existing imbalances are consistent throughout a competitive season, or just natural fluctuations in performance variability. Given the high within-group variability for asymmetry and inconsistencies in limb dominance between sessions, monitoring the mean value for a group of athletes is unlikely to provide any meaningful data; thus, individual monitoring for asymmetry is suggested to be essential. However, understanding what to do with such data on an individual level is not always obvious for practitioners. Numerous studies and reviews have suggested that an asymmetry may only be considered 'real' if the between-limb percentage value is greater than the test variability score (Bishop, 2020; Bishop et al. 2020; Exell et al. 2012). Thus, given test protocols often dictate multiple trials be performed of a given test, this enables practitioners to calculate the CV. Once both inter-limb asymmetry and CV values have been computed, practitioners can clearly see whether the between-limb difference score (asymmetry) is greater than the test variability score (CV). This enables practitioners to distinguish between the 'signal and the noise', which seems especially relevant for a metric like asymmetry, given that it is a ratio number (i.e., made up of two component parts and is often quite noisy).

The final study enabled us to more closely determine the interaction between asymmetry and soccer match-play. Results showed that asymmetry is predominantly independent of external load variables collected during soccer matches with large varied individual responses. In addition, the lack of significant associations found between asymmetry and GPS metrics would indicate that, existing side-to-side differences are largely independent of movement patterns in soccer. However, both the unilateral CMJ and unilateral DJ tests showed significant reductions post soccer matches. Given the distinct lack of research using unilateral jump tests during post-match monitoring strategies, these findings show that both of these unilateral tests are appropriate to use, if aiming to detect acute changes in jump performance. In addition, our methods highlight that not every metric selected was sensitive to change. Specifically, jump height and concentric impulse during the unilateral CMJ showed significant reductions post-matches, whereas peak force showed greater stability with less inherent change. A similar pattern was evident for the unilateral DJ, where jump height and RSI showed meaningful reductions post-matches, whereas GCT showed no change. Not only does this represent a novel finding in the literature, but jump height has come under some critique as being inadequate at detecting change when athletes are in a fatigued state (Gathercole et al. 2015a; Gathercole et al. 2015c). However, it is important to note that this was during bilateral CMJ testing and practitioners can have confidence that jump height during unilateral jump testing, does not follow the same pattern. The relevance here being that if practitioners are limited by small budgets, the use of unilateral jump testing may still be feasible to assess changes in jump height (e.g., using smartphone apps) if bilateral jump testing is not, especially for team sport athletes where competency in unilateral movement patterns is required.

From a statistical analysis perspective, it is not often thought that such information is 'practically applied'. However, practitioners can follow many simple steps, many of which do not require advanced statistical software packages. Firstly, determining differences between test sessions or time points is often done through the use of *t*-tests or ANOVA's. However, when considering such methods for asymmetry, this only allows for analysis of the magnitude. Thus, to analyse the direction of asymmetry, practitioners are advised to also use the Kappa coefficient which enables practitioners to determine levels of agreement for limb dominance in a given task, between test sessions or time points. This can be computed in Microsoft Excel and a previous YouTube video has been recorded, highlighting the step-by-step approach to quantifying the Kappa coefficient for the direction of asymmetry: https://www.youtube.com/watch?v=PVOoBb4rNMk&t=1s. Finally, when aiming to determine multiple correlations against the same test scores, there is an increased risk of type I error. Thus, use of the Bonferroni correction enables practitioners to determine true associations by reducing the risk of subsequent type I error. This too can simply be calculated by taking the traditional *p* value of 0.05 used in statistics and dividing by the number of times a test score is having multiple correlations run against it. For example, in this thesis we used 6 asymmetry metrics to quantify correlations with different speed and CODS tests. Thus, our new *p* value can simply be calculated by dividing 0.05 by 6, which gives us a new *p* value of 0.08. Knowing this, enables practitioners to minimise the risk of reporting 'false-positives' in their data.

9.4. Directions for Future Research

There are numerous areas that could be investigated on the topic of inter-limb asymmetries in the future. Firstly, this thesis chose to select unilateral test measures as per the reason outlined in Chapter 3 and as a consequence, has shown the high degree of variability in asymmetry (particularly the direction of imbalance). Future research could aim to establish the consistency of inter-limb asymmetry through bilateral test measures (e.g., isometric squat, CMJ, DJ), which may prove to be more consistent given the increased stability associated with performing on two limbs. Secondly, given that the relationships between jump asymmetries and measures of athletic performance do not appear consistent over time, it seems prudent to suggest that asymmetry could be measured during the performance task itself. For example, when considering linear speed, if inter-limb differences in force, stiffness or contact times are present, do larger imbalances correspond to slower sprint performance? Similarly, given the prevalence of changing direction in soccer athletes, quantifying side-to-side differences in metrics such as entry/exit velocity and braking forces could serve as a useful method of understanding the relevance of asymmetry. Thirdly, future research could aim to establish a more mechanistic approach to why asymmetry is present. For example, knowing that asymmetry varies considerably between test sessions and time points, a deeper understanding using motion analysis technology and EMG, may highlight whether mechanistic reasons are both evident and consistent, or whether asymmetry is simply a product of natural performance variability. Finally, to the authors' knowledge, minimal prospective studies have been conducted to determine whether asymmetry is a risk factor for injury occurrence. Given the interest surrounding injury prevention/risk management for all athletes, this is likely to be a useful line of investigation for all practitioners working in a support staff capacity.

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APPENDICES:

Appendix A: Ethical Approval Forms

Middlesex University London

London Sport Institute REC

The Burroughs
Hendon
London NW4 4BT

Main Switchboard: 0208 411 5000

11/01/2017

APPLICATION NUMBER: 0989

Dear Chris Bishop

Re your application title: Asymmetry of STR/PWR Tests

Supervisor: Anthony Turner

Thank you for submitting your application. I can confirm that your application has been given approval from the date of this letter by the London Sport Institute REC.

Please ensure that you contact the ethics committee if any changes are made to the research project which could affect your ethics approval.

The committee would be pleased to receive a copy of the summary of your research study when completed.

Please quote the application number in any correspondence.

Good luck with your research.

Yours sincerely

Chair Dr Rhonda Cohen

London Sport Institute REC

Middlesex University London

London Sport Institute REC

The Burroughs
Hendon
London NW4 4BT

Main Switchboard: 0208 411 5000

23/02/2018

APPLICATION NUMBER: 3163

Dear Chris Bishop

Re your application title: Effects of Asymmetries on Speed and CODS

Supervisor: Anthony Turner

Co-investigators/collaborators:

Thank you for submitting your application. I can confirm that your application has been given approval from the date of this letter by the London Sport Institute REC.

Although your application has been approved, the reviewers of your application may have made some useful comments on your application. Please look at your online application again to check whether the reviewers have added any comments for you to look at.

Also, please note the following:

1. Please ensure that you contact your supervisor/research ethics committee (REC) if any changes are made to the research project which could affect your ethics approval. There is an Amendment sub-form on MORE that can be completed and submitted to your REC for further review.

2. You must notify your supervisor/REC if there is a breach in data protection management or any issues that arise that may lead to a health and safety concern or conflict of interests.

3. If you require more time to complete your research, i.e., beyond the date specified in your application, please complete the Extension sub-form on MORE and submit it your REC for review.

4. Please quote the application number in any correspondence.

5. It is important that you retain this document as evidence of research ethics approval, as it may be required for submission to external bodies (e.g., NHS, grant awarding bodies) or as part of your research report, dissemination (e.g., journal articles) and data management plan.

6. Also, please forward any other information that would be helpful in enhancing our application form and procedures - please contact MOREsupport@mdx.ac.uk to provide feedback.

Good luck with your research.

Yours sincerely

Middlesex University London

London Sport Institute REC

The Burroughs
Hendon
London NW4 4BT

Main Switchboard: 0208 411 5000

25/07/2018

APPLICATION NUMBER: 3853

Dear Chris Bishop

Re your application title: Effects of match-play on inter-limb asymmetries

Supervisor: Anthony Turner

Co-investigators/collaborators:

Thank you for submitting your application. I can confirm that your application has been given approval from the date of this letter by the London Sport Institute REC.

Although your application has been approved, the reviewers of your application may have made some useful comments on your application. Please look at your online application again to check whether the reviewers have added any comments for you to look at.

Also, please note the following:

1. Please ensure that you contact your supervisor/research ethics committee (REC) if any changes are made to the research project which could affect your ethics approval. There is an Amendment sub-form on MORE that can be completed and submitted to your REC for further review.

2. You must notify your supervisor/REC if there is a breach in data protection management or any issues that arise that may lead to a health and safety concern or conflict of interests.

3. If you require more time to complete your research, i.e., beyond the date specified in your application, please complete the Extension sub-form on MORE and submit it your REC for review.

4. Please quote the application number in any correspondence.

5. It is important that you retain this document as evidence of research ethics approval, as it may be required for submission to external bodies (e.g., NHS, grant awarding bodies) or as part of your research report, dissemination (e.g., journal articles) and data management plan.

6. Also, please forward any other information that would be helpful in enhancing our application form and procedures - please contact MOREsupport@mdx.ac.uk to provide feedback.

Good luck with your research.

Yours sincerely

Appendix B: Published Articles from this Thesis

Asymmetries of the Lower Limb: The Calculation Conundrum in Strength Training and Conditioning

Chris Bishop, MSc,[1] Paul Read, PhD, CSCS*D,[2] Shyam Chavda, MSc, CSCS,[1] and Anthony Turner, PhD, CSCS*D[1]
[1]London Sport Institute, Middlesex University, London, United Kingdom; and [2]School of Sport, Health and Applied Science, St Mary's University, London, United Kingdom

ABSTRACT

ASYMMETRY DETECTION HAS BEEN A TOPIC OF INTEREST IN THE STRENGTH AND CONDITIONING (SC) LITERATURE WITH NUMEROUS STUDIES PROPOSING MANY DIFFERENT EQUATIONS FOR CALCULATING BETWEEN-LIMB DIFFERENCES. HOWEVER, THERE DOES NOT SEEM TO BE A CLEAR DELINEATION AS TO WHICH EQUATION SHOULD BE USED WHEN QUANTIFYING ASYMMETRIES. CONSEQUENTLY, THE AUTHORS HAVE UNCOVERED 9 DIFFERENT EQUATIONS THAT POSE CONFUSION AS TO WHICH METHOD THE SC SPECIALIST SHOULD USE DURING DATA INTERPRETATION. THE AIM OF THIS ARTICLE IS TO IDENTIFY THE DIFFERENT EQUATIONS CURRENTLY BEING USED TO CALCULATE ASYMMETRIES AND OFFER PRACTITIONERS A GUIDE AS TO WHICH METHOD MAY BE MOST APPROPRIATE WHEN MEASURING ASYMMETRIES.

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INTRODUCTION

The concept of asymmetries has been the topic of numerous research studies, some of which have identified that such a phenomenon is detrimental to performance (4,10,12). Asymmetries in power ~10% have been shown to result in a loss of jump height (4), and slower change of direction speed times (12), suggesting it would be beneficial to minimize these differences. For such a widely researched concept, it is surprising that few studies have offered a definition of this term. However, Keeley et al. (16) propose that "Asymmetrical strength across the lower extremities can be defined as the inability to produce a force of contraction that is equal…." Although the majority of studies refer to the differences between limbs, it is important to understand that this is not always the case. Intralimb variations (differences within the same limb) will be evident when performing repeated athletic tasks and are most likely magnified during maximal efforts. Consequently, Exell et al. (8) suggest that asymmetry can only truly be classified as "real" if the between-limb difference is greater than the intralimb variation.

Typically, asymmetries have been reported as a percentage with distinctions being made between dominant and nondominant, right and left, stronger and weaker, or preferred and nonpreferred limbs. These distinctions provide different "reference values," thus allowing asymmetries to be calculated for a given test or variable. However, the wide variety in such reference values may have an effect on the result being conveyed. For example, an athlete may state that their right limb is their dominant, but if scores are inputted into an equation using the stronger and weaker classification, a different score may be reported if the stronger limb is not the dominant limb. Furthermore, if the stronger and weaker method is used, data interpretation over extended periods may lose context particularly as higher scores can change as a result of injury occurrence (34). Consequently, the reference value will have a profound effect on the asymmetry result, emphasizing the importance of distinguishing between the different methods of calculations noted in the body of available research to date.

Thus far, relatively simple tests, such as the back squat (9,11,23,30), countermovement jumps (CMJ) (4,14,39),

KEY WORDS:
asymmetries; lower limb; equations; symmetry angle

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3rd International Conference on
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Inter-limb asymmetries: methods of calculation, effects on physical performance and training strategies to reduce imbalances

Chris Bishop
Middlesex University, UK

Inter-limb asymmetries refers to the performance of one limb in relation to the other and has been widely investigated in the sports science literature. The majority of literature has focused on injury risk and occurrence, with differences greater than ~15% suggested as a threshold where athletes may be at heightened risk. Interestingly, numerous methods of quantifying these between-limb differences have been identified and with multiple equations being proposed, it is challenging for practitioners to understand the most appropriate method for calculating these differences. Furthermore, despite the volume of literature pertaining to this topic, few have related their findings to physical performance measures. Of those that have, inter-limb differences in strength have reported a detrimental effect on jumping and sport-specific skills. When asymmetries have been quantified during jumping-based tasks, results are less conclusive with some studies showing a detrimental effect on change of direction speed and some not. Additional studies have calculated inter-limb asymmetries during sport-specific actions and again, shown mixed findings. Finally, the cumulative body of literature appears to lean towards a tendency that heightened inter-limb asymmetries may be detrimental to physical performance; thus, methods to reduce these between-limb differences have also been proposed.

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BRIEF REVIEW

Considerations for Selecting Field-Based Strength and Power Fitness Tests to Measure Asymmetries

Chris Bishop,[1] Anthony Turner,[1] Paul Jarvis,[1] Shyam Chavda,[1] and Paul Read[2,3]

[1]School of Science and Technology, London Sports Institute, Middlesex University, London, United Kingdom; [2]School of Sport, Health and Applied Science, St Mary's University, London, United Kingdom; and [3]Athlete Health and Performance Research Center, Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar

Abstract

Bishop, C, Turner, A, Jarvis, P, Chavda, S, and Read, P. Considerations for selecting field-based strength and power fitness tests to measure asymmetries. *J Strength Cond Res* 31 (9): 2635–2644, 2017—The prevalence of lower limb asymmetries has been reported in numerous studies; however, methodological differences exist in the way they can be detected. Strength and jumping-based tasks have been most commonly used to examine these differences across both athlete and nonathlete populations. The aim of this review was to critically analyze the utility of strength and jumping tests that are frequently used to measure asymmetry. Reliability, validity, and considerations for assessment are examined to enhance test accuracy and effectiveness in the quantification of asymmetries during strength and jumping-based tasks. MEDLINE and SPORTDiscus databases were used with specific search terms to identify relevant articles in both athlete and nonathlete populations. The findings of the current review indicate that assessing interlimb differences during strength and jumping-based tasks may result in different levels of asymmetry; thus, interlimb differences seem to be task-dependent. Consequently, quantification during both types of assessment is warranted, and a selection of tests has been suggested to measure asymmetries in both strength and jumping-based tasks.

Key Words interlimb differences, reliability, jumping

Introduction

The concept of asymmetries has attracted much interest in strength and conditioning (S&C) in recent years. Multiple studies have reported the prevalence of asymmetries during a variety of jumping (7,23,31,62) and strength-based assessments (4,24,44,53,55); however, a critical analysis of their utility for measuring interlimb differences and clear guidelines for implementation are sparse. Within the available literature, methodological differences exist regarding the type of tests used and their administration procedures. The countermovement jump (CMJ) and single leg CMJ (SLCMJ) have been most commonly used (7,13,34,40,44,60), most likely due to their ease of application. However, solely measuring lower-body jumping-based tasks in a vertical direction will reduce the ecological validity for a range of sports which require movements in multiple planes of motion and a range of physical qualities. Previous data also indicate that measures of strength, such as the back squat (22,44,55), isometric squat or isometric midthigh pull (IMTP) (4,25,29,62), and isokinetic knee flexion or extension (15,18,53,56) have shown adequate sensitivity to identify between-limb differences. Furthermore, any highlighted interlimb differences in strength and jumping tasks have shown decrements in physical performance (4,7,66), increased injury risk (33), and reduced performance in sport-specific tasks (26). Therefore, to provide an accurate profile to screen athletes for the presence of asymmetry, a battery of tests may be required because of the potential for task sensitivity across a range of physical competencies.

When calculating asymmetries, a variety of approaches have been used which define limb differences in terms of dominance, strength, preference, or simply a right or left distinction (10). For example, studies pertaining to soccer frequently define the dominant limb as the favored "kicking leg" (15,53), which seems valid considering the nature of such a task. However, recent research has highlighted poor levels of agreement (40%) between perceived limb dominance and the highest score attained (23). In addition, Zifchock et al. (67) suggested that numerous asymmetry equations emphasize the use of a "reference value" (such as the dominant limb or highest score); however, clarity is sometimes lacking as to why one limb is chosen over the other. Therefore, precision on defining limb dominance is critical and must retain specificity to the task in question.

A combination of factors exist that should be considered before the selection of appropriate tests to measure

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Journal of Strength and Conditioning Research

Interlimb Asymmetries: Understanding How to Calculate Differences From Bilateral and Unilateral Tests

Chris Bishop, MSc,[1] Paul Read, PhD, CSCS*D,[2] Jason Lake, PhD,[3] Shyam Chavda, MSc,[1]
and Anthony Turner, PhD, CSCS*D[1]
[1]School of Science and Technology, London Sport Institute, Middlesex University, London, United Kingdom; [2]Athlete Health and Performance Research Centre, Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar; and [3]Department of Sport and Exercise Sciences, University of Chichester, West Sussex, United Kingdom

ABSTRACT

INTERLIMB ASYMMETRIES HAVE BEEN A POPULAR TOPIC OF INVESTIGATION IN THE STRENGTH AND CONDITIONING LITERATURE. RECENTLY, NUMEROUS EQUATIONS HAVE BEEN HIGHLIGHTED THAT CAN QUANTIFY THESE BETWEEN-LIMB DIFFERENCES. HOWEVER, NO DISTINCTION WAS PROVIDED ON WHETHER THEIR USE WAS APPLICABLE TO BOTH BILATERAL AND UNILATERAL TESTS. THIS ARTICLE PROVIDES A FRAMEWORK FOR SELECTING THE MOST APPROPRIATE ASYMMETRY EQUATION BASED ON THE SELECTED TEST METHOD, ENSURING ACCURATE CALCULATION AND INTERPRETATION. IN ADDITION, CONSIDERATIONS FOR DATA ANALYSIS HAVE ALSO BEEN INCLUDED AS A GUIDE FOR PRACTITIONERS ON THE RELEVANCE OF MONITORING INTERLIMB DIFFERENCES LONGITUDINALLY.

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INTRODUCTION

Interlimb asymmetries have been a common source of investigation in recent years and refer to the concept of comparing the function of one limb in respect to the other. A recent systematic review examining the effects of between-limb differences on physical and sporting performance demonstrated equivocal findings (8). In summary, larger lower-limb asymmetries in strength may be indicative of reduced jumping ability and power output (1,22); however, when these differences are quantified during jumping tasks, their effect on locomotive activities seems inconclusive (13,16,18). From an injury perspective, older literature has suggested that an asymmetry threshold of >15% marks the point of heightened risk (3,20). However, much of the available literature has drawn this conclusion from identifying ~15% differences in healthy subjects, and there is currently a paucity of evidence to support this notion using prospective cohort analysis. Given the inconsistency in these findings, further research is warranted to examine the effects of asymmetry on both injury and performance-based outcomes.

Multiple methods exist to quantify interlimb asymmetries and will likely be dictated by a range of factors (7–9). Such considerations include the needs of the athlete, availability of testing equipment, and reliability of the chosen test (9). Once these factors have been accounted for (and assuming an asymmetry profile is required), practitioners must consider whether interlimb differences are best quantified bilaterally or unilaterally. The needs analysis of the athlete or sport will provide some clarification to this question and determine whether both methods are used as part of an athlete test battery. Once the appropriate tests have been selected, an asymmetry profile can be created; however, it is essential that the calculation used to quantify between-limb differences matches the specifics of the test method.

KEY WORDS:
double leg; formulas; single-leg; symmetry

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Effects of inter-limb asymmetries on physical and sports performance: a systematic review

Chris Bishop[a], Anthony Turner[a] and Paul Read[b]

[a]School of Science and Technology, London Sport Institute, Middlesex University, London, UK; [b]Athlete Health and Perfomance Research Centre, Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar

ABSTRACT
The prevalence of inter-limb asymmetries has been reported in numerous studies across a wide range of sports and physical qualities; however, few have analysed their effects on physical and sports performance. A systematic review of the literature was undertaken using the Medline and SPORT Discus databases, with all articles required to meet a specified criteria based on a quality review. Eighteen articles met the inclusion criteria, relating participant asymmetry scores to physical and sports performance measures. The findings of this systematic review indicate that inter-limb differences in strength may be detrimental to jumping, kicking and cycling performance. When inter-limb asymmetries are quantified during jumping based exercises, they have been primarily used to examine their association with change of direction speed with mixed findings. Inter-limb asymmetries have also been quantified in anthropometry, sprinting, dynamic balance and sport-specific actions, again with inconsistent findings. However, all results have been reported using associative analysis with physical or sport performance metrics with no randomised controlled trials included. Further research is warranted to understand the mechanisms that underpin inter-limb differences and the magnitude of performance changes that can be accounted for by these asymmetries.

ARTICLE HISTORY
Accepted 14 July 2017

KEYWORDS
Between-limb differences; imbalances; strength; jumping

1. Introduction

The concept of inter-limb asymmetries compares the performance of one limb in respect to the other and has been widely investigated in the available literature (Keeley, Plummer, & Oliver, 2011). Numerous classifications of quantifying these inter-limb differences have been established including dominant vs. non-dominant (Newton et al., 2006; Rouissi et al., 2016; Stephens, Lawson, DeVoe, & Reiser, 2007), stronger vs. weaker (Impellizzeri, Rampinini, Maffiuletti, & Marcora, 2007; Sato & Heise, 2012), right vs. left (Atkins, Bentley, Hurst, Sinclair, & Hesketh, 2016; Zifchock, Davis, Higginson, & Royer, 2008) and injured vs. non-injured (Ardern, Webster, Taylor, & Feller, 2011; Barber, Noyes, Mangine, McColskey, & Hartman, 1990; Greenberger & Paterno, 1995; Grindem et al., 2011; Rohman, Steubs, & Tompkins, 2015) limbs. The wide range of classifications has meant that no uniform method of quantifying inter-limb differences exists to date, with the exception of reporting these asymmetries as a percentage difference from one limb in respect to the other; thus, this review will discuss asymmetries in this context also.

Within the literature, a stronger focus surrounding injury risk and occurrence appears to have been investigated when compared to physical or sports performance. Previous research has highlighted that both athlete and non-athlete populations who exhibit inter-limb asymmetries > 15% have been associated with increased injury incidence when compared to groups who score below this threshold (Barber et al., 1990; Grindem et al., 2011; Impellizzeri et al., 2007). Athletes who have suffered anterior cruciate ligament (ACL) injuries have been a popular stream of investigation (Barber et al., 1990; Grindem et al., 2011; Jordan, Aagaard, & Herzog, 2014; Logerstedt et al., 2012; Noyes, Barber, & Mangine, 1991; Reid, Birmingham, Stratford, Alcock, & Giffin, 2007), and a variety of hop tests have proven valid and reliable measures of quantifying inter-limb differences between the injured and non-injured limb (Reid et al., 2007; Rohman et al., 2015; Ross, Langford, & Whelan, 2002). Consequently, asymmetries of < 10% has been proposed as the target for patient discharge when athletes are returning to sport (Kyritsis, Bahr, Landreau, Miladi, & Witvrouw, 2016; Rohman et al., 2015), although it should be noted that this is an arbitrary threshold. That said, increased symmetry could be considered as a marker of successful rehabilitation, and increase confidence in the athlete and clinician that a safe and effective return to sport is possible.

However, the role of inter-limb asymmetries and their effects on physical or sports performance is less well known. Previous studies have identified the presence of inter-limb differences in a range of populations (Atkins et al., 2016; Ceroni, Martin, Delhumeau, & Farpour-Lambert, 2012; Impellizzeri et al., 2007; Maloney, Fletcher, & Richards, 2016; Rohman et al., 2015), and a variety of sports such as sprinting (Exell, Irwin, Gittoes, & Kerwin, 2016; Meyers, Oliver, Hughes, Lloyd, & Cronin, 2017; Rumpf et al., 2014), kickboxing (Stanton, Reaburn, & Delvecchio, 2015), swimming (Evershed, Burkett,

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sports

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Article

Using Unilateral Strength, Power and Reactive Strength Tests to Detect the Magnitude and Direction of Asymmetry: A Test-Retest Design

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Abstract: The aims of the present study were to determine test-retest reliability for unilateral strength and power tests used to quantify asymmetry and determine the consistency of both the magnitude and direction of asymmetry between test sessions. Twenty-eight recreational trained sport athletes performed unilateral isometric squat, countermovement jump (CMJ) and drop jump (DJ) tests over two test sessions. Inter-limb asymmetry was calculated from both the best trial and as an average of three trials for each test. Test reliability was computed using the intraclass correlation coefficient (ICC), coefficient of variation (CV) and standard error of measurement (SEM). In addition, paired samples *t*-tests were used to determine systematic bias between test sessions and Kappa coefficients to report how consistently asymmetry favoured the same side. Within and between-session reliability ranged from moderate to excellent (ICC range = 0.70–0.96) and CV values ranged from 3.7–13.7% across tests. Significant differences in asymmetry between test sessions were seen for impulse during the isometric squat ($p = 0.04$; effect size = −0.60) but only when calculating from the best trial. When computing the direction of asymmetry across test sessions, levels of agreement were fair to substantial for the isometric squat (Kappa = 0.29–0.64), substantial for the CMJ (Kappa = 0.64–0.66) and fair to moderate for the DJ (Kappa = 0.36–0.56). These results show that when asymmetry is computed between test sessions, the group mean is generally devoid of systematic bias; however, the direction of asymmetry shows greater variability and is often inter-changeable. Thus, practitioners should consider both the direction and magnitude of asymmetry when monitoring inter-limb differences in healthy athlete populations.

Keywords: Inter-limb differences; limb dominance; variability

1. Introduction

Inter-limb asymmetry refers to differences in the performance or function of one limb with respect to the other [1,2]. Strength and jumping-based tests are often used to quantify these differences when assessing the physical characteristics of athletes [3–5], largely because these are considered fundamental physical qualities to enhance athletic performance. Strength testing methods to quantify asymmetry have included the back squat [5,6], isometric squat and mid-thigh pull [7,8] or isokinetic dynamometry [9,10]. Jump tests such as countermovement jumps (CMJ) [3–5,11,12] and drop jumps (DJ) [13,14] are also commonly assessed to quantify asymmetry, most likely because of their similarity to sport-specific movement patterns, ease of implementation and time-efficient nature.

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Original Research

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The Association Between Interlimb Asymmetry and Athletic Performance Tasks: A Season-Long Study in Elite Academy Soccer Players

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Abstract

Bishop, C, Read, P, Bromley, T, Brazier, J, Jarvis, P, Chavda, S, and Turner, A. The association between interlimb asymmetry and athletic performance tasks: A season-long study in elite academy soccer players. *J Strength Cond Res* XX(X): 000–000, 2020—The aims of this study were to determine the association between asymmetry and measures of speed and change of direction speed (CODS) performance throughout a competitive soccer season and, determine whether any observed changes in asymmetry were associated with changes in speed and CODS performance. Eighteen elite male under-23 academy soccer players performed unilateral countermovement jumps, unilateral drop jumps (DJ), 10- and 30-m sprints, and 505 CODS tests at pre, mid, and end of season. No significant relationships were evident during preseason or midseason between asymmetry and speed or CODS performance. Significant correlations were shown at the end of season between DJ height asymmetry and 10-m sprint time ($\rho = 0.62$; $p = 0.006$) and 505 time on the right limb ($\rho = 0.65$; $p = 0.003$). No significant correlations between changes in asymmetry and changes in speed or CODS were evident at any time point. Although numerous studies have reported associations between asymmetry and reduced athletic performance, it seems that these associations with speed and CODS do not track consistently over time. Thus, suggestions for the reduction of asymmetry that may indirectly enhance athletic performance cannot be made.

Key Words: between-limb differences, jumping, change of direction speed, speed

Introduction

Soccer is a high-intensity, intermittent team sport that requires the development of multiple athletic qualities including sprinting, jumping, and changing direction to optimize physical performance (32). Frequent repetitions of these movements that involve significant musculoskeletal forces and joint loads can result in between-limb asymmetry in functional performance where preferred lower-limb dominance may be evident (2,5,7,25). This may be further confounded by heightened volumes of training and match play occurring at different points throughout a competitive soccer season. Thus, testing these physical qualities represent ecologically valid methods of assessment for soccer athletes.

There are a wide range of assessment methods that can be used to measure interlimb asymmetry. Jump testing, in particular, is a simple and time-efficient method commonly used in soccer and also has the advantage of providing information relating to the interlimb asymmetry profiles. Selecting tests, such as the countermovement jump (CMJ), drop jump (DJ), and their associated unilateral versions, enable practitioners to assess different athletic qualities (e.g., slow and fast stretch-shortening cycle characteristics), and determine how interlimb differences vary between tasks. Although measuring asymmetry during sprint tasks is also possible (e.g., between-limb differences in ground reaction forces), this often requires expensive equipment, which may not always be conducive to test protocols with elite-level players in the field. Further to this, previous research has highlighted a distinct lack of associations between sprint asymmetry and sprint performance (18,28), but significant correlations between jump height asymmetry and reduced sprint and change of direction speed (CODS) in youth (5) and adult (7) soccer athletes, thus further reinforcing the use of jump tasks for measuring between-limb differences.

Research investigating the association between asymmetry and athletic performance has shown equivocal findings (2,5,7,12,20,22–24,27). For example, Lockie et al. (24) reported no significant correlations between speed or CODS tasks and jump height or distance asymmetry in male collegiate athletes. Similarly, Dos'Santos et al. (12) showed no association between single leg and triple hop for distance asymmetry and 2 CODS tasks. By contrast, Bishop et al. (5) showed moderate correlations ($r = 0.49$–0.59) between jump height asymmetry from the unilateral CMJ and slower 5-, 10-, and 20-m sprint performance in youth female soccer players. In addition, Bishop et al. (7) showed moderate relationships ($r = 0.52$–0.66) between unilateral DJ asymmetries and slower 10- and 30-m and 505 CODS performance in adult female soccer players. Thus, given the conflicting findings in the literature to date, further research on the association between asymmetry and athletic performance is warranted.

When interpreting studies investigating the association between jump asymmetry and athletic performance, it should also be noted that all studies have been conducted at a single time point (2,5,7,12,20,22–24,27). Previous research has highlighted that

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Magnitude or Direction? Seasonal Variation of Interlimb Asymmetry in Elite Academy Soccer Players

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Abstract

Bishop, C, Read, P, Chavda, S, Jarvis, P, Brazier, J, Bromley, T, and Turner, A. Magnitude or direction? Seasonal variation of interlimb asymmetry in elite academy soccer players. *J Strength Cond Res* XX(X): 000–000, 2020—Previous research has highlighted a distinct lack of longitudinal data for asymmetry. The aims of this study were to provide seasonal variation data for the magnitude and direction of asymmetry. Eighteen elite male academy soccer players (under-23) performed unilateral countermovement jumps (CMJs) and unilateral drop jumps (DJs) during pre-season, mid-season, and end of season time points. Recorded metrics for asymmetry included jump height and concentric impulse for the CMJ, and jump height and reactive strength index for the DJ. The magnitude of asymmetry showed trivial to small changes throughout the season (CMJ effect size [ES] range = −0.43 to 0.05; DJ ES range = −0.18 to 0.41). However, Kappa coefficients showed poor to substantial levels of agreement for the direction of asymmetry during the CMJ (Kappa = −0.06 to 0.77) and DJ (Kappa = −0.10 to 0.78) throughout the season. These data show that when monitoring asymmetry, the magnitude alone may provide a false impression of consistent scores over time. By contrast, monitoring the direction of asymmetry highlights its task and variable nature and is suggested as a useful tool for practitioners who wish to monitor asymmetry over the course of a competitive soccer season.

Key Words: between-limb differences, longitudinal tracking, limb dominance

Introduction

Jump tests are commonly used for monitoring performance changes and neuromuscular readiness in soccer athletes (9,19,26,31). However, longitudinal tracking throughout a season has been reported more sparingly. Casajus (9) monitored jump height during the countermovement jump (CMJ) and squat jump (SJ) tests in 15 professional soccer players, although data were only collected in September and February, which likely represent time points near the start and middle of a competitive season. Results showed no significant differences between time points. By contrast, the CMJ was used by Haugen (19) to assess seasonal variation in vertical jump performance in 44 Norwegian professional soccer players. Results showed mean jump height (in cm) of 37.4 ± 4.0 for pre-season, 38.1 ± 4.0 in-season, and 38.6 ± 3.9 in the off-season. Significant differences were evident between pre-season and off-season, with effect sizes (ESs) between time points ranging from 0.15 to 0.30. With significant changes in jump performance potentially evident throughout a soccer season, this type of monitoring may allow practitioners a better understanding regarding the specific demands players may face at different stages of the season.

Players often experience heightened training volumes during pre-season (16) and increased fixture density during mid-season (8), with the effects of cumulated loading potentially driving sport-specific adaptations by the end of the season (1,27). In addition, it appears that bilateral jump tests have been the primary method to track longitudinal changes in vertical jump performance (9,11,19), with limited data available to examine seasonal changes in unilateral tests. Despite bilateral jumps often being used in routine test batteries with strong reliability (11,17), many sporting actions occur unilaterally for soccer players (e.g., sprinting, cutting, and kicking). Thus, the implementation of unilateral jump tests seems like an ecologically valid suggestion for the assessment of jump performance. Furthermore, the aforementioned studies only tracked jump height, which has been shown to be somewhat insensitive to change when using jump tests to detect neuromuscular fatigue (17). Thus, a more in-depth analysis of jump strategy may provide more meaningful information relating to how jumps are performed, which practitioners can use to detect acute changes in their athletes' movement patterns (13,17). Furthermore, this information is scarce using unilateral jump test measures and is warranted longitudinally.

Recent research has investigated the prevalence of asymmetry from unilateral jump tests and reported correlations with measures of athletic performance (3,6,15,22,24). However, these studies only reported asymmetry scores at a single time point. Previous literature has highlighted that longitudinal data pertaining to asymmetry are missing (7,25) and could be used to inform the monitoring process. Furthermore, seasonal changes in the direction of asymmetry to provide an indication as to which limb is dominant are also unknown. Bishop et al. (2) examined agreement between peak force and impulse metrics during the

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Original Research

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Effects of Soccer Match-Play on Unilateral Jumping and Interlimb Asymmetry: A Repeated-Measures Design

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Abstract

Bishop, C, Read, P, Stern, D, and Turner, A. Effects of soccer match-play on unilateral jumping and interlimb asymmetry: a repeated-measures design. *J Strength Cond Res* XX(X): 000–000, 2020—The aims of this study were two-fold: (a) determine the effects of repeated soccer match-play on unilateral jump performance and interlimb asymmetries and (b) examine associations between asymmetry and commonly reported external load variables collected during competition. Single-leg countermovement jumps and drop jumps were collected before and immediately after 5 soccer matches in elite academy soccer players. Global positioning system data were also collected during each match as part of the routine match-day procedures. Single-leg countermovement jump height and concentric impulse showed significant reductions after matches ($p < 0.01$; effect size [ES]: −0.67 to −0.69), but peak force did not ($p > 0.05$; ES: −0.05 to −0.13). Single-leg drop jump height and reactive strength also showed significant reductions after matches ($p < 0.01$; ES: −0.39 to −0.58). No meaningful reductions in asymmetry were present at the group level, but individual responses were highly variable. Significant associations between postmatch reactive strength asymmetry and explosive distance ($r - 0.29$; $p < 0.05$), relative explosive distance ($r - 0.34$; $p < 0.05$), high-speed running ($r - 0.35$; $p < 0.05$), and relative high-speed running ($r - 0.44$; $p < 0.01$) were observed. These findings show that unilateral jump tests are more appropriate than asymmetry to detect real change after soccer competition, and practitioners should be cautious about using asymmetry to inform decision-making during the temporal recovery period.

Key Words: between-limb differences, countermovement jump, drop jump, external load

Introduction

Investigating the association between jump asymmetry and measures of athletic performance has been a popular topic, with a recent rise in such studies using soccer players (5,6,8,9,28). Numerous studies in this population have shown that between-limb differences during jump tests are associated with reduced speed and change of direction speed (CODS) performance (5,8,9,15). By contrast, 2 studies have reported no association between asymmetry and athletic performance, both of which used elite-level male and female players (6,28). Although speculative, it seems likely that elite players would have enhanced strength and power compared with youth or academy players. Given that strength has been shown to be a key factor in the reduction of between-limb asymmetries (4), this may be a possible reason why no associations were evident between asymmetry and performance in elite players. However, all aforementioned studies have collected data from routine fitness testing sessions and reported relationships with surrogate measures of athletic performance (e.g., speed, CODS). Given the conflicting findings between asymmetry and performance and the variable nature of asymmetry (5,8,18,30), this tells us little about the associations between asymmetry and in-game soccer movement patterns.

Soccer is a high-intensity, intermittent sport that requires players to sprint, jump, kick, and change direction on multiple occasions in response to different stimuli (41). Time-motion analysis data have shown that elite soccer players cover distances on average of 10–11 km in matches (34). Matches can also include up to 168 high-intensity actions (37), 1,200–1,400 changes of direction (3), and up to 15 jumps per match (31). Given that many of these actions occur unilaterally, the development of interlimb asymmetries is to be expected, which is supported in previous research by Hart et al. (24), who showed that asymmetry is a by-product of competing in a single-sport over time.

Jump testing has been a common form of monitoring neuromuscular fatigue in soccer athletes (29,38,40). Studies often use simulated soccer protocols rather than competitive matches to determine acute responses (23,39), with both jump height and reactive strength index (RSI) performance shown to significantly decline immediately after protocols in the bilateral countermovement jump (CMJ) and drop jump (DJ) tests. However, given many movement patterns in soccer occur unilaterally (e.g., cutting, sprinting, and kicking), the use of single-leg jump tests would also provide an ecologically valid method of assessment. Single-leg tests also have the advantage of providing asymmetry data, even when twin force plate systems are not available. To the best of the authors' knowledge, only 1 study to date has investigated how both single-leg jump performance and interlimb asymmetry respond to competitive soccer match-play. Bromley et al. (11) performed single-leg countermovement jumps (SLCMJs) before,

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