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

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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.

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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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& Mellifont, 2014), basketball (Schiltz et al., 2009), and rowing (Buckeridge, Hislop, Bull, & McGregor, 2012). In addition, some research has examined inter-limb asymmetries across a range of physical competencies including strength (Bailey, Sato, Burnett, & Stone, 2015; Bazyler, Bailey, Chiang, Sato, & Stone, 2014; Sato & Heise, 2012), power (Bell, Sanfilippo, Binkley, & Heiderscheit, 2014; Benjanuvatra, Lay, Alderson, & Blanksby, 2013; Hoffman, Ratamess, Klatt, Faigenbaum, & Kang, 2007), and leg stiffness (Hobara, Inoue, & Kanosue, 2013; Maloney, Fletcher, & Richards, 2015; Maloney, Richards, Nixon, Harvey, & Fletcher, 2016). Whilst it is logical to assume that minimising these differences is desirable, determining whether this has an actual measurable effect on physical or sport performance still remains unclear.

Available literature has shown that inter-limb asymmetries ~10% result in reductions in jump height (Bell et al., 2014), and slower change of direction speed times (Hoffman et al., 2007), indicating that the reduction of these differences may be favourable. However, other studies have shown conflicting results (Bini & 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 data are available to support this notion (Hart et al., 2016). Furthermore, inter-limb asymmetries for kinetic and kinematic variables may show different values; thus, not all observed side to side differences may be relevant to the performance outcome (Exell et al., 2016; Rannama, Port, Bazanov, & Pedak, 2015). By more clearly understanding the effects of inter-limb asymmetries on physical and sports performance, it will provide practitioners with important information for the design of targeted testing and 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 effects on 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.

2. Methods

2.1 Literature search methodology

Original and review journal articles were retrieved from electronic searches of Medline and SPORT Discus databases. Figure 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

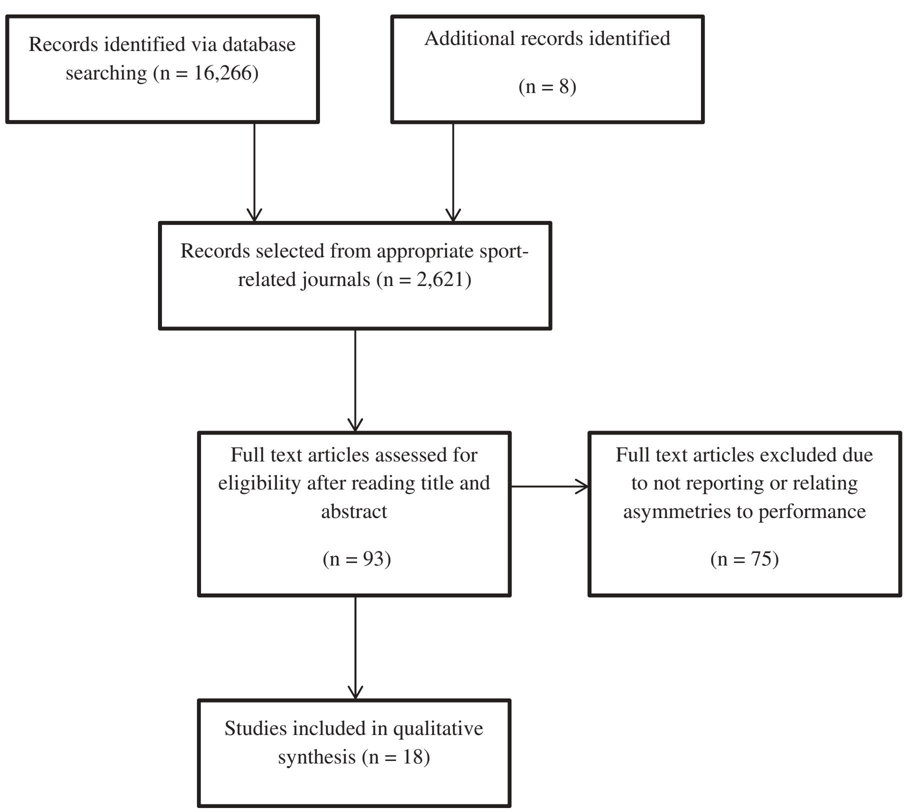

Figure 1. Flow diagram showing the identification and selection of studies in the available body of literature for the current review.

Table 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

prevalence of asymmetries in the population sample tested. The final search date was 9 November, 2016.

2.2 Grading article quality

A quality review was conducted in line with previous suggestions (Black, Gabbett, Cole, & Naughton, 2016). Each study was appraised using nine criteria (Table 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 associated studies with the topic of inter-limb asymmetries and effects on 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% (Table 2–5). To be sure of an appropriate level of quality, only articles that scored > 75% were considered for the final analysis.

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 Table 2–5 for details on study methodologies), 3 of these studies focused on asymmetries in strength, 3 examine asymmetries during jumping-based tasks, 7 during sporting actions, and 5 related asymmetries in dynamic balance, anthropometry, and sprinting to physical performance.

Table 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 = 36)	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 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, Richards, et al. (2016)	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 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%
Morouco 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 (n = 10)	Metrics: kicking accuracy, foot and ball velocity	5 kicks of a rolling and stationary ball	89%
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. 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, touchdown distance, net horizontal and vertical impulse, maximum vertical force, mean support moment, net ankle/knee/hip work	Mean velocity (m/s)	100%

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.

Furthermore, a wide range of performance outcome measures were employed to demonstrate the effects of inter-limb asymmetries on physical or sports performance (see Table 2–5). 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.

4. Discussion

The aim of this systematic review was to critically evaluate the available literature pertaining to inter-limb asymmetries and critically evaluate their effects on physical and sport performance. Inter-limb differences in strength, dynamic balance, and anthropometry appear to have a detrimental effect on 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.

4.1 Asymmetries in strength

Bailey, Sato, Alexander, Chiang, and Stone (2013) reported mean asymmetries during the isometric mid-thigh pull (IMTP) of 6.6 ± 5.1%, and moderate negative correlations between the peak force (PF) 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. While a large amount of variance remains unexplained, these data provide an indication that asymmetries of a greater magnitude may contribute to reduced 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, Nimphius, Spiteri, and Newton (2014) reported that higher 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 20m 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". Strength imbalance was measured via bilateral and unilateral isometric squats 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%. 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 to a higher standard, although further research is warranted to fully corroborate this theory. Furthermore, in a group of competitive cyclists, peak torque asymmetries of the knee extensors (at 180°sec^{-1}) 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, based on the available data, it would appear that there is a negative relationship between inter-limb asymmetries in strength and jumping, kicking and sprint cycling performance. However, when interpreting these findings, caution should be applied as the study designs utilised correlational analysis. Further research should aim to quantify how much variance in "loss of performance" can be attributed to inter-limb asymmetries in strength.

4.2 Asymmetries during jumping tasks

Conflicting findings were shown in studies measuring the performance effects of inter-limb asymmetries during jumping-based tasks. 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 change of direction speed (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 single leg countermovement jump (SLCMJ). This was combined with weak correlations between the SLCMJ non-dominant limb and the L-run for both dominant ($r = -0.36$; $p < .05$) and non-dominant ($r = -0.37$; $p < .05$) directions; and no significant relationships 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 & Young, 2006).

Maloney, Richards, et al. (2016) examined the relationship between asymmetries measured during single leg drop jumps 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 drop jump asymmetry variables were statistically significant. Inter-limb asymmetries were also calculated for left and right total time during the CODS test, although no significant differences were noted. Considering the sample in this study were not an athletic population and with asymmetries being previously suggested to be a product of playing sport over time (Hart et al., 2016), results may be different if an athlete sample was tested. These results indicate that minimising differences between limbs during unilateral drop jumping could be advantageous to enhance cutting performance. It is worth noting that Maloney, Richards, et al. (2016) 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.

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 & Hume, 2015). These results are unexpected as intuitively, larger asymmetries should be associated with reductions in 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: r = 0.53; 60: r = 0.56; 80: r = 0.56; 100: r = 0.40 and 120: 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 & Jensen, 2012).

Conflicting findings regarding the effects of asymmetry on swimming performance have also been reported. Dos Santos, Pereira, Papoti, Bento, and Rodacki (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 200m 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, Morouco, Marinho, Fernandes, and Marques (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 50m 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 (Morouco 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 Dos Santos et al's, (2013) study exhibited inter-limb differences > 10%. Thus, asymmetry may not have been a decisive factor in deciding the performance outcome for this sample. Despite these results, it is suggested that coaches aim to minimise notable differences between limbs, especially those > 10%.

More definitive results have been reported for the sport of futsal in professional and amateur populations. Barbieri, Gobbi, Santiago, and Cunha (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 higher asymmetries for the non-dominant limb. 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°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, Mellifont, & Burkett, 2009). Test set up involved the placement of different footballs at 0.3, 0.9, and 1.5m 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.

4.4 Asymmetries during dynamic balance, anthropometry, and sprinting tasks

4.4.1 Dynamic balance

Dynamic balance refers to "the ability to move and change directions under various conditions without falling" (Clark, Lucett, & Sutton, 2012). Gonzalo-Skok, Serna, Rhea, and Marin (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 = −0.520 to −0.773; p < 0.05) with CMJ height; a key measure of basketball performance (Fort-Vanmeerhaeghe, Gual, Romero-Rodriguez, & Unnitha, 2016; Read et al., 2014). In addition, dorsiflexion asymmetries (measured during a weight bearing lunge test) were negatively correlated (r = −0.523; 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. This is somewhat supported by Jordan et al. (2014) who highlighted the complexity of how inter-limb asymmetries changed from one side to the other during different loading phases of a CMJ, in athletes with prior ACL injuries. 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 dorsi-flexion 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, Cook, & Kent, 2006). Therefore, it would appear prudent to both minimise inter-limb differences in dynamic balance and optimise ankle range of motion for superior jumping and CODS performance.

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 9cm (effect size = $d > 0.8$). 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 100m. 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.

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 60m. Multiple kinetic and kinematic variables were reported (see Table 5) in respect to inter-limb asymmetries with results correlated to mean sprint velocity. Surprisingly, mean group 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. Directions for future research

Due to the paucity of appropriate data, 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 majority of existing research has focused on the measurement of asymmetry at a singular time point; thus, limited data are available pertaining to longitudinal changes in asymmetry and their impact on performance. So far, studies have focused on how inter-limb asymmetries change after a 6–8 week training intervention (Bazyler et al., 2014; Brown et al., 2017; Gonzalo-Skok et al., 2017; Sannicandro, Cofano, Rosa, & Piccinno, 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, to the authors' knowledge, 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 post-season is common) and it should not be assumed that asymmetries reported during pre-season would be the same during mid or post-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 regression analysis as a tool to determine how much of a change in performance is accounted for by inter-limb asymmetries. 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 further consideration for study designs would be the implementation of randomised controlled trials. Minimal literature has focused on training interventions to reduce asymmetries, especially with the use of a control group (Iacono, Padulo, & Ayalon, 2016; Sannicandro et al., 2014). For example, a targeted training intervention that utilised three groups: one that reduced inter-limb asymmetries, a second that exacerbated them and a third acting as a control may provide a clearer picture as to whether reducing between-limb differences are required for optimal physical performance.

The mechanisms or underlying causes of how inter-limb differences occur is another area that has not been widely investigated in the current body of literature. For example, while inter-limb asymmetries in power may be related to a reduction in jump height (Bell et al., 2014), a deeper understanding of why these differences exist will allow for targeted training interventions to be developed to minimise asymmetry. To support this further, Young, Cormack, and Crichton (2011) showed that the strategies used in executing a jump were equally as important to monitor as the movement outcome, i.e., the height of the jump itself. Thus, future research should investigate the mechanisms that are associated with greater asymmetries during various physical performance tests or sports skills.

A higher frequency of injuries is also commonly reported during the latter stages of matches for team sport athletes (Ekstrand, Hagglund, & Walden, 2011; Price, Hawkins, Hulse, & Hodson, 2004). Thus, quantifying the effects of fatigue on asymmetries may assist in further understanding mechanisms of injury and performance loss during these crucial periods. To the authors' knowledge, only two studies have examined the effects of fatigue on inter-limb asymmetries. Radzak, Putnam, Tamura, Hetzler, and Stickley (2017) measured kinetic and kinematic asymmetries during gait in both rested and fatigued states. Fatigue was determined when rate of perceived exertion (RPE) 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_2 max. Small (1–6%) reductions 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, Patrick, and Reiser (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 vertical ground reaction force 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 not actually measured in the study, merely inferred from the chosen protocol; thus, future research should aim to quantify fatigue as well where possible. 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.

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 detrimental effect on 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; 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 emphasises the complexity of asymmetries and their relationships with measures of physical and sports performance; highlighting the need for further research.

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