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Review

Why Sports Should Embrace Bilateral Asymmetry: A Narrative Review

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Abstract: (1) Background: Asymmetry is ubiquitous in nature and humans have well-established bilateral asymmetries in their structures and functions. However, there are (mostly unsubstantiated) claims that bilateral asymmetries may impair sports performance or increase injury risk. (2) Objective: To critically review the evidence of the occurrence and effects of asymmetry and sports performance. (3) Development: Asymmetry is prevalent across several sports regardless of age, gender, or competitive level, and can be verified even in apparently symmetric actions (e.g., running and rowing). Assessments of bilateral asymmetries are highly task-, metric-, individual-, and sport-specific; fluctuate significantly in time (in magnitude and, more importantly, in direction); and tend to be poorly correlated among themselves, as well as with general performance measures. Assessments of sports-specific performance is mostly lacking. Most studies assessing bilateral asymmetries do not actually assess the occurrence of injuries. While injuries tend to accentuate bilateral asymmetries, there is no evidence that pre-existing asymmetries increase injury risk. While training programs reduce certain bilateral asymmetries, there is no evidence that such reductions result in increased sport-specific performance or reduced injury risk. (4) Conclusions: Bilateral asymmetries are prevalent in sports, do not seem to impair performance, and there is no evidence that suggests that they increase injury risk.

Keywords: symmetry; bilateral asymmetry; interlimb asymmetry; laterality; injury risk; performance

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1. Introduction—the Inevitability and Omnipresence of Asymmetry

In sports training and fitness contexts, symmetry intuitively seems to be a concept that practitioners chase in the hope that it may enhance performance and/or reduce injury risk. Such is the strength of this belief that several studies associate lower limb bilateral asymmetries (e.g., ground reaction forces and kinematic analyses) with increased injury risk *despite not actually having assessed any actual risk* [1–10], i.e., the occurrence of injuries was not registered in such studies. Such unsubstantiated discourse misleads the readers and may even detract from analyzing other (relevant) variables of those works. Training programs are often designed to decrease interlimb asymmetry and may achieve small to moderate (but commonly non-significant) reductions [11,12] and, more rarely, small to large reductions in asymmetry [13]. When such programs are successful in achieving what they had proposed to achieve (i.e., reducing interlimb asymmetries), the authors may (erroneously) assume that increased symmetry is beneficial, without actually assessing the effect of these changes on injury risk [2]. Even a systematic review stated that interlimb asymmetries in several so-called "functional tasks" (e.g., isokinetic knee extension and flexion, single-leg vertical jump, and single-leg hop) were undesirable and should be properly remedied [5], despite injury risk not being formally assessed in any capacity.

This search for bilateral symmetry (which includes bilateral trunk asymmetries and also interlimb asymmetries) seems to derive more from deeply held beliefs than from empirical findings [14], and risks placing performance and injury prevention programs on the wrong track. Incidentally, craniocaudal and dorsoventral asymmetries are promptly accepted (i.e., people understand that we need one head on top and two feet on the bottom, and that we have two eyes in front of the head but none in the back). Somehow, it is with bilateral asymmetry in sport that some in our profession seem to struggle to appreciate. However, there is hope: the 10th edition of the ACSM guidelines for exercise testing and prescription makes no mention of symmetry in general exercise prescription [15], unlike the 9th edition [16]. Across the entire 10th edition of the guidelines, the only reference to symmetry is the suggestion of symmetrical and rhythmical movement for people with athetoid cerebral palsy [15].

Biologically, the healthy development of human embryos requires breaking several symmetries, including dorsoventral and craniocaudal [17]; unsurprisingly, proper embryologic developmental also requires breaking left–right symmetry in vertebrates, including humans [17–21]. Consequently, human anatomy is abundant with bilateral asymmetries. Despite an apparent external symmetry, there is considerable asymmetry in thoracic and abdominal organs [19,21]. For example, the diaphragm is asymmetric, usually reaching one rib higher on the right side (due to the influence of the liver) and one lumbar vertebra lower on the right side (due to a longer pillar) [22]. The aorta (which is also asymmetric) presses against the vertebral column and usually produces a slight thoracic curvature with convexity towards the right side [22]. Many other asymmetries can be pinpointed with respect to internal organs (e.g., the liver, heart, lungs, colon, pancreas, etc.), which are all commonly known. However, there are many additional bilateral asymmetries in vascular networks, the lymphatic drainage system, and neural pathways [22]. In some cases, nerves not only traverse distinct paths on the right and the left side of the body, but they also present histological differences, such as in the case of the recurrent laryngeal nerve in humans [23,24].

Importantly, bilateral anatomical asymmetries in humans extend to the upper and lower limbs as well (e.g., widths, lengths, neuromuscular paths, the different number of muscle bellies, and among many other features) and have been widely described in the literature [22,25–29]. A recent review has synthesized interlimb asymmetries in the hamstrings' structure and functionality, highlighting that important intraindividual asymmetries may exist (some of which are not changeable with training) [30]. Naturally, laterality (i.e., a lateral preference for using one limb over the other in certain tasks) coupled with interlimb anatomical asymmetries suggests that common activities such as walking and running should result in significant interlimb asymmetries in gait (kinetic and kinematic) in healthy populations and athletes [31–33], and that sports may actually require magnifying certain asymmetries [14,34] (e.g., sports with highly unilaterally-biased actions).

Given all the above, asymmetry seems to be part of nature and integral to human biology and behavior. In sports, interlimb asymmetries are highly task- and metric-specific [7,11,12,14,34–43] and so should be analyzed within proper context. The goal of this narrative review was to provide an account on the role of asymmetry in sports, focusing on its relationships with performance and injury occurrence. We chose to perform a narrative review to deliver a broad and critical overview of these topics, focusing on key concepts and trying to tell a compelling story.

2. Bilateral Asymmetry Is Ubiquitous in Sports Performance

Bilateral asymmetry (a broad term referring to bilateral trunk asymmetries or interlimb asymmetries) should be expected to be and is (probably) not even clinically relevant below the *arbitrary* thresholds of 5–15% [5,7,11,44–47], with an emphasis on the arbitrariness of such thresholds since they are task- and metric-specific [7,11,12,34–39,42,48–50] and likely also individual-specific [42,49–53]. Laterality (including, but not limited to, handedness, mastication, and eye dominance) is a well-established feature in the animal kingdom, including humans, and has been shown to be associated with increased functional performance [54–59]. Importantly, both limb dominance and preference may also be task-specific [34]. Therefore, interlimb asymmetries should not be automatically associated with performance impairments [14,36,60]. Team sports such as basketball, handball, or volleyball, to name some notorious examples, may boost upper limb asymmetries due to their highly specialized and differentiated demands, and the same could be said of racquet sports such as tennis, padel, or badminton. In the case of the lower limbs, bilateral asymmetries are the norm in both general populations and in athletes [12]. For example, in 38 male adult soccer players, resting tensiomyography assessments showed significant interlimb asymmetries [61]. The vastus medialis contraction time, rectus femoris sustained time and half-relaxation time, and biceps femoris sustained time were greater in the dominant limb, while vastus lateralis contraction time and delay time were greater in the non-dominant limb [61].

Moreover, we should consider the "noisy" character of asymmetry and the inconsistency of outcomes, whereby in test–retest studies the group mean asymmetry often appears to be relatively stable, but the standard deviation (SD) of the mean is almost always very large (i.e., 50–100% of the mean asymmetry value) [38,49,52,62]. In contrast to the mean, when individual datapoints are considered, changes in asymmetry's magnitude and direction are usually quite large [38,39,49,50,52,53,62–66], suggesting caution when interpreting the mean value of any interlimb asymmetry data. In fact, interlimb asymmetries should not even be considered "true" asymmetries if their value is equal to or smaller than the inherent variability of any given test [42,53] (e.g., coefficient of variation and typical error of measurement). Additionally, limb preference and limb dominance are not necessarily coincident; we refer the readers to the work of Virgile and Bishop [34] for an exploration of this topic. To truly elucidate the relevance of asymmetry in sports performance, we must understand: (1) the occurrence and relationships of bilateral asymmetry with athletic performance, and (2) the effects of training interventions on interlimb asymmetries.

2.1. Occurrence and Relationship of Bilateral Asymmetry with Athletic Performance

A recent systematic review showed that, among several populations (including 17 studies with athletes), inter-limb strength asymmetries ranged from near symmetry to asymmetries larger than 15%, without clear relationships with independent performance tasks (such as isokinetic dynamometry, jump tests, and seated shot put, among others) [46]. Furthermore, additional research has shown that in sports research, no clear-cut associations exist between bilateral asymmetries and performance [14]. In addition, any findings from cross-sectional studies should be taken with a pinch of salt, since the relationships between interlimb asymmetry (magnitude and direction) and performance are not necessarily consistent across a sports season [34,39,42,63,64,67]. One study assessed the ground reaction forces (GRF) of 13 plyometrics-trained subjects (23 $\pm$ 3 years, 8 male and 5 female) after a 45-cm drop jump whereby the subjects had to change their lead leg (i.e., the leg initiating the movement to step off the box) [1]. Upon landing, the lead leg generated greater forces than the trail leg. Interestingly, pairwise comparisons showed that significant interlimb differences occurred only when the right leg led the movement, with the right leg making earlier ground contact and generating greater force and impulse than the left leg. Limb symmetry indices (LSI) generally showed asymmetries $\geq$10% [1]. This shows that even in a simple drop jump task (with low contextual interference), athletes exhibit marked interlimb asymmetry in their performance. However, the drop jump height was not assessed, and so it is unclear how the observed asymmetries impacted jump performance.

In high-level male (n = 38) and female judokas (n = 23), the maximum isometric strength of the shoulder external rotators was significantly superior (albeit with a small effect size of $\eta^2 = 0.03$) in the dominant side in comparison with the non-dominant side, but the same was not observed for internal rotation [4]. Asymmetries favoring the dominant side were also detected for the unilateral seated shot put test (small effect, $\eta^2 = 0.07$), but not for the Y balance test [4]. In summary, upper limb dominance (i.e., a bilateral asymmetry) seemed to affect the performance of shoulder external rotations and unilateral seated shot put, but the effects were very small. In 26 male handball players (U18), interlimb asymmetry across a variety of jump and change-of-direction (COD) tests ranged from ~3.7 to ~12.7% [41]. Moderately significant correlations (ρ = 0.41–0.51) were found between isoinertial crossover step asymmetry (but not lateral shuffle step) and a COD of 90° and COD of 180° in both limbs, as well as 20 m sprinting. However, interlimb asymmetries were also quantified in the several single leg jumps and COD tests, which were independent of performance [41].

In a study involving young elite tennis players (*n* = 41; ~50% females) and sex- and age-matched controls (*n* = 41), significant asymmetries were registered in both groups across all seven upper and lower limb tests [68], which broadly assessed strength, reaction time, and COD. While tennis players were significantly more asymmetric than the controls with respect to handgrip strength, they were less asymmetric than the controls in the single leg countermovement jump (CMJ) and 6 m single leg hop tests. These asymmetries were test-specific and, since the different tests were not examined for possible correlations, it is unclear how asymmetric performance in one test could have affected a different test. Significant interlimb morphological asymmetries (e.g., circumferences and widths) were also found for both tennis players and the controls, although these were significantly higher in the tennis players for the upper limbs (but not the lower limbs), which is to be expected given the nature of the sport [68]. Moreover, the data from that study suggested that both morphological and functional asymmetries were not significantly related to each other (i.e., the morphological asymmetries did not affect performance in the strength and COD-related tests) and should best be interpreted independently [68]. Similar results were found by the same research group for a different sample of 22 high-level female tennis players [69].

When performing the volleyball spike (which is a highly asymmetric action, both for the lower and upper limbs), a systematic review showed that attackers landed asymmetrically >65% of times, mostly on the left leg, and significant interlimb kinematic asymmetries were noted for the ankle, knee, and hip joints upon landing (e.g., joint flexion angle, range of motion, maximal flexion velocity, and angle upon initial contact with floor) [70]. Even in highly controlled experimental settings where the athletes were explicitly asked to land on both feet simultaneously [71–73], a unilateral landing was still the norm. Therefore, asymmetric landing strategies seem to be preferred in volleyball [70]. Even in supposedly more symmetric actions such as blocking, players have been shown to be faster moving towards the right side than to the left side of the court even in highly-controlled tasks with reduced contextual interference [74]. However, it is currently unclear how these asymmetries are related to performance outcomes, such as attack or block jump height. Further, it is unknown whether volleyball players' landing asymmetries are associated with a positive, neutral, or negative effect on the performance of these key game actions.

In soccer, interlimb asymmetries ranging from $-11.01 \pm 12.38\%$ (U18) to $-18.43 \pm 12.11\%$ (U16) have been observed in 68 soccer players when performing 90° COD tasks [75]. Note the very large SDs, indicating a large within-group variability. The COD time was significantly lower for the dominant than for the non-dominant side (no effect size available) [75]. In addition, in soccer, a study of 46 male professional players (26 $\pm$ 6 years of age) verified $8.4 \pm 6.6\%$ and $9.0 \pm 7.1\%$ interlimb asymmetries in isometric maximal voluntary contraction (MVC) torque and isokinetic knee peak extension torque. These interlimb asymmetries were smaller than those registered for the rate of early, intermediate, late, and peak torque development (RTD), which ranged from $12.3 \pm 9.9\%$ to $20.6 \pm 14.3\%$ (note the very large SDs) [8]. However, the only asymmetries that were significantly correlated (albeit weakly, i.e., $\rho \leq 0.36$) with the International Knee Documentation Committee and the Lysholm knee-scoring scales were early and intermediate RTD [8], denoting that the different asymmetries were largely independent from performance.

In 16 male soccer players (14.7 ± 0.2 years), no significant relationships were observed between interlimb asymmetry (single-leg Abalakov test, 10 m (5 + 5) and 20 m (10 + 10) COD, and isoinertial power test) and performance tests (10, 20, and 30 m sprints plus CMJ) [43]. The average interlimb asymmetries varied from 3.02 ± 1.74 % (20 m COD) and 21.68 ± 18.85% (peak power in the isoinertial test), but there were very large interindividual variabilities (e.g., 0.14 to 57.37% in peak power in the isoinertial test) [43]. Another soccer-related study followed 18 male U23 players for one season [67]. During both the preseason and midseason, no significant relationships were found between interlimb asymmetries and performance in sprint and COD tests, nor were there significant correlations between changes in asymmetry and changes in sprint and COD performance across the entire season [67]. In the authors' own words, "suggestions for the reduction of asymmetry that may indirectly enhance athletic performance cannot be made" (p. 787) [67].

In young female basketball players (n = 29, 15.7 ± 1.34 years of age), significant interlimb differences were identified for all neuromuscular tasks (single leg CMJ in different directions, star excursion balance test (SEBT), and sprint with a COD) [35]. There was poor agreement (35 to 52%) between the more skilled lower limb and the limb subjectively identified as being the dominant limb, which supports previous suggestions about differences between limb dominance and limb preference [34]. While the bilateral asymmetry indices between the more and less skillful limbs varied from 3.33 ± 2.49% (lateral CMJ distance) and 14.11 ± 8.62% (vertical CMJ height) [35], the authors did not assess the correlations between the magnitudes of asymmetry and the test performances. Therefore, while there were bilateral asymmetries in performance in each test, it is unknown if asymmetries in one test correlated with performance in another test, i.e., if the asymmetries were task-specific or translated into more general performance.

Another study involving 11 female basketball players (U19) performed several tests (10 m sprint, COD 90°, COD 135°, and single leg CMJ in three directions) plus four exercises on a flywheel machine (acceleration step, deceleration step, crossover step, and sidestep) [50]. Significant interlimb asymmetries were shown for all the tests, ranging from 1.26 ± 0.94 % (COD 135°) to 11.75 ± 7.79% (vertical single-leg CMJ). The authors correlated the interlimb asymmetry scores in the flywheel exercises (four exercises, both in concentric and eccentric forms, in a total of eight conditions) and the performance with respect to COD and unilateral jumps for both the highest and lowest performing limbs (in a total of 14 conditions). Significant correlations (ρ = −0.61 to 0.81) were found for only 5 of the 112 cells (i.e., combinations) [50], all of which referred to correlations with the concentric sidestep. When correlating interlimb asymmetry scores in the COD and unilateral jump tests with the flywheel exercises, no significant correlations were found. By and large, interlimb asymmetries were, therefore, not correlated with performance tests.

One study compared 18 professional male soccer players to 23 professional cricket players with respect to performing single-leg CMJ and drop jumps, a 10 m sprint, and a 505 COD [76]. The cricket athletes had significantly greater interlimb asymmetries in jump height (11.49% vs. 6.51%) and in the reactive strength index (RSI; 10.37% vs. 5.95%) than the soccer players [76], suggesting that interlimb asymmetries may also be sport-specific (i.e., certain sports may promote enhanced asymmetries due to their specific performance demands). While these asymmetries in jump height and RSI were moderately correlated with slower 505 COD times in the cricket players (r = 0.56–0.74), they were not correlated with other performance tests [76]. No significant correlations between interlimb asymmetries and performance tests were found for the soccer players [76].

Kinetic and kinematic interlimb asymmetries are frequent even in cyclic, bilateral actions such as running and cycling [31–33,77]. In U15 swimmers (n = 38; half female), the direction of asymmetry (i.e., favoring one limb or the other) was rarely consistent between single-leg CMJ and single-leg standing long jump performances [78]. This implies that the assessment of interlimb asymmetries may be highly task-specific, in line with other works [7,8,11,12,35–38,43,50,63,67]. The asymmetry scores were not significantly different between males and females and were not associated with 25 m and 50 m front crawl swimming performance [78]. Considering the means plus the SDs, the asymmetry levels were roughly within the previously mentioned 10–15% range [78]. However, it should be noted that a recent review underlined the large SDs present in many symmetry-related studies, suggesting that important interindividual variability almost always exists [11]. This may partly explain why relationships between bilateral asymmetry (noisy and fluctuating) and performance (more stable) are often weak or negligible.

The kinematic and kinetic joint parameters were assessed in 10 elite-level male rowers on a rowing ergometer [7]. An average of 5–10% interlimb asymmetry was observed when assessing the kinematic parameters of the ankle and the kinetic parameters of the hip and knee joints (i.e., accelerations) [7]. Asymmetries > 10% were observed for the kinetic ankle parameters, including resultant force and ankle joint acceleration [7]. In this study, the kinetic asymmetries were uncorrelated with kinematic asymmetries and with lower limb length asymmetry [7], further contributing to the notion that asymmetry assessments may be task- and metric-specific [7,8,11,12,35–39,41,43,53,65]. The authors proposed that a low inter-stroke variability in asymmetry could provide a more stable and efficient performance [7]. The inter-stroke variability was said to be associated with 5–10% interlimb asymmetries with respect to the acceleration of the hip and knee joints and in the ankle joint angle, as well as with >10% asymmetries in the resultant force and in the acceleration of the ankle joint [7], but no values were provided to corroborate these claims.

In artistic gymnastics, all beam routines of the qualification round (19 gymnasts) of the B World Cup '2014 were analyzed [79]: the right lower limb initiated 42.3% of all actions, the left limb 29.1%, and both limbs 28.6%, denoting the asymmetric/lateral preferences of top-level gymnasts. Moreover, 60% of the actions on the beam implied a unilateral take-off and/or landing [79]. An analysis of six high-level female artistic gymnasts showed significant kinetic and kinematic interlimb asymmetries in the upper limbs upon contact with the floor when performing the forward handspring on floor [80]. However, in both studies [79,80], the ways in which these asymmetries related to performance were not reported. In summary, asymmetries appear to be the norm in sports, but we need a deeper understanding of how they relate to performance in different tests. As the evidence presented herein shows, the relationship between performance in standardized tests and sports-specific performance is often missing in the available literature to date.

2.2. Effects of Training Interventions to Reduce Bilateral Asymmetries in Sports

The previous section illustrated that bilateral asymmetry seems to be the norm in sports. If a training program aims to reduce bilateral asymmetries (most commonly, interlimb asymmetries), how successful is it? A study aimed to reduce interlimb asymmetries in 24 male adult soccer players (amateur level) [13]. The participants were randomized into a 6-week (twice weekly) unilateral strength- and power-training program or into a control group. Despite the experimental group having improved performance, the interlimb asymmetry was unchanged for the 505 COD test and two of the three jump tests (single-leg CMJ and single-leg broad jump) [13]. There was a moderate reduction in interlimb asymmetry in the single-leg drop jump stiffness ($g = 1.11$) and RSI ($g = 1.00$) [13]. Another randomized study compared an 8-week (twice weekly) strength- and power-training program (focused on the lower limbs and trunk) with controls in 37 female U17 soccer players [81]. The intervention resulted in no meaningful differences in interlimb asymmetries from pre- to post-testing [81]. Similar results were found with a comparable sample of female soccer players ($n = 36$; U14), albeit with a slightly longer intervention (twice weekly for 10 weeks) [82].

A non-randomized study with 20 adult male soccer players compared a 6-week core stability training regimen with controls performing a "standard" warm-up [83], consisting of jogging, dynamic stretching, and mobility [83]. The interlimb asymmetries in single-leg CMJ were reduced after the training program for the "core" training group, but increased in the controls, while no differences in interlimb asymmetry were observed for isokinetic knee testing [83]. Given the details of the actual "core" training regimen that was implemented, it is possible to speculate that the reductions in asymmetry in the jump tests may have come from the weaker limb gaining strength and have nothing to do with core stability. Moreover, the SDs shown in table V of the original study [83] are surprisingly small in comparison with most other studies on the topic.

In 34 male handball players (U17), an 8-week randomized intervention compared the effects of isoinertial and cable-resistance training on interlimb asymmetries [84]. Interlimb asymmetry was reduced in only one of the eight performance tests (unilateral CMJ) [84]. In 22 U16 to U19 basketball players, a randomized study compared unilateral and bilateral resistance training for 6 weeks [85]. Both groups improved in the performance tests such as the CMJ and 25 m sprint, among others. Only the unilateral group showed reduced interlimb asymmetries (no effect size provided) as assessed by the bilateral difference in the maximum power in an incremental unilateral squat test [85]. However, the standardized between-group differences crossed zero (i.e., there was no significant direction of the effects) [85], even while applying 90% confidence limits, which are narrower than the more common 95% limits. A randomized 8-week (twice a week) strength-training program was contrasted with a volume-equated sport-specific training regimen in 31 male volleyball players (aged 14.5 $\pm$ 0.5 years) [86]. Despite significant changes in performance (dynamic balance test, single leg hop, CMJ, and back squat one repetition maximum), no differences were observed with respect to interlimb asymmetry as assessed by the single-leg hop tests [86].

A randomized study with U12 male weightlifters applied a 6-week (twice weekly) hamstring eccentric training program versus controls; no changes in interlimb asymmetry (derived from bilateral differences in the performance of the single leg hop test) were noted from pre- to post-intervention [87]. In a randomized study with twenty-three U14 tennis players (male and female), one group performed 12 sessions (two sessions per week over 6 weeks) focused on balance training, while the other group performed only tennis-specific drills for the same period [88]. The lower limb bilateral asymmetries were significantly reduced in the balance-training group only for the three tests that were performed (single-leg hop, side-hop and side steps, and forward 4.115 m test [4m-SSF]) [88], but there was no assessment of the effect size to quantify the magnitude of the effects. However, no post-test improvements were noted with respect to the COD and speed tests in this group (i.e., the asymmetries were reduced during jumping, but the players did not become faster).

Overall, the efficacy of training programs designed to decrease interlimb asymmetry are heterogeneous [11–13]. Even when training programs reduce interlimb asymmetry with a concomitant increase in the performance of the selected tests (e.g., CMJ and 10 m sprint), the findings are often mixed [12]. It is also possible that the findings are neglecting an important confounder: the ceiling effect [14,53,89]. The "weaker" limb may be further from its maximum capacity, being more sensitive to training stimuli and showing greater improvement than the "stronger" limb [14,89]. This could result in reduced interlimb asymmetry, and is even more likely to occur in the case of already injured athletes [53]. Beyond that, the previously mentioned problems with the reliability of test–retest assessments of lower limb asymmetries and with only analyzing the average values (thereby neglecting to account for the interindividual variability) limit our understanding of how well such programs work on an individual level. Additionally, the aforementioned training programs mostly used standardized physical tests. The few sport-specific assessments were performed under very analytical conditions. Therefore, *it is unclear whether any reductions in interlimb asymmetry were positive or desirable for enhanced athletic or sporting performance*.

2.3. What Does This All Mean?

The sum of these findings shows that interlimb asymmetries are an intrinsic part of high-level performance, even in supposedly more symmetric actions, and the effects of training interventions on asymmetry and their consequences for performance are unclear. Still, it is possible to speculate that even if it was established that asymmetries contribute positively to sports performance, they could produce a trade-off, increasing injury risk [90]. That is the subject of the next section.

3. Asymmetry Is Not Necessarily Related to Injury Occurrence

Expressions such as "injury risk" and "injury prevention" bring about complex concepts such as "predictors" of injury. Prediction requires that a prospective study ascertains a relationship between the parameter and injury *occurrence*, and that a causal relationship is established. Furthermore, for those causal relationships to be interpreted as predictive, they must be replicated and exhibit a good fit in different samples. Commonly, all we have are relationships established for a specific sample *after* the injuries have occurred. More detailed accounts of this debate can be found elsewhere [91–93]. For the remainder of the manuscript, we will refer to injury occurrence instead of injury risk.

It is intuitively accepted that injuries may cause increased asymmetries [45,53,94], while it is not so clear that pre-existing asymmetries increase injury occurrence. Therefore, observational studies comparing healthy versus injured or previously injured subjects are potentially misleading, as they easily invite the readers to invert causality, even when the authors state that only an association was measured. Severe injuries (such as muscle-tendinous ruptures) are likely to increase the naturally occurring asymmetries in athletes, resulting in excessively large interlimb asymmetries, owing to the fact that one limb is incapacitated [53]. Hence, we understand the attempt to minimize such asymmetries during rehabilitation and return to sport or return to play processes [53]. Regardless, we question if fixed, *arbitrary* interlimb symmetry thresholds should always be achieved, as was previously discussed. Unfortunately, several studies relate asymmetries to injury occurrence without even providing basic associative data [1–10], potentially due to a reliance on pre-conceived assumptions and beliefs on the subject. For example, in a previously mentioned study whereby athletes performed a drop jump task [1], the potential implications of the landing asymmetries towards injury occurrence were discussed at length. However, this study did not directly assess injury occurrence, and so such asymmetries are merely the realization of a fact and should not be used to infer subsequent injury occurrence. In this section, we will delve into observational studies first, and prospective studies second.

3.1. What Observational Studies Really Say about Bilateral Asymmetry and Injury Occurrence

In professional soccer and basketball athletes with unilateral chronic ankle instability (CAI), there was interlimb asymmetry between the injured and non-injured feet in the basketball athletes with respect to the vertical time to stabilization during the postural sway upon landing with both legs (~1.3 s required for the injured foot), but not in the soccer athletes [3]. The authors concluded that balance exercises should be provided to basketball and soccer athletes to reduce recurrent ankle sprains. However, no assessment of injury recurrence was provided and so these suggestions remain purely speculative. In the previously cited study with high-level male and female judokas [4], interlimb asymmetries in external rotation strength were normal and there was no an assessment of injury occurrence. Nevertheless, the authors stated that prevention programs should apply similar workloads on both upper limbs and attempt to achieve greater symmetry.

An association study with 33 badminton players (19 male and 14 female; 14.4 $\pm$ 1.2 years of age) assessed interlimb asymmetries in upper and lower limbs through inertial measurement units (IMUs) and compared those with injury history [44]. No significant upper or lower limb asymmetries were detected for the previously bilaterally injured group. Although significant asymmetries were shown for the non-injured (<10%) and for the unilaterally injured group (>10%), the between-groups difference in the asymmetry magnitudes was not statistically different. These results suggest that *some degree* of interlimb asymmetry should always be expected and is not necessarily associated with injury occurrence. In the same vein, knee flexion and extension strength, hop distance, and vertical jump height were compared between 47 athletes with ACL reconstruction and 46 non-injured athletes [45]. The athletes with ACL reconstruction were more asymmetric with respect to knee flexion maximal strength than the non-injured athletes (~17% vs. ~9% interlimb asymmetry, respectively). No between-group differences were found with respect to the interlimb asymmetry of the remaining three tests. For the jump tests, this is not surprising, given that measures of distance and height often mask biomechanical and strategy-based information [95,96]. Indeed, only a minority of athletes (24% in the non-injured group and 17% in the injured group) showed symmetric (i.e., <10% asymmetry) performances in all four tests [45].

In soccer, a study showed that 15 young male players had significant plantar pressure asymmetries (e.g., hallux, fifth metatarsal, and medial rearfoot), with greater pressures applied using the non-preferred foot [6]. These asymmetries were not observed in the 15 matched controls. Despite the authors relating such asymmetries to the risk of stress injuries (it is even in the title of the paper), injury occurrence was not directly assessed. In a study with 159 professional soccer players, interlimb asymmetries in isokinetic knee flexion and extension were unrelated to competitive level or a history of injuries [97]. Still, the authors proposed prescribing exercise to correct for the observed asymmetries. With regard to isokinetic assessments of the knee, interlimb asymmetries of 19.5–31.7% in the knee extension strength and 36.6–51.2% in knee flexion have been shown for elite U16 male soccer players [47], but this study once again did not assess any relationships with injury occurrence.

In 25 teenage cricket fast bowlers (16 with and 9 without lower back pain [LBP]), the *symmetry* of the abdominal muscle morphology (i.e., the combined thickness of the external and internal obliques and transversus abdominis) was actually associated with LBP [98], while the players without LBP had a superior thickness of the abdominal wall contralateral to the dominant upper limb (i.e., the healthy athletes were more symmetric). Possibly, these functional asymmetries are the by-product of the repeated lateral flexion of the trunk during fast bowling actions and this reinforces the concept that some sports may require above-normal bilateral asymmetries to function in a given task [14,34], which has been previously suggested in other sports as well [99].

One study asked 6 rowers with a history of back injuries and 19 non-injured rowers to perform 30 strokes with maximal exertion in a rowing machine [100]; the lower limb GRF asymmetries were not significantly different in the rowers with or without a history of back injury [100]. In 12 professional runners, an association between interlimb asymmetries in the ground contact times and the injury history of the lower limbs in the previous 24 months was established for the 400 m distance, but not for the other distances (600 m, 800 m, and 1000 m) [33]. It was unclear whether such asymmetries induced increased injury occurrence or were caused by previous injuries (i.e., ankle sprains, Achilles tendinopathy, and shin tendinopathy) [33].

This is not to say that any degree of asymmetry is desirable, as it is possible that when surpassing certain thresholds (subject to inter- and intraindividual variation) injury occurrence may increase [60]. Patients with primary ACL reconstruction that underwent 6-month functional and isokinetic testing and a minimum 2-year follow-up were assessed for a secondary ACL injury [101]. Of the 344 patients, 59 (17%) had a secondary ACL injury ~5 years after the primary injury. The LSIs in isokinetic testing were significantly greater in the re-injured group with respect to 60°/s knee extension and flexion. However, regarding knee extension, both groups presented an interlimb asymmetry ≥18%, with only a 7% between-group difference. For knee flexion, both groups presented interlimb asymmetries that might not be considered clinically relevant (≤8%), with only a 5% difference between the two groups. No between-group differences were found for interlimb asymmetries in the single-leg hop and triple hop distances [101]. However, another study found an increased degree of interlimb asymmetry in male athletes with ACL reconstruction (n = 26) versus healthy controls (n = 22) [94], while interlimb asymmetries of 23% (single leg drop jumps) and 17% (single leg vertical jumps) where registered in injured subjects, and only 0–2% asymmetries were observed in healthy athletes.

As noted in a recent systematic review, several studies highlight that limb strength asymmetries could result in increased injury occurrence and/or performance impairments, but without presenting evidence to sustain such claims [46]. One review highlighted that injured and non-injured subjects may present similar interlimb asymmetry levels in kinetic and kinematic parameters when running and cycling, suggesting caution when hypothesizing relationships between asymmetries and injury occurrence [77]. Hearkening back to the systematic review analyzing the landings after attacking actions in volleyball [70], several studies claimed that asymmetric landing would increase injury occurrence; however, this was not sustained by the included studies, as they did not proceed to assess injury occurrence.

When such interlimb asymmetries are ubiquitous, one should think that they might be functional. Few would claim that right-handed people should spend thousands upon thousands of hours writing with their left hand to compensate for the many years writing with the right hand (which also impacts neck and shoulder position and work, with potential consequences for the trunk). Humans are mostly asymmetric in their daily actions (e.g., eating, writing, brushing the teeth, and driving) and people seem to accept those bilateral asymmetries fairly easily. We are aware that sports-related asymmetries are more strength- and power-oriented that these daily activities, and that they are often performed in less controlled environments. Regardless, we should be careful when trying to reduce asymmetries: who knows if they are functional for performance and even for injury occurrence? Moreover, as previously discussed, bilateral asymmetry in standardized tests (at the individual level) changes in time, in both magnitude and direction (i.e., there is large intraindividual variation from session to session) [38,39,42,49,50,52,53,62–66]. This variability may simply be a by-product of motor degeneracy (a well-established concept in motor learning and control), whereby different strategies may be used to achieve the same outcome [102–105].

3.2. What Do Intervention Studies Add to Our Knowledge about the Effects of Bilateral Asymmetry and Injury Occurrence?

Beyond any possible associations between asymmetry and injury occurrence, it is also important to understand if there is any sort of causal relationship between the magnitude of asymmetry and injury occurrence [53]. Specifically, it would be relevant to assess whether interventions aimed to reduce bilateral asymmetries (interlimb asymmetries and bilateral trunk asymmetries) achieve such reductions *and* demonstrate that these reductions in asymmetry lead to decreased injury occurrence. Considering the previous discussions in this manuscript, "reduced asymmetries" should be considered on a task-, metric-, and individual-specific context [7,11,12,34–39,42,48–53]. The consequences of reducing asymmetry may also interact with the absolute baseline values. For example, if an athlete has a stable 30% interlimb asymmetry and a training intervention reduces it by 50%, the reduction from 30% to 15% asymmetry may have a certain impact on injury occurrence (whether that impact is good or bad is another story). The same 50% reduction would not be expected to have an impact if the absolute asymmetry was reduced from 4% to 2%.

Preferably, the interventions should be randomized, and the controls should perform comparable interventions instead of being passive [106]. In Section 2, we explored the findings of several interventions aiming to reduce interlimb asymmetry from an athletic performance perspective [13,81–85,87,88,107], and a similar trend was evident for interventions relating to injury occurrence. As will become clear with the additional examples below, it seems that studies implementing training interventions focused on reducing bilateral asymmetries with the goal of reducing injury occurrence are not actually assessing what they have proposed to. In other words, injury occurrence is not being assessed even when the expression "injury risk" is in the title.

A prospective study implemented an 8-week core stability exercise program with 24 professional athletes (12 of which were controls) ~1 year after anterior cruciate ligament (ACL) injury [2]. In this study (as in many others), the baseline values of interlimb asymmetry were unknown, and so it is unclear how close the post-operative rehabilitation process was to the pre-injury values. Indeed, a recent systematic review of rehabilitation after ACL reconstruction suggested that LSIs may be misleading and that estimated pre-injury capacity may be a more relevant parameter [108]. What good is symmetry if an athlete's overall capacity is still 25% lower than their pre-injury levels? Returning to the study on ACL recovery [2], the LSIs were assessed for single-leg hop and triple hop distances, as well as single-leg-landing kinetics before and after the 8-week intervention. While the experimental group became more symmetric in the distances achieved in the single-leg and triple hops, the GRFs did not change significantly in any of the three axes. In conclusion, despite the more symmetric outcome measures, the GRFs were still asymmetrical [2]. The authors suggested that their core training program produced greater symmetry in the hop tests and therefore increased the readiness to return to sport [2]; however, since there was no assessment of injury occurrence, it is unclear whether a more symmetrical performance in the hop tests translated to a greater or smaller risk. In addition, distance is an outcome measure and provides limited (or no) understanding of neuromuscular jump strategies [62,109], which are also likely to change when athletes are fatigued [110].

Another randomized ACL injury-focused study with 40 patients post-ACL reconstruction compared a biofeedback intervention to an attention control group [111]. Both groups completed a 6-week (12 sessions) intervention including bilateral unweighted squats and were tested using a bilateral stop jump (run 4–5 steps forward, jump off on one foot, land with two feet on force platforms, and then immediately jump up and land back on two feet). The peak knee extension moment symmetry remained unchanged throughout the intervention for both groups, while the biofeedback group exhibited significant decreases in interlimb asymmetry with respect to the peak vertical GRF, but these decreases were not maintained in a follow-up test session 6 weeks later (i.e., at week 12) [111]. This can be a sign that the changes were fleeting and/or that there was a reduced repeatability of the asymmetry scores, as previously discussed. Again, injury occurrence was not assessed in this study [111].

One prospective study with 81 U14 to U18 team sports athletes assessed the interlimb asymmetries for the single leg CMJ and single leg hop test in the pre-season [112], and then registered any injuries occurring during that season. There was a significant association between injury occurrence and bilateral asymmetry in the single leg CMJ (albeit with a small effect, $\eta^2 = 0.08$), but not for the single leg hop test [112], i.e., the association was verified for only one of the two tests and it was minor in magnitude.

3.3. Where Are We At?

What is the overall picture regarding bilateral asymmetries and injury occurrence? A recent systematic review assessed whether bilateral lower limb asymmetry increased injury occurrence in sport [113]. The review outlined low to moderate level evidence and only for an association between asymmetry and injury, without the support of causality. Moreover, the reviewers highlighted inconsistencies in data collection and analyses, casting doubt over their validity [113]. Another recent systematic review on the topic showed highly inconsistent findings and suggested that no clear statement could be provided on an eventual association between bilateral lower limb asymmetries and injury occurrence, which was further complicated by the studies having used different operational definitions of injury (i.e., injury mechanism, time loss, body part, and length of interventions and follow-up) and different metrics to calculate interlimb asymmetry [40]. In addition, even less is known regarding bilateral trunk or upper limb asymmetries (which would be important, especially in sports that are highly asymmetric such as volleyball, water polo, and others) and injury occurrence since most of the consulted literature focused on the lower limbs. In summary, there seems to be no direct evidence from either observational or interventional studies to sustain the claims that interlimb asymmetries increase injury occurrence.

4. Suggestions for Future Studies

Given that so many studies attempt to relate bilateral asymmetries with performance and/or injury occurrence, we provide some suggestions for how such relationships could be established:

1. Start by studying the test–retest reliability for every test used and factor the typical errors (e.g., 5%) into the statistical analyses. Many asymmetries can possibly be explained away within that margin of error. Even asymmetries larger than the test error might (eventually) be explained within the natural fluctuations of performance.
2. Focus the analyses on intraindividual variability to ascertain how reliably each individual responds to the same test on different sessions. If the individual changes their asymmetry scores' magnitude and, especially, direction, perhaps that test is not appropriate for that individual and is providing misleading information. If the changes in magnitude are inferior or equal to the test error, simply ignore it.
3. Tests must be performed frequently and under relatively stable conditions (e.g., regarding the time of day and ambient temperature); otherwise, normal fluctuations in an athlete's performance in the test may be misinterpreted as noteworthy changes (this is valid for all tests, not just for bilateral asymmetries).
4. If an individual responds consistently to a given test, perhaps that test can be used to assess the effects of a training intervention, or to assess how the scores change with fatigue. However, even then, remember to analyze dose-response relationships and perform retention tests where possible to determine how robust the changes are to a detraining period.
5. If the goal is to assess performance, make sure to assess the sport-specific performance, preferably under competition-like conditions. Standardized physical tests or analytical technical assessments may not be representative of performance during an actual competition. Therefore, any asymmetry-related changes in performing standardized testing should not be automatically transferred to sports-specific performance.
6. We need more training interventions focused on establishing cause-and-effect relationships. For example, can certain interventions reduce asymmetries, but also, does such a reduction result in improved performance in the sport or key performance indicators as well? Remember to factor items 1–4 when interpreting the findings from such studies. These interventions should preferably include load-equated controls, be randomized, and apply blind testing.
7. If the goal is to establish the relationships between bilateral asymmetries and injury occurrence, make sure to adequately verify injury or reinjury rates. Otherwise, the studies will remain speculative. Determining that certain athletes have bilateral asymmetries (accepting these are true asymmetries) should not allow researchers to suggest those asymmetries may increase injury occurrence.
8. Injuries are relatively low-frequency events; after all, for most of the duration of a training regimen most athletes are *not* getting injured. While performance can be assessed frequently, assessing injury occurrences and gathering enough data to make inferences require large samples and/or large time windows. Therefore, studies with small samples and narrow periods of time should be very cautious when interpreting injury-related findings.

Figure 1 synthesizes the suggestions for future studies in a user-friendly manner.

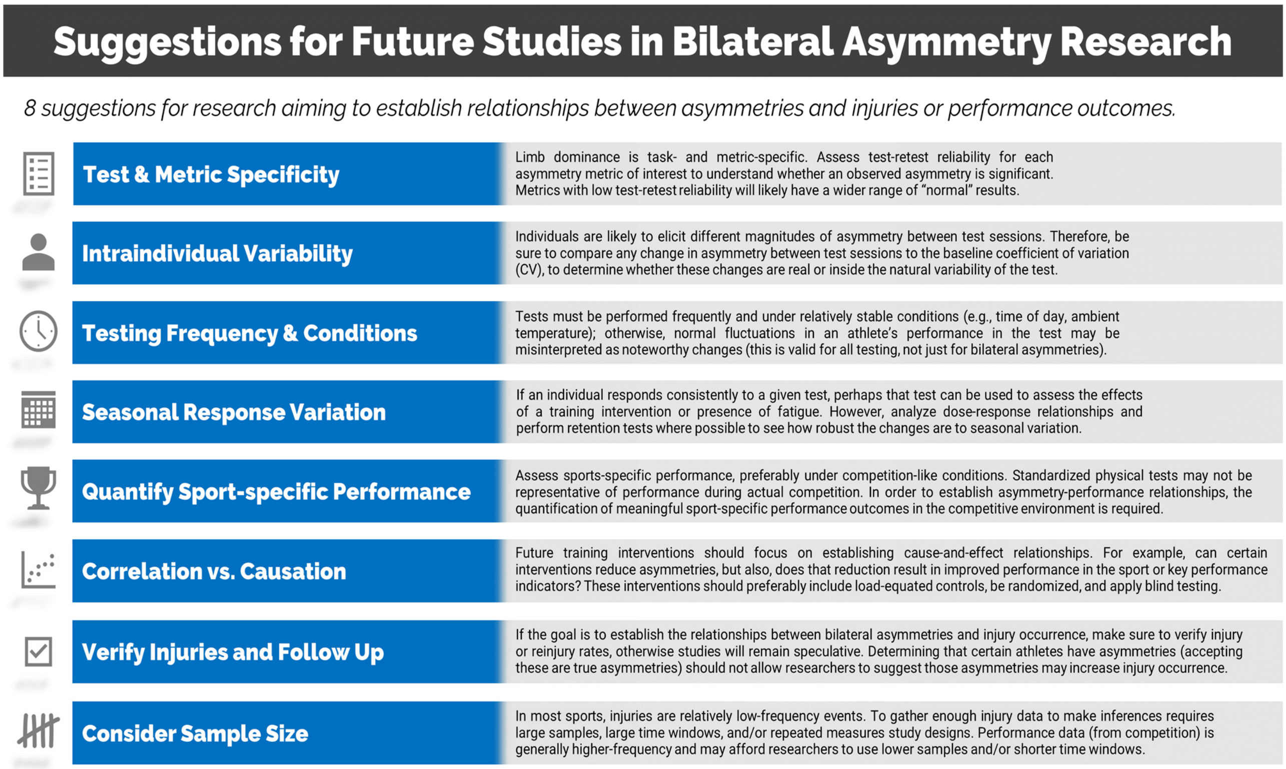

Figure 1. Suggestions for future studies in bilateral asymmetry research.

5. Concluding Remarks

Despite the claims concerning bilateral symmetry, some asymmetry is inevitable, functional (performance-wise), and not related to injury occurrence (at least, not *causative* of greater risk) in sports. From cosmological to biological evolution, all data point towards the necessity and inevitability of asymmetry. Humans promptly accept craniocaudal and dorsoventral asymmetries and should start to accept interlimb asymmetry as a natural (and positive) feature of human structure and performance. The pertinent questions are as follows: how much asymmetry is beneficial, and what is the threshold beyond which it may become dysfunctional? This threshold is likely highly task-, metric-, individual-, and even sport-specific. To complicate matters further, the direction of interlimb asymmetry is not consistent in time even for the same individual. For now, most statements regarding the negative effects of interlimb asymmetry on sports performance or injury occurrence rely on beliefs and are not sustained by data.

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