BRIEF REVIEW

The Relationship Between Asymmetry and Athletic Performance: A Critical Review

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Abstract

Maloney, SJ. The relationship between asymmetry and athletic performance: A critical review. *J Strength Cond Res* 33(9): 2579–2593, 2019—Symmetry may be defined as the quality to demonstrate an exact correspondence of size, shape, and form when split along a given axis. Although it has been widely asserted that the bilateral asymmetries are detrimental to athletic performance, research does not wholly support such an association. Moreover, the research rarely seeks to distinguish between different types of bilateral asymmetry. Fluctuating asymmetries describe bilateral differences in anthropometric attributes, such as nostril width and ear size, and are thought to represent the developmental stability of an organism. There is evidence to suggest that fluctuating asymmetries may be related to impaired athletic performance, although contradictory findings have been reported. Sporting asymmetries is a term that may better describe bilateral differences in parameters, such as force output or jump height. These asymmetries are likely to be a function of limb dominance and magnified by long-standing participation within sport. Sporting asymmetries do not seem to carry a clear influence on athletic performance measures. Given the vast discrepancy in the methodologies used by different investigations, further research is warranted. Recent investigations have demonstrated that training interventions can reduce sporting asymmetries and improve performance. However, studies have not sought to determine whether the influence of sporting asymmetry is independent of improvements in neuromuscular parameters. It may be hypothesized that the deficient (weaker) limb has a greater potential for adaptation in comparison to the strong limb and may demonstrate greater responsiveness to training.

Key Words symmetry, imbalance, power, strength

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Introduction

Symmetry may be defined as the quality of an object to demonstrate an exact correspondence of size, shape, and form across its 2 halves when split along a given axis. In the human body, we typically consider *mirror symmetry* along the coronal axis, which partitions the body into left and right halves. Thus, deviation from mirror symmetry across the coronal axis is termed *bilateral asymmetry.* Although it has been widely asserted that the bilateral asymmetries are detrimental to athletic performance, research does not wholly support such an association. Moreover, the literature rarely seeks to distinguish between different types of asymmetry. The aim of this review is therefore to discuss the various types of asymmetry, examine how they may be developed through participation in sport, and examine their association with measures of athletic performance.

Types of Asymmetry

Deviations from symmetry for a given characteristic can be classified into 1 of 3 types as outlined by Van Valen (70). Illustrations of how these types of asymmetries are distributed are shown in Figure 1A-C. It is important to understand the distribution of these asymmetries because this highlights the patterns and likely prevalence of each type of asymmetry within a population. *Directional asymmetry* describes a characteristic that consistently develops toward a given side. For example, the position and mass of internal organs in the human body are not positioned or distributed symmetrically. *Antisymmetry* describes a characteristic that will typically develop toward a certain side, however, the side to which this occurs is variable. An example of antisymmetry would be handedness or limb preference. Directional asymmetries and antisymmetries are commonly thought to be developmentally controlled and normally adaptive (70). However, the third type of asymmetry is often associated with negative or harmful connotations. Fluctuating asymmetry (FA) describes a characteristic that would be expected to develop symmetrically but deviates from this path (70,72). In the human body, an example of this could be nostril width or ear size. It is argued that these FAs are a marker of environmental stress and the evolutionary "health" of an organism (40,45,72). As noted by Van Valen (70), multiple types of asymmetry can be present for the same character and need not be thought of discrete categories. When seeking to explore potential relationships between asymmetries and

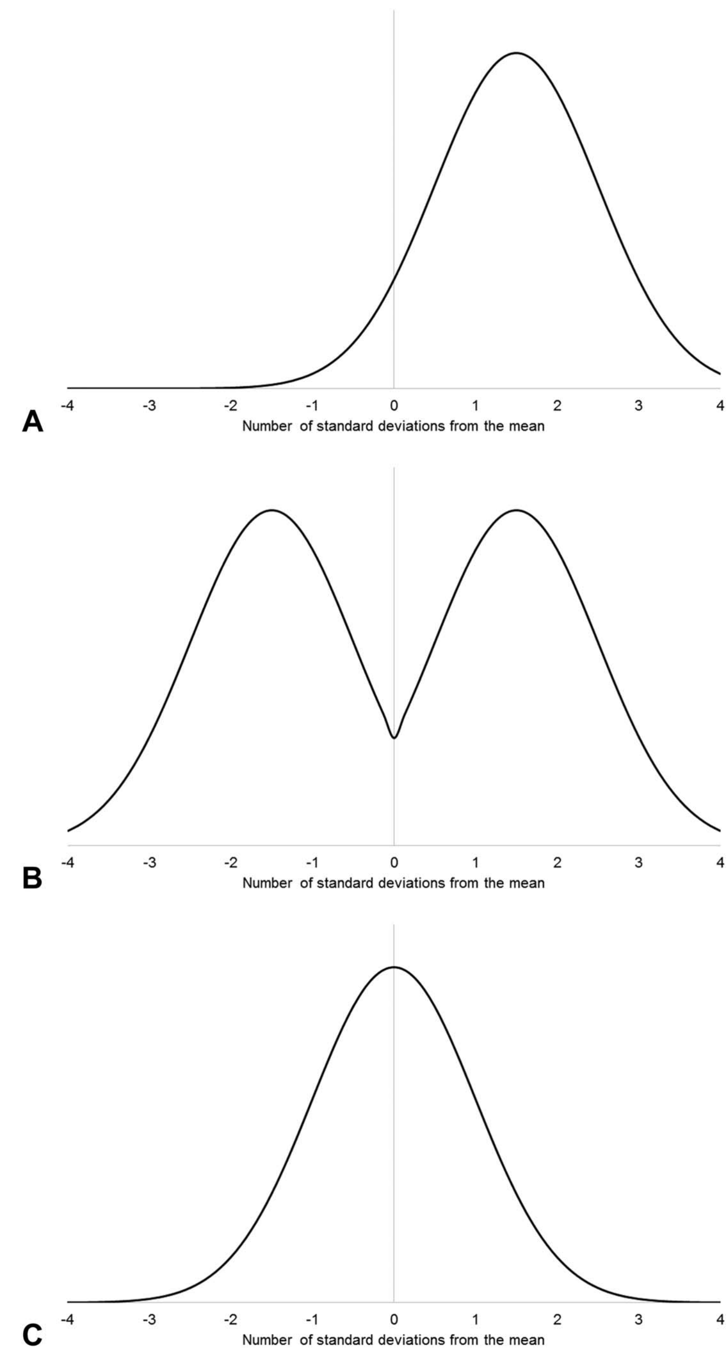

Figure 1. An example of the distribution curves associated with directional asymmetry (A), antisymmetry (B), and fluctuating asymmetry (C).

performance, it is important to consider the type of asymmetry that has been determined.

Laterality and Limb Dominance

Lateral preference, often termed laterality, describes the concept that humans will preferentially use one side of their body when presented with a motor task to perform (11,60). However, in regards to sports performance, it is important to differentiate between laterality (or "skill" dominance) and force dominance (i.e., the limb demonstrating superior force qualities in a given task). For example, Lake et al. (35) did not observe significant asymmetries in the ground reaction force profile of the back squat when categorizing limbs based on perceived handedness (i.e., skill dominance; mean asymmetries between −2.5 and 8.2%) but did observe asymmetry when categorizing based on ground reaction force dominance (mean asymmetries between 13.5 and 20.7%; $p < 0.05$). This replicates the findings of Newton et al. (51) who compared force dominance in female softball athletes within a range of strength and power tasks. Significant asymmetries were not reported in bilateral back squat, bilateral and unilateral vertical jumps, and a 5-hop test when comparing left and right limbs. However, when comparing the dominant limb (i.e., the limb with the greater force, jump height, or hop distance) with the nondominant limb within each task, significant asymmetries were observed in all instances. Nonetheless, it is important to acknowledge that although all 14 softball athletes were right-handed throwers, 4 (29%) were left-handed batters. As such, skill dominance may be considered task specific, and investigations should therefore clearly state how this has been determined within their cohort.

Although skill dominance (i.e., handedness) is likely to influence the direction of force asymmetries (i.e., which arm or leg is stronger), the way this will manifest is dependent on sport-specific demands. For example, the right-handed badminton player would right-leg lunge (34), increasing the likelihood of a right-leg force dominance. In contrast, the right-footed Australian Rules Football player would expose the left leg to repetitive and rapid eccentric loading (26), increasing the likelihood of a left-leg force dominance. It is therefore important that investigations seeking to explore asymmetry clearly define how limbs are categorized and the athletic background of the experimental cohort.

Sporting Demands and Asymmetry

Motor tasks can be grouped in 4 ways in line with propositions made by Guiard (25): (Group 1) unilateral (i.e., long jump take off), (Group 2) bilateral asymmetric (i.e., golf swing), (Group 3) out-of-phase bilateral symmetric (i.e., cycling), and (Group 4) in-phase bilateral symmetric (i.e., weightlifting). It may also be reasonable to consider categorizing sports using this system. For instance, soccer could be classified as a group 2–dominant sport given the presence of group 2 tasks such as kicking, changing direction, and approach jumping. Although the existence of laterality may be clear in group 1 or group 2 tasks, it is perhaps less obvious in group 3 and group 4. A wide-ranging review from Carpes et al. (11) reported notable asymmetries during running and cycling, both group 3 tasks. When considering barbell back squat performance, a group 4 task, a number of investigations have also demonstrated bilateral differences in cohorts with no apparent sport specialization (22,35).

Group 1 sports such as badminton or fencing require athletes to perform a high volume of lunges on the skill-dominant side. So, while a characteristic, such as quadriceps muscle mass, may be expected to be symmetric in the general population, the asymmetric demands of the sports will almost certainly result in asymmetric adaptations. In these instances, the asymmetrical development should not be thought of as a random FA but a functional adaptation to allow the athlete to perform within their sport. Equating this type of "sporting asymmetry" to a marker of developmental dysfunction (i.e., FA) must therefore be questioned. Indeed, this review proposes the definition *sporting asymmetry* as an additional fourth type of asymmetry that is a function of an athlete's long-standing participation in their sport.

Sporting Asymmetry

Such types of sporting asymmetries have been demonstrated in a wide range of populations. This includes group 1 athletes such as long jumpers (33) and fencers (69), group 2 athletes such as Australian Rules footballers (26) and soccer players (54), group 3 athletes such as sprinters (21) and endurance runners (59), and group 4 athletes such as weightlifters (36) and powerlifters (41).

The magnitude of a sporting asymmetry developed by an athlete is likely to depend on the type of sport they play. Bussey (10) examined pelvic asymmetry (determined from height and width measurements between pelvic spinous processes) in 40 elite female athletes and 20 active control subjects; unilateral athletes (field hockey, ice hockey, and speed skating) demonstrated greater pelvic asymmetry than bilateral athletes (triathlon, cross-country running, and single scull rowing) or control subjects ($p = 0.001$ and 0.01, respectively). Luk et al. (41) evaluated asymmetries in force production expressed during single-leg jumping by the National Collegiate Athletic Association Division 3 jump athletes and competitive powerlifters; limb symmetry index was greater in jumpers (6.7 ± 1.8%) than in powerlifters (2.7 ± 0.7%; $p = 0.04$).

The type of activity an athlete is engaged in, together with their volume of exposure to the sport, is likely to influence to magnitude of asymmetry. Hart et al. (27) compared the lower-body musculoskeletal morphology of experienced (>3 years; $n = 28$) and less experienced (≤3 years; $n = 27$) Australian Rules football players. Experienced players exhibited significantly greater interlimb asymmetries in parameters such as tibial mass and cross-sectional area than nonexperienced players. Such findings would suggest that asymmetries are an adaptive consequence that is magnified with long-standing sporting participation.

Fluctuating Asymmetries and Performance

Fluctuating asymmetry should describe a characteristic that would be anticipated to develop symmetrically on both sides of the body (70,72). Deviations from symmetry are therefore hypothesized as to reflect "developmental instability," an organism's inability to withstand environmental stressors without eliciting a morphological response (32). The morphologic presentation of FA is only likely to be small in magnitude unless deviations occur early in embryonic development (32).

Negative relationships between FA and performance had been demonstrated in species such as *Equus caballus* (racehorses) (46), *Canis familiaris* (racing dogs) (49), and *Sturnus valgaris* (starlings) (64) before associations in humans were examined. Human investigations have sought to examine FA using bilateral anthropometric measurements that are unlikely to be greatly impacted through sporting participation. Examples include as nostril width, second to fifth digit length, ear size, and wrist width, all characteristics that would be anticipated to develop symmetrically (47). Table 1 details the key findings from such studies.

A case for potentially deleterious effects of FA on performance can be made given the findings of a number of investigations (40,47,67,68), including those in athletic cohorts (40,67). It has been proposed that FA is a marker of developmental instability caused by environmental stressors (40,47), which may lead to "abnormalities" in the development of attributes, such as maximal strength or aerobic capacity (40). However, evidence to the contrary does exist. Tomkinson and Olds (65) observed no influence of FA on several physiological fitness measures in untrained individuals. A subsequent investigation from the same research group (66) also reported that FA did not discriminate between elite (professional) and subelite (semi-professional) performers in Australian basketball and soccer players.

Although further research is necessary before clear relationships between FA and athletic performance may be concluded, the potential application of such research should also be considered. As proposed by Manning and Pickup (47), the highlighting of symmetric individuals could form part of a talent identification were the efficacy of specific measurements to be determined. For example, Trivers et al. (68) observed that FA at 8 years of age predicted 3–4% of variance in sprint performance 14 years later. Notwithstanding the issues regarding the current balance of evidence to support this notion, using protocols to preferentially select individuals and "breed" them for sporting success must be associated with ethical concerns. It is perhaps pertinent to draw comparisons between the determination of FA and genetic testing, for which a clear consensus statement has been published in the British Journal of Sports Medicine (73). Currently, research is not unanimously clear that FA is detrimental to performance. The magnitude of any potential effect is likely to be small, and FA seems not to be substantially influenced by training (67). For this reason, it is advised that the assessment of FA for talent identification purposes should not be encouraged.

Sporting Asymmetries and Performance

Studies examining the role of bilateral asymmetries in sporting performance do not typically consider characteristics that may be well described as FA. Investigations have typically sought to determine if asymmetries in variables, such as muscle mass, jump height, maximal force, and the like, exhibit relationships with markers of athletic performance, such as jump height or sprint time. This review will seek to group investigations by the type of performance outcome evaluated. A summary of the associative studies evaluated is presented in Table 2.

Jumping Performance

Bailey et al. (1) and Bell et al. (5) present an apparently strong case for asymmetry negatively impacting performance. Bailey et al. (1) reported that peak force asymmetries during an isometric midthigh pull (IMTP) test negatively correlated with jump height and peak power ($r = 0.28$–0.52; all $p < 0.05$). However, the investigation did not examine asymmetry during the jumping tasks, nor does it report the relationship between peak IMTP force and IMTP asymmetry. The presentation of asymmetry has been previously demonstrated to be task specific (2,42), particularly in weaker athletes (2). Bailey et al. (2) compared the asymmetries recorded in jumping and IMTP tasks in a cohort of collegiate athletes. Athletes in the strongest quartile (grouped on peak IMTP force) demonstrated some degree of correspondence between the asymmetries recorded in the different tasks, but athletes in the weakest quartile did not.

It is also important to consider the relationship between training status and asymmetry. Stronger individuals may be anticipated to demonstrate less asymmetry (3,4) and would also be expected to perform better in jumping tasks (63). For example, Bazyler et al. (4) median split recreationally trained male subjects into strong and weak groups based on isometric squat peak force. The reported symmetry index of the strong group (1.9 ± 1.1%) was significantly lower than that of the weak group (3.9 ± 1.8%; $p = 0.007$). Bailey et al. (3) observed similar findings when analyzing peak IMTP force in collegiate athletes. The symmetry index of the strongest decile (4.7 ± 0.1%) was also significantly lower than that of the weakest decile (9.4 ± 0.1%; $p = 0.03$; $d = 0.82$). Importantly, Bazyler et al. (4) noted that the strength-asymmetry relationship can be modulated by training. After a 7-week squat training intervention, both strong and weak groups improved 1-repetition maximum (RM) squat performance (strong: 5.0%, weak: 6.6%; both $p < 0.05$), although only the weak group reduced isometric squat asymmetry (from 3.9 ± 1.8 to 1.9 ± 1.5%; $p < 0.05$). Such findings suggest that the presentation of asymmetry can be greatly affected by an athlete's training status. Where seeking to examine relationships between asymmetry and performance, training status and exercise familiarity must be considered when selecting appropriate tests to identify asymmetry.

Bell et al. (5) reported that differences in countermovement jump (CMJ) height were not statistically significant across different levels of CMJ force or CMJ power asymmetries in collegiate athletes. However, the investigators also grouped athletes into bands of asymmetry (0–5%, 5–10%, 10–15%, and >15%) for analyses. Bell et al. (5) highlighted that an asymmetry in CMJ power of >10% power resulted in

TABLE 1. Summary of studies evaluating fluctuating asymmetries and their association with performance measures.*

Study	Participants	Asymmetry variables	Outcome variables	Findings
Manning and Pickup (47)	50, male, middle-distance runners; age: 24.2 ± 1.0 y	Ear size ASYM	800-m personal best time ($n = 50$)	Nostril (beta = 26.8; $p < 0.05$) and ear (beta = 13.2; $p < 0.01$) ASYM related to slower 800-m time
		Nostril width ASYM	1,500-m personal best time ($n = 27$)	Ear (beta = 10.4; $p < 0.05$) and third digit (beta = 14.0; $p < 0.01$) ASYM related to slower 1,500-m time
		Second–fifth digit length ASYM Wrist width ASYM	Self-reported ranking (i.e., country, national, international)	Ear (beta = −0.98) and nostril (beta = −2.41) ASYM negatively related to ranking (both $p < 0.001$)
Tomkinson and Olds (65)	46, healthy, young adults (M: 21 and F: 25) age: 20.3 ± 3.0 y	Composite ASYM scores for fat (skinfolds), muscle (girth), and bone (lengths and breadths)	Max aerobic capacity CMJ Grip strength	No notable and consistent correlations between ASYM and performance
Tomkinson et al. (66)	13 elite and 13 subelite, male, Australian basketball players; age, 25.1 ± 3.5 y 13 elite and 13 subelite, male, Australian soccer players; age: 23.4 ± 5.1 y	Composite ASYM scores for fat (skinfolds), muscle (girth), and bone (lengths and breadths)	Level of competition (elite or subelite)	No difference in ASYM between elite and subelite
Longman et al. (40)	146 mixed-ability university rowers (M: 76 and F: 70); age: 21.2 ± 3.2 y	Composite ASYM score from second to fourth digit length	2,000-m rowing ergometer time trial	ASYM associated with slower performance in male subjects ($r = 0.44$; $p < 0.001$) and female subjects ($r = 0.45$; $p < 0.001$) ASYM explained 9.5% of variance in male subjects and 14.2% in female subjects
Trivers et al. (68)	163, untrained adults (M: 98 and F: 65); age (2010): 22.6 ± 1.8 y	Composite ASYM score from knee breadth, ankle breath, and foot length	90-m sprint in 2010	Knee ASYM in 1996 explained 4% of variance in 90-m sprint ($p \leq 0.01$) and 3% in 180 m ($p = 0.03$)
		Measures obtained in 1996 (age: ~8 y) and repeated in 2006 (mean age: ~18 y)	180-m sprint in 2010	Knee ASYM in 2006 explained 4% of variance in 90-m sprint ($p \leq 0.01$)
Trivers et al. (67)	73, elite, track and field athletes; age: 23.0 ± 3.2 y 116 age-matched control subjects; age: 23.0 ± 3.6 y	Composite ASYM score from knee breadth, ankle breath, and foot length	IAAF score	Composite ASYM explained 5% of variance in athletes ($p = 0.031$) Knee ASYM explained 5% of variance in athletes ($p = 0.040$)
			Athletic status (athlete or control)	Composite ASYM lower in athletes ($p < 0.001$)

*M = male; F = female; ASYM = asymmetry; CMJ = countermovement jump; IAAF = International Association of Athletics Federations.

decreased jump height of 0.09 m, reporting this as a key finding in their article. However, these comparisons are based upon a group of just 9 athletes exhibiting an asymmetry of >10% in comparison to 158 athletes who recorded asymmetries of <10%. It is also important to note that 34 athletes exhibited a CMJ force asymmetry of greater than 10%, and no such between-group comparisons were alluded to. Interestingly, the authors' tables indicate that athletes with a >15% asymmetry for CMJ force ($n = 7$; 38.8 ± 7.9 cm) demonstrated the highest jump heights in this investigation, compared with 36.1 ± 8.5 cm in athletes with a 0–5% force asymmetry ($n = 88$). Given the small sample sizes and associative relationships observed, not to mention the potentially contradictory findings, assertions that "restoring between-limb power asymmetry would have a positive impact on athletic performance" would appear unfounded. Considering also the findings of Maloney et al. (44), it would seem premature to conclude upon a clear relationship between asymmetry and jumping performance.

Sprinting Performance

Although Sannicandro et al. (57) demonstrated a relationship between asymmetry and impaired sprinting performance, Lockie et al. (39) reported to the contrary. More recent investigations have also not supported any association between asymmetry and sprinting performance (20,28,37,38,48). Sannicandro et al. (57) evaluated asymmetry using single-leg jump height and reported a relationship with 10-m, but not 20-m, sprint performance. However, this investigation was presented as a poster presentation with little methodological detail and analysis of the results. Although cited in subsequent investigations (i.e., Meyers et al. (48)), the results of this investigation should therefore be interpreted with caution. When the same asymmetry test was employed by Lockie et al. (37), no such association was observed.

Lockie et al. (39) determined interlimb concentric strength asymmetries of the knee extensors and knee flexors at angular velocities of 60, 180, and $240°\cdot sec^{-1}$ and eccentric strength asymmetries at $30°\cdot s^{-1}$. The investigators reported that bilateral differences in knee extensor torque at 180° (r = 0.53–0.58; $p < 0.05$) and $240°\cdot s^{-1}$ (r = 0.77–0.90; $p < 0.05$) were associated with faster sprint times across 10-, 20- and 40-m distances (i.e., faster athletes demonstrated greater asymmetry). Strength asymmetries were also determined in a subsequent study from the same research group. Lockie et al. (38) recorded force, power, and velocity asymmetries in a 5RM, rear-foot, elevated, split squat exercise, but this time observing no significant relationships between asymmetries and sprint times.

Asymmetries within sprinting kinetics and kinematics have been examined in 3 investigations (20,28,48). All 3 studies have reported significant interlimb asymmetries; however, none have reported an association between asymmetry and overall sprint performance (20,28,48). Although the findings of Meyers et al. (48) were observed in a cohort of 11- to 16-year-old boys, Exell et al. (20) and Haugen et al. (28) sampled from populations of well-trained sprint athletes. Haugen et al. (28) also evaluated the influence of asymmetry on an intraindividual level. Between sprinters best and worst sprint trials, there were no differences in the magnitude of asymmetries recorded. On consideration of the current evidence base, it would therefore appear that asymmetries should not be considered detrimental to sprinting performance.

Change of Direction Performance

As change-of-direction (COD) performance is a group 1 unilateral task, it may be reasonable to propose that asymmetries would be less likely to influence performance than type 3 or 4 bilateral tasks. Performances in COD tasks rely on the extension forces generated by single limb, as opposed to an interlimb "trade-off" that is evident during bilateral tasks. Indeed, it appears likely that asymmetries evident during bilateral tasks are a function of neural (i.e., regulation of interlimb effort) and not mechanical (i.e., maximal force production capacity) factors (6,42,61).

As seen in Table 2, the majority of the literature does not support an association between asymmetry and COD performance (14,16,17,30,37). These investigations have all evaluated COD performance in athletes, where this attribute would be anticipated to be an important determinant of sporting performance. The aforementioned study by Lockie et al. (39) is 1 of the 2 investigations that did report an association between asymmetry and COD performance. As the authors observed in regard to linear sprint performance, asymmetry in high-velocity ($240°\cdot s^{-1}$) knee extensor torque correlated with faster T-Test times in team-sport athletes ($r = 0.57$; $p = 0.002$). Conflicting findings were reported by Maloney et al. (43) in recreationally trained individuals, demonstrating that drop jump height asymmetry was linked to impaired COD performance ($R = 0.60$; $p = 0.009$). However, asymmetry within the COD test itself (i.e., faster vs. slower limb cutting time) was not associated with overall COD performance. Importantly, Maloney et al. (43) also noted that the direction of asymmetry during the drop jump did not correspond well with the direction of asymmetry during the COD test (i.e., the left limb may perform better in the drop jump task but perform worse in the COD task). Poor agreement for COD asymmetries with both hop (17) and IMTP (16) asymmetries has also been reported, further highlighting the task specificity of asymmetries. Moreover, as has been previously discussed, asymmetries could be consequential of a lower general training status and motor competence within a given task. Maloney et al. (43) sampled individuals with a lower training status in comparison to the other investigations, and their results should be interpreted with this in mind.

Table 2. Summary of studies evaluating sporting asymmetries and their association with performance measures.*

Study	Participants	Asymmetry variables	Outcome variables	Findings
Jump performance				
Bailey et al. (1)	36, male, collegiate athletes; age: 20.3 ± 1.0 y	IMTP peak force ASYM	SJ height (0- and 20-kg load)	ASYM associated with lower jump height in SJ ($r = -0.52$ and -0.39; both $p < 0.001$)
			CMJ height (0 kg and 20 kg load)	ASYM associated with lower jump height in SJ ($r = -0.47$ and -0.49; both $p < 0.001$)
Bell et al. (5)	167, mixed-sport, NCAA Division 1 athletes (M: 103 and F: 64); age: 20.0 ± 1.2 y	CMJ peak force ASYM CMJ peak power ASYM	CMJ height	Athletes grouped into 0–5%, 5–10%, 10–15%, and >15% levels of ASYM CMJ height not significantly different between levels of force ($p = 0.37$) or power ($p = 0.08$) ASYM 10% power ASYM ($n = 9$) associated with decreased CMJ height ($d = 0.80$)
Maloney et al. (44)	18 recreationally trained male subjects; age: 22 ± 4 y	SL DJ height ASYM SL DJ vertical, ankle, and knee stiffness ASYM	SL DJ height (mean of both limbs)	DJ height not correlated with DJ height ASYM ($r = -0.35$; $p = 0.15$). DJ height not correlated with vertical ($r = -0.08$; $p = 0.74$), ankle ($r = -0.28$; $p = 0.26$), or knee ($r = 0.06$; $p = 0.81$) stiffness ASYM
Sprint performance				
Sannicandro et al. (57)	25, elite, male soccer players; age: 26.1 ± 2.9 y	SL CMJ height ASYM	10-m sprint time 20-m sprint time	ASYM associated with slower 10 m time ($r = 0.70$; $p < 0.001$) but not 20-m time ($r = 0.22$; $p =$ ns)
Lockie et al. (39)	16, male, team sport athletes; age: 23.3 ± 5.3 y	Knee extensor torque ASYM at 60, 180, and 240°·s^{-1}	10-m sprint time	Knee extensor torque ASYM at 180° ($r = 0.53$–0.58; $p < 0.05$) and 240°·s^{-1} ($r = 0.77$–0.90; $p < 0.05$) associated with faster sprint times (all distances)
		Knee flexor torque ASYM at 60, 180, and 240°·s^{-1}	20-m sprint time 40-m sprint time	A median-sprint fast group had greater extensor ASYM at 240°·s^{-1} (11.7 vs. 4.1%; $p = 0.03$)
Lockie et al. (37)	30, male, team sport athletes; age: 22.6 ± 3.9 y	SL CMJ height ASYM SL broad jump distance ASYM SL lateral jump distance ASYM	5-m sprint time 10-m sprint time 20-m sprint time	No correlation between any ASYM and performance at any distance ($r = -0.18$–0.08)
Exell et al. (20)	8, trained, male sprinters (max velocity: 9.05 ± 0.37 m·s^{-1}); age: 22 ± 5 y	Composite sprint kinetics ASYM score Composite sprint kinematics ASYM score	Mean velocity in 60-m sprint	Sprint velocity not correlated with kinetic ($p = 0.40$) or kinematic ($p = 0.19$) ASYM scores

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Meyers et al. (48)	344 school-aged boys; age: 13.2 ± 1.4y	Spatiotemporal ASYM in sprint Modelled force and stiffness ASYM in sprint	Maximal velocity in 35-m sprint	No relationship between the magnitude of ASYM in any variable and maximal velocity
Haugen et al. (28)	22, male, competitive sprinters (100-m PB: 10.86 ± 0.22 s); age: 23 ± 3 y	Various kinematic ASYMs in stride cycle	20-m flying sprint time	No correlations between ASYM and performance ($r = -0.37–0.40$) No changes in ASYM between sprinters' best and worst trials
Lockie et al. (38)	8, strength-trained males; age: 23.4 ± 1.5 y	Force, power, and velocity ASYM in 5RM rear-foot elevated split squat	5-m sprint time 10-m sprint time 20-m sprint time	No significant correlations between ASYM and performance ($r = -0.81–0.40$)
Change of direction performance				
Hoffman et al. (30)	62, male, NCAA Division 3, American football players; age: 19.7 ± 1.4 y	SL CMJ power ASYM	3-cone drill time (dominant and nondominant limbs)	No correlation between SL CMJ power ASYM and 3-cone drill time ($r = 0.11$) No significant difference between dominant (8.02 ± 0.51 s) and nondominant (7.97 ± 0.51 s) sides in 3-cone drill
Lockie et al. (39)	16, male, team sport athletes; age: 23.3 ± 5.3y	Knee extensor torque ASYM at 60, 180, and 240°·s^{-1} Knee flexor torque ASYM at 60, 180, and 240°·s^{-1}	T-Test time	Knee extensor torque ASYM at 240°·s^{-1} ($r = 0.57$; $p = 0.002$) associated with faster T-Test time
Lockie et al. (37)	30, male, team sport athletes; age: 22.6 ± 3.9 y	SL CMJ height ASYM SL broad jump distance ASYM SL lateral jump distance ASYM	5-0-5 test time (left and right directions) T-Test time (left and right directions)	No relationship between any ASYM and any 5-0-5 or T-Test performance ($r = -0.08$ to 0.19)
Chiang (14)	27, NCAA Division 1, soccer players (M: 12 and F: 15); age: 21.0 ± 1.3 y	IMTP peak force ASYM	Modified 5-0-5 test time (left and right directions)	Athletes median split into high (≥6%) and low (≤4%) ASYM groups based on IMTP force No difference between groups for partial or total 5-0-5 time in either direction
Maloney et al. (43)	18, recreationally trained male subjects	SL DJ height ASYM	2 × 90° cut CODS test time (left and right directions)	DJ height ASYM 2nd predictor variable in regression model for CODS time and correlated with slower CODS ($r = 0.60$; $p = 0.009$)
	Age: 22 ± 4 y	SL DJ vertical, ankle, and knee stiffness ASYM CODS test time ASYM		CODS test ASYM not correlated with CODS performance ($r = 0.38$; $p = 0.13$) ASYM in CODS test summated force correlated with slower CODS ($r = 0.47$; $p = 0.049$)
		CODS test force profile ASYM		Low correspondence between ASYM reported in the CODS test vs. DJ test

Dos'Santos et al. (17)	22, mixed-sport, collegiate athletes; age: 21.8 ± 3.4y	SL hop distance	Modified 5-0-5 test time (left and right directions)	No significant correlations between hop or triple hop ASYM and either measure of CODS performance ($r \leq 0.35$)
		SL triple hop distance	Single 90° cut test time	Low correspondence (32–35%) between ASYM reported in the CODS test vs. hop tests
Dos'Santos et al. (16)	20, mixed-sport, collegiate athletes; age: 21.0 ± 1.9 y	SL IMTP peak force ASYM	Modified 5-0-5 test time (left and right directions)	No difference in CODS performance between "high" vs. "low" ASYM groups
		SL impulse (at both 200 and 300 ms) ASYM		Low correspondence (40–60%) between ASYM reported in the CODS test vs. IMTP test
Strength performance				
Sato and Heise (58)	28, male, collegiate athletes; age: 20.3 ± 1.1 y	Standing weight distribution ASYM	1RM back squat relative to body mass	No difference in squat 1RM ($p = 0.51$) between median-split equal (1.21 ± 0.24 $kg \cdot kg^{-1}$) and unequal (1.25 ± 0.27 $kg \cdot kg^{-1}$) weight distribution groups
Bazyler et al. (4)	16, recreationally trained males; age: 20.8 ± 2.0 y	Isometric squat peak force at 90 and 120° ASYM	1RM back squat	Athletes median-split into strong and weak groups based on squat 1RM
			Isometric squat peak force at 90 and 120°	Peak force ASYM greater in the weak group at 90° ($p = 0.045$) and 120° ($p = 0.007$)
Bailey et al. (3)	129, mixed-sport, NCAA Division 1 athletes (M: 64 and F: 65); age: 18–23 y	IMTP peak force ASYM	IMTP peak force	Athletes grouped into top (strong; $n = 13$) and bottom weak; $n = 13$) 10% based on IMTP force
		IMTP RFD ASYM		Peak force ($d = 0.82$) and RFD ($d = 0.90$) ASYM greater in the weak group (both $p < 0.05$)
Cycling performance				
Rannama et al. (53)	16, competitive, male, road cyclists; age: 20.6 ± 3.7 y	Peak isokinetic torque ASYM of ankle, knee and hip in flexion and extension (60, 180, and $240° \cdot s^{-1}$)	Power output in 5-s sprint cycle test	Knee extension torque ASYM at $180° \cdot sec^{-1}$ negatively correlated to power output ($r = -0.50$; $p < 0.05$)
		Kinematic ASYM of ankle, knee, hip, trunk, and pelvis in cycle test		Trunk ($r = -0.65$) and pelvis ($r = -0.63$) kinematic ASYM negatively correlated to power output (both $p < 0.01$)
Bini and Hume (7)	10 (male) competitive cyclists or triathletes; age: 32 ± 10 y	Effective and total pedal force production ASYM in time trial	4-km cycling time trial	Effective force ASYM ($r = -0.72$; $p = 0.03$) but not total force ASYM ($r = 0.01$; $p = 0.98$) related to improved time trial performance
García-López et al. (23)	47 road cyclists of different performance levels (UCI Pro-Tour, UCI Continental, subelite, under 23 and club teams) Age: not reported	Kinetic and kinematic ASYM in cycle ergometry at 200, 250, and 300 W	Performance level	ASYM small (<2%) and independent of performance level

(continued on next page)

Bini et al. (8)	15 competitive cyclists or triathletes (M: 11 and F: 4); age: 37 ± 12 y	Total pedal force production ASYM in time trial	20-km cycling time trial	No relationship between ASYM and time trial performance ($r = 0.01$; $p = 0.73$)
Swimming performance				
dos Santos et al. (18)	18, trained, male swimmers; age: 21.7 ± 5.0 y	Kinetic ASYM in swimming test	Tethered front crawl swimming performance (2 min)	Athletes median-split into fast and slow groups based on performance Peak ($p = 0.017$) and mean ($p = 0.040$) force ASYM lower in fast group
Morouço et al. (50)	18, trained, young, male swimmers; age: 15.6 ± 2.1 y	Kinetic ASYM in swimming test	Tethered front crawl swimming performance (30-s)	No relationship between ASYM and performance
Kicking performance				
Hart et al. (26)	31, subelite, male Australian Rules footballers; age: 22.1 ± 2.8 y	Isometric SL squat peak force at 120° ASYM	Kicking accuracy (Australian Rules football)	Athletes median split into accurate ($n = 15$) and inaccurate ($n = 16$) groups based on performance Force ASYM greater in inaccurate group ($p = 0.002$) Negative correlation between force ASYM and accuracy ($r = -0.52$; p value not reported)
Vieira et al. (71)	17, elite, male, futsal players; age: 26.3 ± 3.3 y	Isokinetic torque and power ASYM	Kicking accuracy (futsal)	No relationship between ASYM and accuracy

*M = male; F = female; ASYM = asymmetry; IMTP = isometric midthigh pull; RFD = rate of force development; SL = single leg; SJ = squat jump; CMJ = countermovement jump; DJ = drop jump; CODS = change of direction speed; RM = repetition maximum; NCAA, National Collegiate Athletic Association; ns = not significant; pb = personal best; W = watts.

TABLE 3. Summary of training interventions evaluating sporting asymmetries and their association with performance measures.*

Study and intervention	Participants	Asymmetry variables	Outcome variables	Intervention outcomes
Impellizzeri et al. (31) 7–9 wk of individualized rehab training	7, mixed-sport athletes 8–12 wk after ACL reconstruction (M: 5 and F: 2); age: 23 ± 2 y	Peak force ASYM in CMJ	Peak force in CMJ (left and right limbs)	ASYM reduced from (23 ± 3%) to (10 ± 4%) after the intervention ($p = 0.02$) Peak force increased by 35% ($p = 0.02$) in the injured leg but not changed in the noninjured leg (6%; $p = 0.50$)
Sannicandro et al. (56) 6-wk UNI balance training vs. tennis training CON	23, young, tennis players (M: 15 and F: 8); age: 13 ± 1 y; UNI: 11, CON: 12	SL hop distance ASYM SL lateral hop distance ASYM 4m-SSF CODS test time ASYM	Foran CODS test time 10- and 20-m sprint time	Only UNI significantly reduced ASYM in SL hop, lateral hop, and 4m-SSF tests No change in Foran CODS test or sprint performance in either group
Bazyler et al. (4) 7-wk, BI, dynamic and isometric squat training	16 recreationally trained males; age: 20.8 ± 2.0 y	Isometric squat peak force at 90 and 120° ASYM	1RM back squat Isometric squat peak force at 90 and 120°	Athletes median split into strong and weak groups based on preintervention squat 1RM Both groups improved 1RM (strong = 5.0%, weak = 6.6%; $p < 0.05$) The weak group reduced ASYM at both 90 and 120° ($p < 0.05$), but the strong group did not
Gonzalo-Skok et al. (24) 6-wk UNI vs. BI training intervention	22, elite, young, male, basketball players; age: 16.9 ± 2.1 y; UNI: 11, BI: 11	Peak power ASYM during incremental SL squat test	BI and UNI squat power CMJ height V-cut and 180° (left and right limbs) CODS test times 5-, 10-, and 25-m sprint time	Only UNI reduced ASYM (UNI = very likely, BI = unclear) Improvements in 180° CODS (left limb), and SL squat power likely greater in UNI
Brown et al. (9) 6-wk, UNI, "add-on" resistance training intervention performed on weak leg only	1 male rugby union athlete; age: 29 y	Horizontal force ASYM in treadmill sprint	Horizontal force (weak and strong legs), maximal velocity and peak power in treadmill sprint	Horizontal force in the weak leg increased by 26% and ASYM was reduced by 19% Maximal velocity increased by 2% and peak power by 15%

*M = male; F = female; UNI = unilateral; BI = bilateral; CON = control; ASYM = asymmetry; SL = single leg; CMJ = countermovement jump; CODS = change of direction speed; RM = repetition maximum.

Strength Performance

The types of strength performances evaluated in the extant literature have all been type 4 tasks, which may be expect to carry the highest prerequisite level of symmetry. Sato and Heise (58) observed no effect of weight distribution asymmetry (determined during quiet standing) on maximal squat performance. However, Bailey et al. (2) have since reported that weight distribution asymmetry may not correspond well with measures determined during tasks, such as squatting. Subsequent investigations from the same research group have determined force asymmetries during bilateral tasks and do report a negative association between asymmetry and maximal strength performance (3,4). It has not yet been established if asymmetries determined during unilateral tasks may be related to bilateral strength performance.

Cycling Performance

The presence of kinetic asymmetries within cycling has reported for several decades (13,15,19,29). Investigations had previously reported that an increase in cadence workload is associated with a reduction in the presentation of asymmetry (12,55,62). However, examination of the relationship between asymmetry and performance has only recently been examined.

Given the apparently symmetrical action of cycling, a type 3 task, it is perhaps unexpected that Bini and Hume (7) observed a significant positive relationship between asymmetries in effective pedaling force and 4-km time trial performance (i.e., larger asymmetries were associated with faster times). However, Bini and Hume (7) reported no relationship for total pedaling force, a finding subsequently replicated (8). The findings of García-López et al. (23) also question the existence of an association between asymmetry and performance. Kinetic or kinematic asymmetries determined during cycling did not differ between elite and subelite cyclists.

Rannama et al. (53) have reported that asymmetry may negatively influence performance. The investigators determined peak isokinetic torque asymmetries and examined their relationship with power output during a 5-second maximal cycle test. It was reported that asymmetries of the knee extensors at $180°\cdot s^{-1}$ negatively correlated with power output, but correlations were not observed for other joints or at slower or faster velocities. Rannama et al. (53) also detected negative relationships between kinematic asymmetries (determined during cycling) of the trunk and the pelvis with power output but not for the ankle, knee, and hip–the joints responsible for force production during cycling.

Other Performance Tasks

Two studies have examined asymmetries during front crawl swimming and their association with swimming performance, yielding conflicting results. dos Santos et al. (18) suggested a deleterious effect of kinetic asymmetry on performance over a 2-minute duration, whereas Morouço et al. (50) did not report such an effect over a 30-second duration. Whether this discrepancy could be related to the duration of the performance or the ages of the cohorts evaluated (age: ~22 vs. ~16 years) could be further explored.

Similar disparate findings have been reported for kicking performance. Hart et al. (26) reported a negative effect of isometric strength asymmetry on kicking accuracy in Australian Rules football. When evaluating isokinetic torque asymmetry and kicking accuracy in futsal, Vieira et al. (71) did not observe an association. Once more, the lack of consistency between asymmetry measures and cohorts evaluate makes it hard to draw any conclusions.

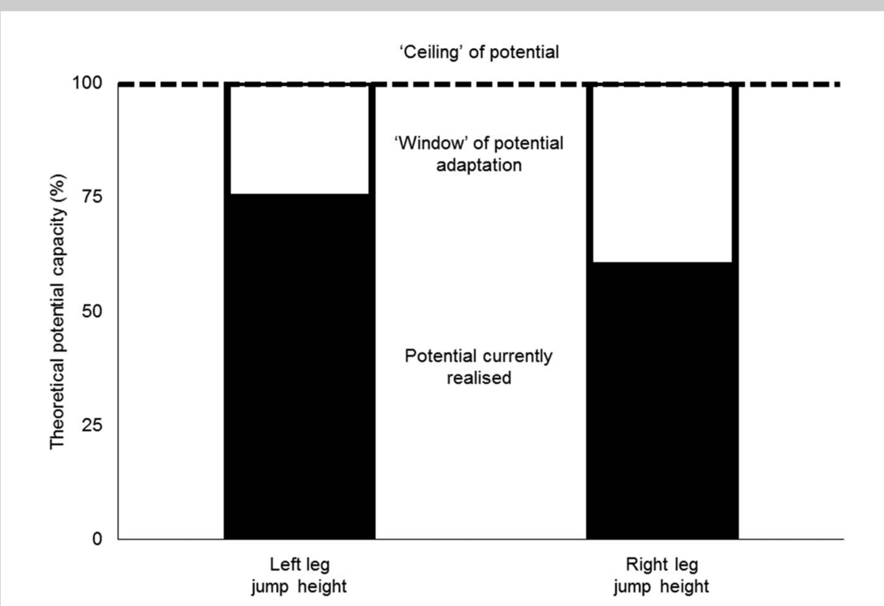

Figure 2. A theoretical illustration of the greater window for adaptation in the deficient limb.

Training, Asymmetry and Performance

Although associative studies (Table 2) may provide indications as to the potential influence of asymmetries on performance, it is important to consider how changes in asymmetries relate to change in performance. Table 3 outlines the studies that have examined the influence of training interventions on asymmetries and performance outcomes.

The findings of Bazyler et al. (4) suggest that bilateral training demonstrates the potential to reduce asymmetry. Nonetheless, it would seem that unilateral training interventions may be preferential to bilateral interventions if seeking to reduce asymmetry (24,56). However, although Gonzalo-Skok et al. (24) reported that unilateral training was associated with better COD performance, Sannicandro et al. (56) reported otherwise. The case study detailed by Brown et al. (9) supports the notion that targeted unilateral training can reduce asymmetry and improve sprint performance, although have no control to gauge this against.

Bazyler et al. (4) noted that both strong and weak athletes improved squat performance, but only observed a reduction in asymmetry for weak athletes. The authors concluded performance improvements in weak athletes (and those exhibiting preintervention asymmetry) may be associated with concomitant decreases in asymmetry. Similarly, Impellizzeri et al. (31) reported improvements in force output of the weak limb, but not the strong limb, but did so in a recently injured cohort, and conclusions need to be interpreted with this in mind.

Although clear inferences cannot be drawn given the current body of literature, there is some evidence to suggest that athletes demonstrating preintervention asymmetry may experience concomitant increases in performance and reduction in asymmetry. At this stage, it is not possible to determine if the effect of reducing asymmetry on performance is independent of the general improvements in neuromuscular capacity.

Development Windows and Diminishing Returns

A bilateral sporting asymmetry indicates the existence of a unilateral deficiency. For example, the left leg can achieve a jump height of 0.30 m during a single-leg CMJ, but the right leg can only achieve 0.24 m. This scenario suggests that the weaker limb is underdeveloped (Figure 2). In training, the principle of diminishing returns describes the notion that the potential for positive adaptations to occur will decrease as the system becomes more positively adapted (52). Thus, the overall stress applied to the system will need to increase for adaptation to continue to occur. This review has previously established that, in sport, the force dominant side will experience more stress than the nondominant side. Over a period of months, years, and decades, this will lead to the accumulation of a greater overall "training volume" for the dominant side and, in line with the principle of diminishing returns, a gradual narrowing of the potential for subsequent adaptation to occur (Figure 2). Therefore, in relative terms, the potential for adaptation should be wider in the nondominant side and could be identified as a window for development. With this approach in mind, the training program would merely be seeking to pick the low-hanging fruit rather than be directly "targeting" the reduction of asymmetry. Such a viewpoint could explain the findings observed within some of the training interventions, which have been discussed (4,9,24).

Conclusions

A clear link between asymmetry and athletic performance cannot be currently determined given the lack of consistency between investigations. Fluctuating asymmetries such as nostril width or ear size have been used as surrogate markers of developmental stability. There is evidence associating FAs with impaired performance; however, these types of asymmetry have not been evaluated with the same prolificacy as "sporting" asymmetries. Sporting asymmetries, such as force output or jump height, are likely to be a function of limb dominance and magnified by an athletes' long-standing participation within his or her sport. Sporting asymmetries do not seem to carry a clear influence on athletic performance measures given the current balance of the available literature. Research to date has not has only marginally addressed how specific sporting backgrounds may modulate any relationships between sporting asymmetry and performance. For example, the potential for the influence of sporting asymmetry on performance to differ between bilateral- and unilateral-dominant athletes has not been explored. Recent investigations have demonstrated that training interventions can reduce sporting asymmetries and improve performance. However, these studies have not sought to evaluate the extent to which the reduction in asymmetry may be associated with the improvement in performance. There is a clear need for randomized controlled trials that seek to differentiate between training-induced improvements in outcome variables (i.e., max force, jump height, etc) and the direct reduction in sporting asymmetries.

Practical Applications

Asymmetry has been widely asserted as detrimental to athletic performance, but this proposition is not strongly supported by scientific evidence and the type of asymmetry is often not defined. Fluctuating asymmetries are thought to indicate the developmental stability of an organism and may be negatively associated with performance. Nonetheless, the application of FA testing within strength and conditioning would be unlikely to influence practice. Many "sporting" asymmetries are a consequence of limb dominance and are magnified by sporting participation. Reported findings to date have failed to demonstrate a clear influence of sporting asymmetries on performance. Accordingly, testing for the existence of asymmetries, fluctuating or sporting, for potential intervention planning may not be beneficial. Training interventions can reduce sporting asymmetries and improve performance, although it is yet to be determined if such changes are related or independent of one another. It is perhaps best for the practitioner to view sporting asymmetries in the light of "development windows" that can be targeted for attaining more general neuromuscular improvements.

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References

1. Bailey, C, Sato, K, Alexander, R, Chiang, CY, and Stone, MH. Isometric force production symmetry and jumping performance in collegiate athletes. *J Trainology* 2: 1–5, 2013.
2. Bailey, CA, Sato, K, Burnett, A, and Stone, MH. Carry-over of force production symmetry in athletes of differing strength levels. *J Strength Cond Res* 29: 3188–3196, 2015.
3. Bailey, CA, Sato, K, Burnett, A, and Stone, MH. Force production asymmetry in male and female athletes of differing strength levels. *Int J Sports Physiol Perform* 10: 504–508, 2015.
4. Bazyler, CD, Bailey, CA, Chiang, CY, Sato, K, and Stone, MH. The effects of strength training on isometric force production symmetry in recreationally trained males. *J Trainology* 3: 6–10, 2014.
5. Bell, DR, Sanfilippo, JL, Binkley, N, and Heiderscheit, BC. Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. *J Strength Cond Res* 28: 884–891, 2014.
6. Benjanuvatra, N, Lay, BS, Alderson, JA, and Blanksby, BA. Comparison of ground reaction force asymmetry in one- and two-legged countermovement jumps. *J Strength Cond Res* 27: 2700–2707, 2013.
7. Bini, RR and Hume, PA. Relationship between pedal force asymmetry and performance in cycling time trial. *J Sports Med Phys Fitness* 55: 892–898, 2015.
8. Bini, RR, Jacques, TC, Sperb, CH, Lanferdini, FJ, and Vaz, MA. Pedal force asymmetries and performance during a 20-km cycling time trial. *Kinesiology* 48: 193–199, 2016.
9. Brown, SR, Feldmann, ER, Cross, MR, Helms, ER, Marrier, B, Samozino, P, and Morin, JB. The potential for a targeted strength training programme to decrease asymmetry and increase performance: A proof-of-concept in sprinting. *Int J Sports Physiol Perform* 12: 1392–1395, 2017.
10. Bussey, G. Does the demand for asymmetric functional lower body postures in lateral sports relate to structural asymmetry of the pelvis? *J Sci Med Sport* 13: 360–364, 2010.
11. Carpes, FP, Mota, CB, and Faria, IE. On the bilateral asymmetry during running and cycling–A review considering leg preference. *Phys Ther Sport* 11: 136–142, 2010.
12. Carpes, FP, Rossato, M, Faria, IE, and Bolli Mota, C. Bilateral pedaling asymmetry during a simulated 40-km cycling time trial. *J Sports Med Phys Fitness* 47: 51–57, 2007.
13. Cavanagh, PR, Petak, KL, Shapiro, R, and Daly, D. Bilateral asymmetry in work output during cycling ergometer pedaling. *Med Sci Sport Exerc* 6: 80–81, 1974.
14. Chiang, CY. Lower body strength and power characteristics influencing change of direction and straight-line sprinting performance in Division 1 soccer players. In: *Department of Exercise and Sport Sciences*: East Tennessee State University, 2014.
15. Daly, DJ and Cavanagh, PR. Asymmetry in bicycle ergometer pedalling. *Med Sci Sport Exerc* 8: 204–208, 1976.
16. Dos'Santos, T, Thomas, C, Jones, PA, and Comfort, P. Asymmetries in isometric force-time charcteristics are not detrimental to change of direction speed. *J Strength Cond Res*, 2017. Epub ahead of print.
17. Dos'Santos, T, Thomas, C, Jones, PA, and Comfort, P. Asymmetries in single and triple hop are not detrimental to change of direction speed. *J Trainology* 6: 35–41, 2017.
18. dos Santos, KB, Pereira, G, Papoti, M, Bento, PCB, and Rodacki, A. Propulsive force asymmetry during tethered-swimming. *Int J Sports Med* 34: 606–611, 2013.
19. Edeline, O, Polin, D, Tourny, C, and Weber, J. Effect of workload on bilateral pedaling kinematics in non-trained cyclists. *J Hum Mov Stud* 46: 493–517, 2004.
20. Exell, T, Irwin, G, Gittoes, M, and Kerwin, D. Strength and performance asymmetry during maximal velocity sprint running. *Scand J Med Sci Sports* 27:1273–1282, 2017.
21. Exell, TA, Gittoes, MJR, Irwin, G, and Kerwin, DG. Gait asymmetry: Composite scores for mechanical analyses of sprint running. *J Biomech* 45: 1108–1111, 2012.
22. Flanagan, SP and Salem, GJ. Bilateral differences in the net joint torques during the squat exercise. *J Strength Cond Res* 21: 1220–1226, 2007.
23. García-López, J, Díez-Leal, S, Larrazabel, J, and Ogueta-Alday, A. No bilateral asymmetry during pedalling in healthy cyclists of different performance levels. Presented at 33rd International Conference on Biomechanics in Sports, Poitiers, France, 2015.
24. Gonzalo-Skok, O, Tous-Fajardo, J, Suarez-Arrones, L, Arjol-Serrano, JL, Casajús, JA, and Mendez-Villanueva, A. Single-leg power output and between-limbs imbalances in team-sport players: Unilateral versus bilateral combined resistance training. *Int J Sports Physiol Perform* 12: 106–114, 2017.
25. Guiard, Y. Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model. *J Mot Behav* 19: 486–517, 1987.
26. Hart, NH, Nimphius, S, Spiteri, T, and Newton, RU. Leg strength and lean mass symmetry influences kicking performance in Austrailian football. *J Sports Sci Med* 13: 157–165, 2014.
27. Hart, NH, Nimphius, S, Weber, J, Spiteri, T, Rantalainen, T, Dobbin, M, and Newton, RU. Musculoskeletal asymmetry in football athletes: A product of limb function over time. *Med Sci Sport Exerc* 48: 1379–1387, 2016.
28. Haugen, T, Danielsen, J, McGhie, D, Sandbakk, O, and Ettema, G. Kinematic stride cycle asymmetry is not associated with sprint performance and injury prevalence in athletic sprinters. *Scand J Med Sci Sports* 28: 1001–1008, 2018.
29. Hoes, MJA, Binkhorst, RA, Smeekes-Kuyl, AE, and Vissers, AC. Measurement of forces exerted on pedal and crank during work on a cycle ergometer at different loads. *Int Z Angew Physiol* 26: 33–42, 1968.
30. Hoffman, JR, Ratamess, NA, Klatt, M, Faigenbaum, AD, and Kang, J. Do bilateral power deficits influence direction-specific movement patterns? *Res Sports Med* 15: 125–132, 2007.
31. Impellizzeri, FM, Rampinini, E, Maffiuletti, N, and Marcora, SM. A vertical jump force test for assessing bilateral strength asymmetry in athlete. *Med Sci Sport Exerc* 39: 2044–2050, 2007.
32. Klingenberg, CP. A developmental perspective on developmental instability: Theory, models and mechanisms. In: *Developmental Instability: Causes and Consequences.* M Polak, ed. Oxford, MS: Oxford University Press, 2003. pp. 14–34.
33. Kobayashi, Y, Kubo, J, Matsuo, A, Matsubayashi, T, Kobayashi, K, and Ishii, N. Bilateral asymmetry in joint torque during squat exercise performed by long jumpers. *J Strength Cond Res* 24: 2826–2830, 2010.
34. Kuntze, G, Mansfield, N, and Sellers, W. A biomechanical analysis of common lunge tasks in badminton. *J Sports Sci* 28: 183–191, 2010.
35. Lake, JP, Lauder, MA, and Smith, NA. Does side dominance affect the symmetry of barbell end kinematics during lower-body resistance exercise? *J Strength Cond Res* 25: 872–878, 2011.
36. Lauder, MA and Lake, JP. Biomechanical comparison of unilateral and bilateral power snatch lifts. *J Strength Cond Res* 22: 653–660, 2008.
37. Lockie, RG, Callaghan, SJ, Berry, SP, Cooke, ER, Jordan, CA, Luczo, TM, and Jeffriess, MD. Relationship between unilateral jumping ability and asymmetry on multidirectional speed in team-sport athletes. *J Strength Cond Res* 28: 3557–3566, 2014.

38. Lockie, RG, Risso, FG, Lazar, A, Giuliano, DV, Stage, AA, Liu, TM, Beiley, MD, Hurley, JM, Torne, IA, Stokes, JJ, Birmingham-Babuta, SA, Davis, DL, Orjalo, AJ, and Moreno, MR. Between-leg mechanical differences as measured by the Bulgarian split-squat: Exploring asymmetries and relationships with sprint acceleration. *Sports* 5: 65, 2017.

39. Lockie, RG, Shultz, AB, Jeffriess, MD, and Callaghan, SJ. The relationship between bilateral differences of knee flexor and extensor isokinetic strength and multi-directional speed. *Isokinet Exerc Sci* 20: 211–219, 2012.

40. Longman, D, Stock, JT, and Wells, JC. Fluctuating asymmetry as a predictor for rowing ergometer performance. *Int J Sports Med* 32: 606–610, 2011.

41. Luk, HY, Winter, C, O'Neill, E, and Thompson, BA. Comparison of muscle strength imbalance in powerlifters and jumpers. *J Strength Cond Res* 28: 23–27, 2014.

42. Maloney, SJ, Fletcher, IM, and Richards, J. A comparison of methods to determine bilateral asymmetries in vertical leg stiffness. *J Sports Sci* 34: 829–835, 2016.

43. Maloney, SJ, Richards, J, Nixon, DGD, Harvey, LJ, and Fletcher, IM. Do stiffness and asymmetries predict change of direction performance? *J Sports Sci* 35: 547–556, 2017.

44. Maloney, SJ, Richards, J, Nixon, DG, Harvey, LJ, and Fletcher, IM. Vertical stiffness asymmetries during drop jumping are related to ankle stiffness asymmetries. *Scand J Med Sci Sports* 27: 661–669, 2017.

45. Manning, JT, Koukourakis, K, and Brodie, DA. Fluctuating asymmetry, metabolic rate and sexual selection in human males. *Evol Hum Behav* 18: 15–21, 1997.

46. Manning, JT and Ockenden, L. Fluctuating asymmetry in racehorses. *Nature* 370: 185–186, 1994.

47. Manning, JT and Pickup, LJ. Symmetry and performance in middle distance runners. *Int J Sports Med* 19: 205–209, 1998.

48. Meyers, RW, Oliver, JL, Hughes, MG, Lloyd, RS, and Cronin, JB. Asymmetry during maximal sprint performance in 11- to 16-year-old boys. *Pediatr Exerc Sci* 29: 94–102, 2017.

49. Møller, AP and Swaddle, JP. Developmental instability and performance. In: *Asymmetry, Developmental Stability and Evolution.* Oxford, MS: Oxford University Press, 1997. pp. p 154.

50. Morouço, PG, Marinho, DA, Fernandes, RJ, and Marques, MC. Quantification of upper limb kinetic asymmetries in front crawl swimming. *Hum Movement Sci* 40: 185–192, 2015.

51. Newton, RU, Gerber, A, Nimphius, S, Shim, JK, Doan, BK, Robertson, M, Pearson, DR, Craig, BW, Häkkinen, K, and Kraemer, WJ. Determination of functional strength imbalance of the lower extremities. *J Strength Cond Res* 20: 971–977, 2006.

52. Peterson, MD, Rhea, MR, and Alvar, BA. Applications of the dose-response for muscular strength development: A review of meta-analytic efficacy and reliability for designing training prescription. *J Strength Cond Res* 19: 950–958, 2005.

53. Rannama, I, Port, K, Bazanov, B, and Pedak, K. Sprint cycling performance and asymmetry. *J Hum Sport Exerc* 10: S247–S258, 2015.

54. Rouissi, M, Chtara, M, Owen, A, Chaalali, A, Chaouachi, A, Gabbett, T, and Chamari, K. Effect of leg dominance on change of direction ability amongst young elite soccer players. *J Sports Sci* 34: 542–548, 2016.

55. Sanderson, DJ. The influence of cadence and power output on the biomechanics of force application during steady-rate cycling in competitive and recreational cyclists. *J Sports Sci* 9: 191–203, 1991.

56. Sannicandro, I, Cofano, G, Rosa, RA, and Piccinno, A. Balance training exercises decrease lower-limb strength asymmetry in young tennis players. *J Sports Sci Med* 13: 397–402, 2014.

57. Sannicandro, I, Piccinno, A, Rosa, RA, and De Pascalis, S. Correlation between functional asymmetry of professional soccer players and sprint. *Br J Sports Med* 45: 370–371, 2011.

58. Sato, K and Heise, GD. Influence of weight distribution asymmetry on the biomechanics of a barbell back squat. *J Strength Cond Res* 26: 342–349, 2012.

59. Seminati, E, Nardello, F, Zamparo, P, Ardigò, LP, Faccioli, N, and Minetti, AE. Anatomically asymmetrical runners move more asymmetrically at the same metabolic cost. *PLoS One* 8: e74134, 2013.

60. Serrien, DJ, Ivry, RB, and Swinnen, SP. Dynamics of hemispheric specialization and integration in the context of motor control. *Nat Rev Neurosci* 7: 160–166, 2006.

61. Simon, AM and Ferris, DP. Lower limb force production and bilateral force asymmetries are based on sense of effort. *Exp Brain Res* 187: 129–138, 2008.

62. Smak, W, Neptune, RR, and Hull, ML. The infuence of pedaling rate on bilateral asymmetry in cycling. *J Biomech* 32: 899–906, 1999.

63. Suchomel, TJ, Nimphius, S, and Stone, MH. The importance of muscular strength in athletic performance. *Sports Med* 46: 1419–1449, 2016.

64. Swaddle, JP. Within-individual changes in developmental stablilty affect flight performance. *Behav Ecol* 8: 601–604, 1997.

65. Tomkinson, GR and Olds, TS. Physiological correlates of bilateral symmetry in humans. *Int J Sports Med* 21: 545–550, 2000.

66. Tomkinson, GR, Popović, N, and Martin, M. Bilateral symmetry and the competitive standard attained in elite and sub-elite sport. *J Sports Sci* 21: 201–211, 2003.

67. Trivers, R, Fink, B, Russell, M, McCarty, K, James, B, and Palestis, BG. Lower body symmetry and running performance in elite Jamaican track and field athletes. *PLoS One* 9: e113106, 2014.

68. Trivers, R, Palestis, BG, and Manning, JT. The symmetry of children's knees is linked to their adult sprinting speed and their willingness to sprint in a long-term Jamaican study. *PLoS One* 8: e72244, 2013.

69. Turner, A, Bishop, C, Chavda, S, Edwards, M, Brazier, J, and Kilduff, LP. Physical characteristics underpinning lunging and change of direction speed in fencing. *J Strength Cond Res* 30: 2235–2241, 2016.

70. Van Valen, L. A study of fluctuating asymmetry. *Evolution* 16: 125–142, 1962.

71. Vieira, L, Serenza, F, de Andrade, VL, de Paula Oliveira, L, Mariano, FP, Santana, JE, and Santiago, PR. Kicking performance and muscular strength parameters with dominant and non-dominant limbs in Brazilian elite professional futsal players. *J Appl Biomech* 32: 578–585, 2016.

72. Watson, PJ and Thornhill, R. Fluctuating asymmetry and sexual selection. *Trends Ecol Evol* 9: 21–25, 1994.

73. Webborn, N, Williams, A, McNamee, M, Bouchard, C, Pitsiladis, Y, Ahmetov, I, Ashley, E, Byrne, N, Camporesi, S, Collins, M, Dijkstra, P, Eynon, N, Fuku, N, Garton, FC, Hoppe, N, Holm, S, Kaye, J, Klissouras, V, Lucia, A, Maase, K, Moran, C, North, KN, Pigozzi, F, and Wang, G. Direct-to-consumer genetic testing for predicting sports performance and talent identification: Consensus statement. *Br J Sports Med* 49: 1486–1491, 2015.