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Review article

The Calculation, Thresholds and Reporting of Inter-Limb Strength Asymmetry: A Systematic Review

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Abstract

The prevalence of inter-limb strength differences is well documented in the literature however, there are inconsistencies related to measurement and reporting, and the normative values and effects associated with inter-limb asymmetry. Therefore, the aims of this systematic review were to: 1) assess the appropriateness of existing indices for the calculation of asymmetry, 2) interrogate the evidence basis for literature reported thresholds used to define asymmetry and 3) summarise normative levels of inter-limb strength asymmetry and their effects on injury and performance. To conduct this systematic review, scientific databases (PubMed, Scopus, SPORTDiscus and Web of Science) were searched and a total of 3,594 articles were retrieved and assessed for eligibility and article quality. The robustness of each identified asymmetry index was assessed, and the evidence-basis of the identified asymmetry thresholds was appraised retrospectively using the references provided. Fifty-three articles were included in this review. Only four of the twelve identified indices were unaffected by the limitations associated with selecting a reference limb. Eighteen articles applied a threshold to original research to identify "abnormal" asymmetry, fifteen of which utilised a threshold between 10-15%, yet this threshold was not always supported by appropriate evidence. Asymmetry scores ranged between and within populations from approximate symmetry to asymmetries larger than 15%. When reporting the effects of strength asymmetries, increased injury risk and detriments to performance were often associated with larger asymmetry, however the evidence was inconsistent. Limitations of asymmetry indices should be recognised, particularly those that require selection of a reference limb. Failure to reference the origin of the evidence for an asymmetry threshold reinforces doubt over the use of arbitrary thresholds, such as 10-15%. Therefore, an individual approach to defining asymmetry may be necessary to refine robust calculation methods and to establish appropriate thresholds across various samples and methodologies that enable appropriate conclusions to be drawn.

Key words: Imbalance, power, functional performance, between-limb, injury, performance.

Introduction

Strength asymmetry, defined as a lack of equality between limbs or muscle groups, has been the topic of interest for various studies over recent years, particularly in strength and conditioning literature, due to the effect of asymmetry on injury and performance. It is often considered that strength asymmetries of 10-15% or more are problematic (Barber et al., 1992; Rohman et al., 2015; Kyritsis et al., 2016) and as such, measures should be taken to reduce imbalances. Therefore, inter-limb strength deficits have been investigated in a range of populations to better understand the prevalence and subsequent effects of strength asymmetry. However, a more recent perspective questions the use of pre-determined thresholds due to the task-, metric- and population-specific nature of asymmetry (Dos'Santos et al., 2017b; Bishop et al., 2019c; b; Read et al., 2021). Instead, a more individual approach to asymmetry has been proposed, which considers sample-specific thresholds and individual variability (Dos'Santos et al., 2021; Bishop, 2021).

The literature has reported varying magnitudes of inter-limb strength asymmetry, from close to perfect symmetry to greater than 15% asymmetry across sexes, age groups, activity levels and injury status (Eitzen et al., 2010; Jones and Bampouras, 2010; Ceroni et al., 2012; Laroche et al., 2012; Ruas et al., 2015; Leister et al., 2018; O'Malley et al., 2018; Hoogeslag et al., 2019; Dai et al., 2019). In general, the evidence suggests that larger imbalances in strength are associated with detriments to performance in jumping, sprinting and change of direction (Bell et al., 2014; Bishop et ak., 2018b; Bishop et al., 2021b; Michailidis et al., 2020). Strength differences between limbs have also been associated with an increased risk of prospective injury (Croisier et al., 2008; Brumitt et al., 2013), which indicates that inter-limb imbalances should be reduced. However, conflicting evidence exists to suggest that strength asymmetry may not always cause dysfunction (Lockie et al., 2014; Opar et al., 2015; Dos'Santos et al., 2018). Furthermore, larger asymmetries measured in higher division soccer players as compared to lower division players, suggests that competitive level may influence strength asymmetry (Ferreira et al., 2018). Therefore, inter-limb imbalances may even be desirable in some cases.

Strength asymmetries reported in the literature have been assessed using various protocols. The isokinetic dynamometer is commonly used as it is considered the gold-standard for measuring strength due to its high reliability when measuring isometric and isokinetic peak torque *in vivo* (Maffiuletti et al., 2007; Tsiros et al., 2011). However, it is often unfeasible to employ expensive experimental set-ups and lengthy protocols in a field-based setting. Furthermore, poor reporting and standardisation of appropriate dynamometer testing protocols in the literature poses further challenges when assessing asymmetries in strength (Baltzopoulos et al., 2012). Functional performance tests, including various jumping and hopping tests (Bishop et al., 2017), have been proposed as valid and reliable field-based

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alternatives to single-joint strength measurements performed on an isokinetic dynamometer (Maulder and Cronin, 2005; Impellizzeri et al., 2007). However, recent evidence suggests that the asymmetries determined from field-based tests have limited between-session reliability, despite good reliability in single-leg performance variables between sessions (Pérez-Castilla et al., 2021). This study also demonstrates task and metric sensitivity, as well as inconsistencies in the magnitude and direction of asymmetries measured one week apart. Task sensitivity can be overcame by implementing a battery of tests (Bishop et al., 2017) however, practitioners should also consider test-retest reliability of asymmetry scores before classifying an individual's asymmetry profile.

Methodological differences also exist in the calculation of asymmetry scores, with various indices reported in the literature. Often, asymmetries are calculated as a percentage, where one limb is normalised to the reference limb (Eitzen et al., 2010; Ceroni et al., 2012; Schmitt et al., 2015; Palmieri-Smith and Lepley, 2015; Leister et al., 2018) however, some indices divide the absolute difference between limb values by the value of the desirable limb (Impellizzeri et al., 2007; Jones and Bampouras, 2010; Laroche et al., 2012). Both approaches require a distinction between limbs such as injured/uninjured, right/left, and dominant/nondominant, where one limb is assumed to be the stronger or better performing of the two limbs. Alternatively, the numerator can be divided by a statistic derived from both limb values such as the mean, sum of, minimum or maximum value (Bell et al., 2014; Bailey et al., 2015; Dai et al., 2019). However, there are limitations associated with selecting a reference limb or value, which can lead to inflated scores and different values of asymmetry depending on which limb is stronger (Bishop et al., 2016). Furthermore, inconsistencies in the indices employed in the literature limits comparison between studies. It should also be noted that the literature includes references to both symmetry and asymmetry, which requires the reader to be observant of the opposite terminologies. However, this poses less of a challenge for data comparison than using different input variables and mathematical processes. This is because 0% asymmetry is equivalent to 100% symmetry, which marks the absence of asymmetry and therefore, complete symmetry.

Additionally, differences exist for the interpretation of asymmetry scores. Commonly a threshold of between 10-15% is used to identify abnormal differences between limbs (Croisier et al., 2002; Rohman et al., 2015; Ruas et al., 2015; Schmitt et al., 2015; Kyritsis et al., 2016; Ebert et al., 2018). However, inconsistent findings in the literature associated with the magnitude of asymmetry for specific groups and the subsequent effect on injury and performance, indicate that the use of arbitrary thresholds lacks a solid evidence base. Thus, it is crucial to ensure interpretation of inter-limb strength asymmetry is based upon original evidence and draws upon appropriate methodological practices. This would enable researchers and practitioners to distinguish between asymmetries that are problematic and those that may be functional.

Therefore, the aims of this systematic review were to: 1) assess the appropriateness of existing quantitative methods for the calculation of asymmetry, 2) interrogate the evidence basis for literature reported thresholds used to define asymmetry and 3) summarise normative levels of inter-limb strength asymmetry and their effects on injury and performance.

Methods

The systematic review was designed according to PRISMA guidelines (Moher et al., 2009, 2015; Liberati et al., 2009).

Search strategy

Articles were retrieved from the following databases: PubMed, Scopus, SPORTDiscus with Full Text, and Web of Science.

The search process (Figure 1) was divided into two stages to capture all relevant articles. Both stages were designed to retrieve articles that clearly addressed the methods associated with measuring strength asymmetry, including isolated strength, functional performance and power, to ensure appropriate understanding and comparison of methodologies could be made. For stage one, the search strategy was designed to exclude participants with neurological disorders, as such disorders are likely to influence asymmetry methodology and outcomes.

Search terms and combinations for stage one were informed by existing literature and included:

1. *(Asymmetr* OR Symmetr* OR Imbalance* OR "Side to side" OR "Limb dominance" OR "Leg dominance" OR "Limb preference" OR "Leg preference")*
2. *AND (Calculat* OR Measur* OR Reliability OR Reproducibility OR Validity OR Accuracy OR Effectiveness OR Repeatability OR Equations OR Formula*)*
3. *AND (Strength OR Power)*
4. *NOT (Patholog* OR Disorder OR Disease OR Dysfunction OR Syndrome OR Spastic* OR Defect OR Disability OR Ataxia OR Chorea OR Dystonia OR "Multiple system atrophy" OR Myoclonus OR "Progressive supranuclear palsy" OR "Restless legs" OR Tourette* OR Tic OR Tremor* OR "Multiple Schlerosis" OR Stroke OR Epilepsy)*

Stage two was designed to ensure articles investigating individuals with lower body disability, but an absence of disease or neurological injury could be identified, as these articles were likely to be excluded from stage one results due to the fourth string of search terms. The upper body function of wheelchair users may be considered normal or high functioning. As such, articles retrieved from stage 2 were expected to offer additional insight into methodologies associated with strength, power or functional performance asymmetry that might otherwise be missed by the search terms of stage one.

Search terms for stage two were informed by existing literature and included:

1. *(Asymmetr* OR Symmetr* OR Imbalance* OR "Side to side" OR "Limb dominance" OR "Leg dominance" OR "Limb preference" OR "Leg preference")*
2. *AND (Calculat* OR Measur* OR Reliability OR Reproducibility OR Validity OR Accuracy OR Effectiveness OR Repeatability OR Equations OR Formula*)*
3. *AND (Strength OR Power)*
4. *AND (Wheelchair*)*

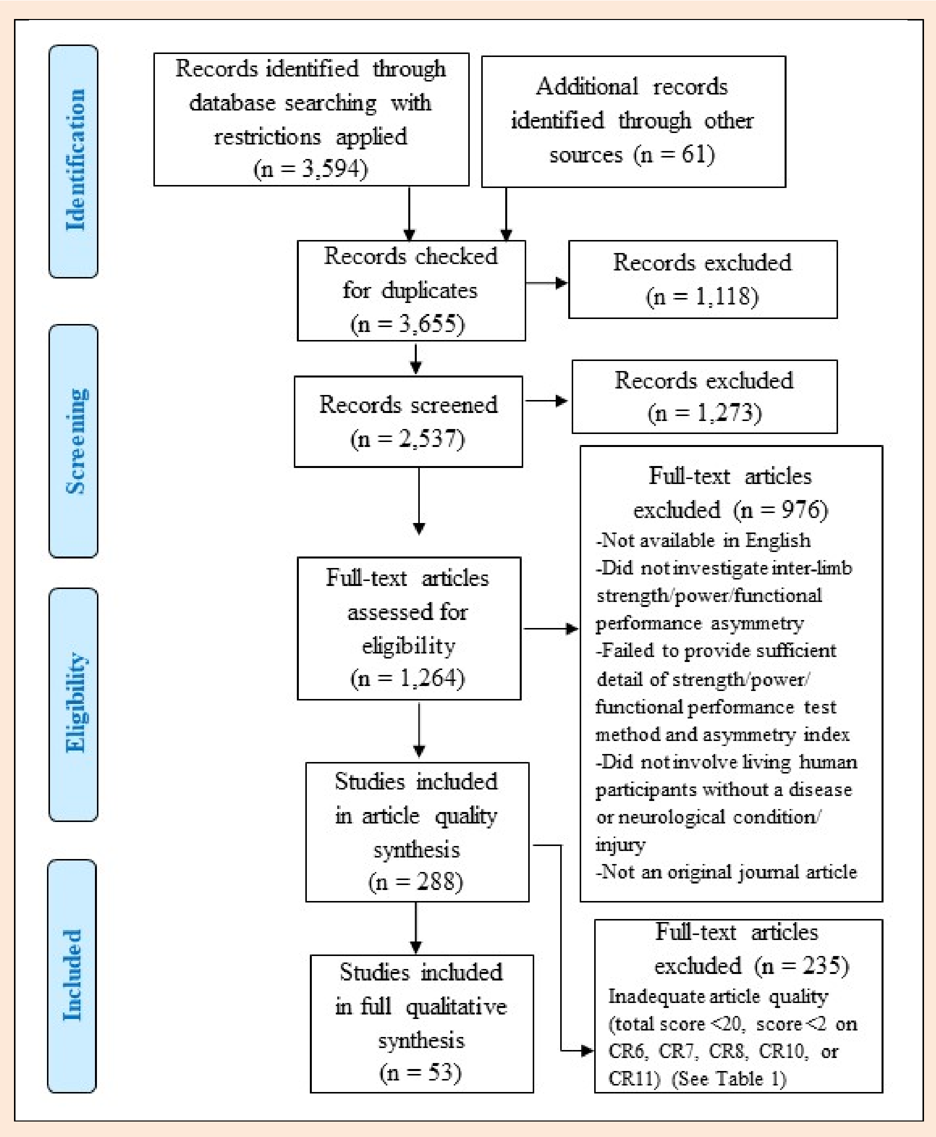

Figure 1. Flow diagram showing the identification and selection of the articles for this review.

Additional searches were conducted in Google Scholar and an institutional library database in an attempt to retrieve full-text articles if they were not available via the aforementioned databases. Searches were conducted between January and March 2020. Reference lists of the included full-text articles were also screened for relevant articles investigating strength, power or functional performance asymmetry that were not identified by initial searches.

Screening and Eligibility criteria

Restrictions were applied to limit the searches to journal articles, available in English. Database searches were limited to articles available in full text, investigating human participants and published in sport and exercise science related journals where possible. No further limiters were applied to ensure a wide scope for the review. Identified articles were exported to the referencing software, Mendeley, where duplicates were removed. The title and abstract of retrieved articles were screened to exclude articles unrelated to sport and exercise science and articles not available in full text. The remaining full-text articles were then screened for eligibility and only included if they met the inclusion criteria. Inclusion criteria required articles to be original journal articles, available in English and involving living human participants without disease or a neurological condition/injury. Articles were required to investigate inter-limb strength asymmetry and provide comprehensive detail of the measurement methods and asymmetry index calculation to allow for a critical examination of the study results.

Risk of Bias

A sample (n = 252, approximately 10%) of the articles retrieved from the initial searches after removing duplicates were screened for eligibility (excluding article quality) independently by a primary and secondary reviewer. Upon consistent agreement between reviewers, the remaining articles were screened by the primary reviewer only. The secondary reviewer was responsible for monitoring this process to reduce the risk of bias. Where disputes arose, decisions were settled through discussion between both reviewers. Article quality was assessed in accordance with the screening protocol already stated, where a sample (n = 28, approximately 10%) was assessed for agreement before the remaining articles were screened.

Article quality assessment

Article quality was assessed using a modified version of a previously developed scale, established for use in systematic reviews (Peters et al., 2010). The scale was modified to ensure a critical appraisal of the current review's aims relating to strength and strength asymmetry testing (Table 1). The scale evaluated article quality based on twelve criteria, which were each scored on a scale between 0-2 (where 2 = Yes, 1 = Lacks Detail and 0 = No). Summation across all criteria provided a total score, expressed as a percentage. To enhance the quality of this review, articles were required to reach a total score of 20/24 (83%). This equates to a score of 0 for up to two of the criteria or a score of 1 for up to four of the criteria. As thresholds used to identify 'high quality' articles vary in the literature (Peters et al., 2010; Ceyssens et al., 2019; Nugent et al., 2021), the 83% threshold used for the current review was devised based upon individual scores achieved across all twelve criteria, with the aim of including only the highest quality research. Articles were also required to score 2/2 on 5 of the 12 criteria which specifically addressed the study protocol (CR6), outcome variables (CR7), test method (CR8), asymmetry index (CR10), and results (CR11) as complete scores in these areas were necessary to provide the information required to satisfy the aims of the review.

Data extraction

For this review, the term 'strength' was used to describe any strength-based assessment including isolated strength, functional strength and power tests. The following data were extracted from each source using data extraction forms developed *a priori*: (1) study design, (2) sample characteristics, (3) inclusion/exclusion criteria, (4) strength asymmetry test, (5) strength calculation/index, (6) strength asymmetry threshold, (7) comparators (8) outcome measures, (9) intervention, (10) follow-up, and (11) main findings. An extracted data table of sample characteristics, tests and outcome variables was constructed as applicable to this review (Table 2).

Data synthesis

The extracted data was used to explore literature features related to population-specific characteristics, testing methods, calculations, and asymmetry thresholds. To examine the robustness of asymmetry calculations, a quantitative analysis of the asymmetry indices was performed using hypothetical scores for three separate scenarios; 1) symmetry, where limb A=B, 2) asymmetry, where limb A>B, and 3) asymmetry, where limb A<B (Supplementary Material Table S1).

Where an asymmetry threshold was applied in the methodology of the study, the evidence base for the stated threshold was traced retrospectively. The evidence base was further examined to explore whether the study identified the origin of the evidence, where the stated threshold was based on original data examined in the study itself. Where the included article itself was not the origin of the evidence, the references provided to support its use were identified and assessed (direct citations). Where the direct citations failed to provide the origin of the evidence, references provided by the direct citations were identified and assessed (indirect citations). The evidence base for the stated threshold in the study was categorised according to the following Tier system, where the included article:

Tier 1: Provided the origin of the evidence for the threshold
Tier 2: Directly cited the origin of the evidence
Tier 3: Indirectly cited the origin of the evidence
Tier 4: Failed to provide or cite the origin of the evidence

Included articles that provided either Tier 1 or 2 evidence were considered to be more reputable because the origin of the threshold was based upon original findings from the included article or its direct citations. However, it should be noted that interrogation of the research quality for each evidence source was beyond the scope of this review.

Table 1. Article Quality Assessment Tool (adapted from Peters et al., 2010)

Criterion
CR1. Are the research objectives or aims clearly stated?
CR2. Is the study design clearly described?
CR3. Is the sample size used justified?
CR4. Are inclusion/exclusion criteria clearly stated?
CR5. Are appropriate subject information and anthropometric details provided?
CR6. Is the strength/power/functional performance asymmetry protocol properly described?
CR7. Are the variables used to measure strength/power/functional performance properly defined in the introduction or methods section?
CR8. Are the tests used to measure strength/power/functional performance properly described?
CR9. Are the instruments/measurements used to measure strength/power/functional performance validated for strength measurements (previously trialled, piloted or published)?
CR10. Is an inter/between-limb strength/power/functional performance asymmetry calculation provided or referenced appropriately?
CR11. Are the main outcomes of the study relating to strength/power/functional performance asymmetry clearly reported?
CR12. Are the limitations of the study clearly described?

Each criterion was scored as follows, 2= Yes; 1 = Limited Detail; 0 =No

Table 2. Summary of sample demographics and methods used to measure inter-limb strength asymmetry in the included articles (N = 53)

Article	Quality Score	Total Sample Size (N)	Sample Characteristics								Strength Asymmetry Test									Strength Asymmetry Metric									
											Isolated						Functional												
			Male	Female	Injured/Post-Surgery	Uninjured	Athlete	Non-Athlete	Young (≤55yrs)	Old (>55yrs)	Isokinetic Dynamometer	Stabilised Dynamometer	Hand-Held Dynamometer	Weight-Training Machine	Multi-Joint Strength Test	Nordic Hamstring	Jumping/Hopping	Push-Up	Seated Shot-Put	Torque	Force	Power	Impulse	Jump/Hop Height	Jump/Hop/Throw Distance	Vertical GRF	1-RM	Work Done	RFD
Abourezk et al., (2017)	22	36	✓	✓	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Ageberg & Roos, (2016)	23	54	✓	✓	✓	-	-	✓	✓	-	-	-	-	✓	-	-	✓	-	-	-	-	✓	-	✓	✓	-	-	-	-
Almeida et al., (2019)	24	70	✓	✓	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Ardern et al., (2015)	21	42	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Batty et al., (2019)	22	10	✓	✓	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Benjanuvatra et al., (2013)	20	58	✓	✓	-	✓	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	✓	✓	-	✓	-	-	-
Bishop et al., (2019c)	20	28	?	?	-	✓	✓	-	✓	-	-	-	-	-	✓	-	✓	-	-	-	✓	-	✓	✓	-	-	-	-	-
Bishop et al., (2019d)	21	16	-	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
Bookbinder et al., (2020)	23	52	✓	✓	✓	✓	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Bourne et al., (2015)	22	17	✓	-	✓	✓	✓	-	✓	-	-	-	-	-	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-
Carabello et al., (2010)	23	93	✓	✓	-	✓	-	✓	✓	✓	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	✓	-	-
Chmielewski et al., (2014)	20	12	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-
Clark & Mullally, (2019)	23	23	-	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Coratella et al., (2018)	24	27	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Costa Silva et al., (2015)	20	22	?	?	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Dai et al., (2018)	23	49	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	✓	-	-	✓	-	-	✓	-	-	-	-	-
de Lira et al., (2017)	21	11	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Dos’Santos et al., (2017a)	23	22	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
Dos'Santos et al., (2018)	22	20	✓	-	-	✓	✓	-	✓	-	-	-	-	-	✓	-	-	-	-	-	✓	-	✓	-	-	-	-	-	-
Falstrom et al., (2017)	24	15	-	✓	✓	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
Fort-Vanmeerhaeghe et al., (2015)	21	29	-	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Fort-Vanmeerhaeghe et al., (2016)	20	79	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
Guney-Deniz et al., (2019)	24	87	✓	✓	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	-	-	-	✓	-	-	-	-
Hadzic et al., (2010)	20	18	✓	✓	✓	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Harput et al., (2018)	22	72	✓	-	✓	-	-	✓	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	-	-	-	✓	-	-	-	-
Hart et al., (2014)	20	31	✓	-	-	✓	✓	-	✓	-	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	-
Hiemstra et al., (2008)	23	48	✓	✓	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-

GRF = Ground Reaction Force, 1-RM = 1-Repetition Maximum, RFD = Rate of Force Development

Table 2. Continue…

Article	Quality Score	Total Sample Size (N)	Sample Characteristics								Strength Asymmetry Test									Strength Asymmetry Metric									
											Isolated						Functional												
			Male	Female	Injured/Post-Surgery	Uninjured	Athlete	Non-Athlete	Young (≤55yrs)	Old (>55yrs)	Isokinetic Dynamometer	Stabilised Dynamometer	Hand-Held Dynamometer	Weight-Training Machine	Multi-Joint Strength Test	Nordic Hamstring	Jumping/Hopping	Push-Up	Seated Shot-Put	Torque	Force	Power	Impulse	Jump/Hop Height	Jump/Hop/Throw Distance	Vertical GRF	1-RM	Work Done	RFD
Holsgaard-Larsen et al., (2015)	24	48	✓	-	✓	✓	-	✓	✓	-	-	✓	-	-	-	-	✓	-	-	✓	-	-	-	✓	✓	-	-	-	-
Hubbard et al., (2007)	23	60	✓	✓	✓	✓	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	✓	✓	✓	-	-	-	-	-	-	-
Hughes et al., (2019)	21	12	✓	✓	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Kaminska et al., (2015)	22	34	✓	-	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-
Lisee et al., (2019)	23	11	✓	✓	-	✓	✓	✓	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	✓	-	-	✓	-	-	-	-
Lloyd et al., (2020)	21	43	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	✓	-	-	-	✓	-	-	-	-
Lockie et al., (2012)	20	16	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-	-	-	-	-
Lockie et al., (2014	21	30	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Lockie et al., (2013)	20	16	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Lockie et al., (2016)	21	19	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
Madruga-Parera et al., (2019)	22	41	?	?	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
Madruga-Perera et al., (2020)	20	42	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Maloney et al., (2016)	21	18	✓	-	-	✓	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
Menzel et al., (2013)	20	46	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	✓	✓	-	-	✓	-	✓	-
Miles et al., (2019)	22	66	✓	-	✓	✓	✓	-	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	-	✓	-	-	-	-	-	-
Opar et al., (2015)	22	21	✓	-	✓	✓	✓	-	✓	-	-	-	-	-	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-
Peebles et al., (2019)	23	30	✓	✓	✓	-	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
Redden et al., (2018)	24	13	✓	-	-	✓	✓	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-
Reid et al., (2007)	23	42	✓	✓	✓	-	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
Riemann & Davies, (2019)	20	24	✓	✓	-	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	✓	-	-	-	✓	-	-	-	-
Suchomel et al., (2016)	22	13	✓	-	-	✓	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	✓	✓	✓	-	-	-	-	-	✓
Vanderstukken et al., (2019)	21	50	✓	-	-	✓	✓	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-	-	-	-	-
Welling et al., (2019)	23	68	✓	-	✓	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Xergia et al., (2013)	24	44	✓	-	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	-	-	-	-	✓	-	-	-
Zwolski et al., (2015)	22	13	✓	✓	✓	-	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Zwolski et al., (2016)	22	45	-	✓	✓	✓	✓	-	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	-	-	-	-	✓	-	-	-
Total			**4**	**2**	**2**	**4**	**3**	**2**	**5**	**1**	**2**	**1**	**2**	**3**	**3**	**2**	**2**	**1**	**2**	**2**	**1**	**7**	**6**	**1**	**1**	**4**	**1**	**2**	**1**

GRF = Ground Reaction Force, 1-RM = 1-Repetition Maximum, RFD = Rate of Force Development

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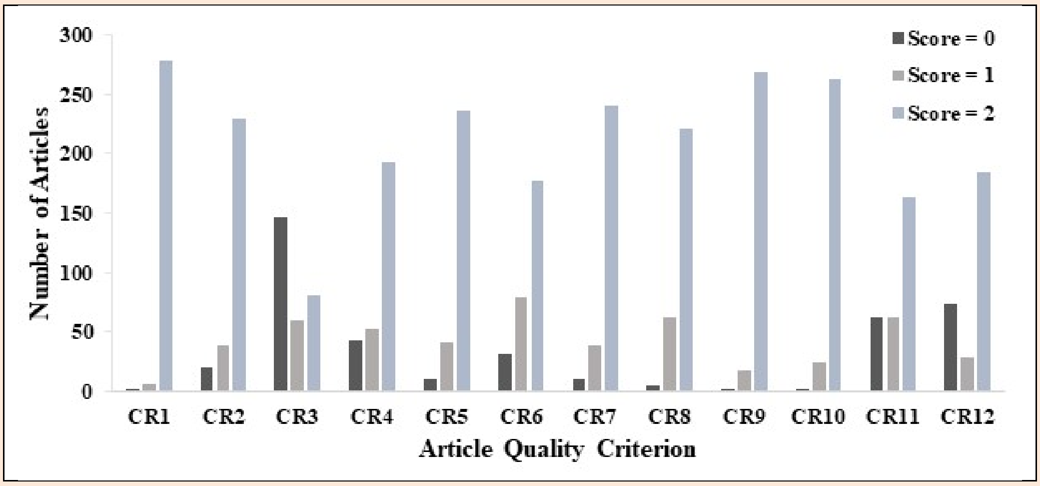

Figure 2. Distribution of quality scores for the articles assessed for eligibility (n = 288), where a score of 0 = No, 1 = Limited Detail and 2 = Yes (see Table 1).

Results

A total of 3,594 articles were retrieved from initial searches using PubMed, Scopus, SPORTDiscus with Full Text and Web of Science. A further 61 relevant articles were identified by reviewing the reference lists of the included articles. The title and abstracts of 1,264 articles met the screening criteria, and the remaining full-text articles that fulfilled the eligibility criteria were assessed for article quality (n = 288).

Article Quality Assessment

Most of the articles (n = 251, 87%) assessed for article quality scored ≥17, and the lowest scoring article received a total score of 9 out of 24. For 11 of the 12 criteria, over half of the 288 articles (57-97%) scored the maximum when each criterion was assessed individually (Figure 2). Typically, articles scored worse on CR3, which addressed sample size justification, with 147 (51%) articles scoring 0. The most common items that resulted in a score of 2 refer to the reporting of research objectives (CR1; 97%), utilisation of validated strength tests (CR9; 93%) and provision of an inter-limb asymmetry calculation (CR10; 91%). Of the 288 articles assessed, 149 (52%) received a total score of 20/24 and were considered for the full review. For the five selected criteria, the remaining 149 articles tended to score lower for reporting of the study protocol (CR6) and main findings (CR11). Fifty-three of the remaining articles scored 2 out of 2 on all five items and were included in the review.

Study description

The included articles investigated a range of populations, including individuals who were injured or post-surgery, athletes, females and older individuals, however some groups were less represented than others (Table 2). Sample groups were defined according to the definitions applied by the included articles. As such, participants referred to as ‘athletes’ or ‘players’ at any activity level were included in the athlete group and older adults included participants over 55 years as defined by the only article to investigate this population (Carabello et al., 2010). There was crossover for sample characteristics such that studies could be counted more than once, for example, female athletes following Anterior Cruciate Ligament Reconstruction (ACLR) would be counted in the female, athlete and post-surgery groups. Additionally, wheelchair users are not represented in this review despite Stage Two of the search strategy which was designed to retrieve studies investigating this sample demographic, as the related articles failed to fulfil the inclusion criteria. Various tests were implemented to measure inter-limb asymmetry in strength, power and functional performance outcomes including isokinetic dynamometry, stabilised dynamometry, hand-held dynamometry, weight-training machine tests, multijoint strength tests, the Nordic Hamstring test, push-up test and seated shot put test (Table 2). Some studies implemented multiple strength, power, or functional performance assessments, so were counted more than once across tests.

Twelve index types were identified from the literature (Table 3). The indices were often referred to by different names and were applied for various limb comparisons. Five different methods of defining a limb comparison were made: 1) involved/uninvolved, 2) dominant/nondominant, 3) right/left, 4) stronger/weaker and 5) stance/skill. Limbs were sometimes referred to by different names but were grouped together, such as injured/uninjured instead of involved/uninvolved. For this review, the indices were numbered from 1-12 to avoid confusion caused by inconsistent nomenclature, however each article’s specific terminology is also provided (Table 3). Index-1, often referred to as the Limb Symmetry Index, was the most used index across the included articles (N = 20) and provides an index of symmetry between limbs. Index-7 was the next most common (N = 13) but provides an index of asymmetry rather than symmetry. Of the twelve identified indices, only four (Index-9, 10, -11, and -12) individually produced the same magnitude of asymmetry for scenarios 2 and 3 (Table 3, Supplementary Material Table S1), demonstrating that they work independent of the limb that performs better

(Table 4). However, not all scores were comparable to one another. The stronger/weaker distinction was the only limb comparison that worked consistently across all twelve indices, enabling each index to produce the same magnitude of asymmetry for scenarios 2 and 3, independent of direction.

Thirty of the included articles referred to asymmetry scores in terms of a threshold (Table 5). Most commonly, asymmetry thresholds between 10-15% were described (n = 27); with twelve articles referring to a single threshold of 10%, eight articles referring to 15% and seven articles describing asymmetries at thresholds of 10% and 15%, two of which also investigated 20% asymmetry. The remaining articles (N = 3) used an alternative threshold of the mean + 0.2 standard deviations. Eighteen articles applied a threshold to original data, using a threshold defined in their methodology. Retrospective analysis of the evidence base revealed that 33% (n = 6) of the eighteen articles provided Tier 1 or Tier 2 evidence (Figure 3).

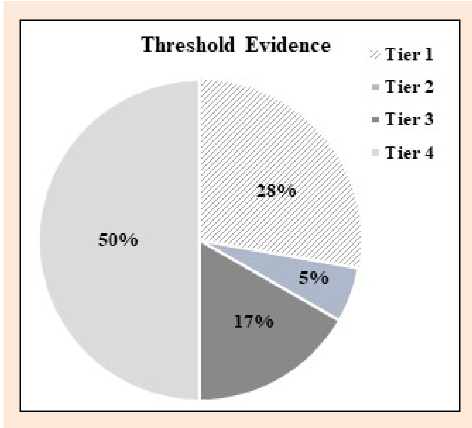

Figure 3. Evidence provided by the included articles for the asymmetry thresholds they employed, where Tier 1 indicates the article provides the origin of the evidence for the threshold, Tier 2 indicates the article directly cites the origin of evidence, Tier 3 indicates the article indirectly cites the origin of the evidence and Tier 4 indicates the article fails to provide or cite the origin of the evidence.

Table 3. Asymmetry Index types identified from the included articles (N = 53).

Index Calculation	Article	Index Name	Limb Comparison
$Index\ 1 = \frac{B}{A} \cdot 100$	Abourezk et al., (2017)	Limb Symmetry Index	Involved/Uninvolved
	Ageberg & Roos, (2016)	Limb Symmetry Index	Involved/Uninvolved
	Batty et al., (2019)	Limb Symmetry Index	Involved/Uninvolved
	Bookbinder et al., (2020)	Limb Symmetry Index	Involved/Uninvolved Dominant/Nondominant
	Falstrom et al., (2017)	Limb Symmetry Index	Involved/Uninvolved Dominant/Nondominant
	Guney-Deniz et al., (2019)	Limb Symmetry Index, Quadriceps/ Hamstring Index	Involved/Uninvolved
	Harput et al., (2018)	Limb Symmetry Index	Involved/Uninvolved
	Hart et al., (2014)	Unilateral Strength Imbalance	Stance/Skill
	Holsgaard-Larsen et al., (2015)	Between-Limb Asymmetry Ratio	Involved/Uninvolved Dominant/Nondominant
	Hubbard et al., (2007)	Symmetry Index	Involved/Uninvolved
	Hughes et al., (2019)	Quadriceps/ Hamstring Index	Involved/Uninvolved
	Kaminska et al., (2015)	Limb Symmetry Index	Involved/Uninvolved Right/Left
	Lisee et al., (2019)	Limb Symmetry Index	Stronger/Weaker
	Lloyd et al., (2020)	Symmetry	Stronger/Weaker
	Peebles et al., (2019)	Limb Symmetry Index	Involved/Uninvolved
	Reid et al., (2007)	Limb Symmetry Index	Involved/Uninvolved
	Welling et al., (2019)	Limb Symmetry Index	Involved/Uninvolved Stronger/Weaker
	Xergia et al., (2013)	Limb Symmetry Index	Involved/Uninvolved Dominant/Nondominant
	Zwolski et al., (2015)	Quadriceps-Limb Symmetry Index	Involved/Uninvolved
	Zwolski et al., (2016)	Limb Symmetry Index	Involved/Uninvolved Dominant/Nondominant
$Index\ 2 = \frac{A}{B} \cdot 100$	Chmielewski et al., (2014)	Limb Symmetry Index	Dominant/Nondominant
	Clark & Mullally, (2019)	Limb Symmetry Index	Right/Left
$Index\ 3 = \left[1 - \left(\frac{B}{A}\right)\right] \cdot 100$	Hadzic et al., (2010)	Strength asymmetry	Dominant/Nondominant
$Index\ 4 = 100 - \left[\left(\frac{B}{A}\right) \cdot 100\right]$	Almeida et al., (2019)	Limb Symmetry Index	Involved/Uninvolved

A = uninvolved/uninjured/non-operative/non-surgical, dominant/preferred, right, stronger/better performing, or stance/support limb value
B = involved/injured/operative/reconstructed/surgical, non-dominant/non-preferred, left, weaker/lesser performing, or skill/kicking limb value
* indicates the study used multiple indices, so appears more than once in this table

Table 3. Continue…

Index Calculation	Article	Index Name	Limb Comparison
$Index\ 5 = \frac{100}{A} \cdot B \cdot -1 + 100$	Bishop et al., (2019c)	Asymmetry	Stronger/Weaker
	Bishop et al., (2019d)	Asymmetry	Stronger/Weaker
	Madruga-Perera et al., (2020)	Asymmetry	Stronger/Weaker
$Index\ 6 = \frac{A}{B}$	Ardern et al., (2015)	Bilateral Ratio	Stance/Skill
	Riemann & Davies, (2019)	Limb Symmetry Index	Dominant/Nondominant
$Index\ 7 = \frac{(A - B)}{A} \cdot 100$	Coratella et al., (2018)	Asymmetry	Stronger/Weaker
	de Lira et al., (2017)	Muscular Strength Asymmetry	Dominant/Nondominant
	Dos'Santos et al., (2018)	Asymmetry Index	Right/Left Dominant/Nondominant
	Dos'Santos et al., (2017a)	Asymmetry Index	Right/Left Dominant/Nondominant
	Fort-Vanmeerhaeghe et al., (2016)	Asymmetry Index	Dominant/Nondominant Stronger/Weaker
	Fort-Vanmeerhaeghe et al., (2015)	Asymmetry Index	Stronger/Weaker
	Hiemstra et al., (2008)	Strength Deficit	Involved/Uninvolved
	Lockie et al., (2012)	Bilateral Difference	Stronger/Weaker
	Lockie et al., (2013)	Bilateral Difference	Stronger/Weaker
	Lockie et al., (2014)	Bilateral Asymmetry	Stronger/Weaker
	Lockie et al., (2016)	Asymmetry	Stronger/Weaker
	Madruga-Parera et al., (2019)	Asymmetry	Stronger/Weaker
	Vanderstukken et al., (2019)	Bilateral Strength Asymmetry	Stronger/Weaker
$Index\ 8 = \frac{(B - A)}{A} \cdot 100$	Carabello et al., (2010)	Asymmetry	Stronger/Weaker
$Index\ 9 = \frac{(A - B)}{Max(A, B)} \cdot 100$	Benjanuvatra et al., (2013)	Index of Asymmetry	Right/Left
	Dai et al., (2019)	Bilateral Asymmetry Index	Dominant/Nondominant
	Menzel et al., (2013)	Limb Symmetry Index	Right/Left
	Miles et al., (2019)	Asymmetry Index	Dominant/Nondominant Involved/Uninvolved
	Redden et al., (2018)	Percentage Difference	Right/Left
$Index\ 10 = \frac{(A - B)}{(A + B)} \cdot 100$	Suchomel et al., (2016)	Symmetry Index	Stronger/Weaker
	Costa Silva et al., (2015)	Bilateral Asymmetry Index	Dominant/Nondominant
$Index\ 11 = \frac{\left[45 - arctan\left(\frac{B}{A}\right)\right]}{90} \cdot 100$	Maloney et al., (2016)	Symmetry Angle	Right/Left
	Redden et al., (2018)	Symmetry Angle	Right/Left
$Index\ 12 = \ln\left(\frac{B}{A}\right) \cdot 100$	Bourne et al., (2015)	Between-Limb Imbalance	Right/Left Involved/Uninvolved
	Opar et al., (2015)	Between-Limb Imbalance	Right/Left Involved/Uninvolved

A = uninvolved/uninjured/non-operative/non-surgical, dominant/preferred, right, stronger/better performing, or stance/support limb value
B = involved/injured/operative/reconstructed/surgical, non-dominant/non-preferred, left, weaker/lesser performing, or skill/kicking limb value
* indicates the study used multiple indices, so appears more than once in this table

Discussion

The aims of this systematic review were to assess the appropriateness of quantitative methods implemented to calculate and interpret strength asymmetry, to assess the evidence base for defining thresholds for abnormal asymmetry and to review normative levels of inter-limb strength asymmetry and its effects. This review summarises common practices for the study of inter-limb strength asymmetry and provides an overview of normative values and the effects of asymmetry as reported in the literature. This research highlights the importance of understanding the limitations of an approach when calculating asymmetry and interpreting scores across studies.

Asymmetry Indices

Various calculations have been documented in the literature to quantify inter-limb differences, many of which are referred to by multiple names and are used for different limb comparisons. Amongst the fifty-three articles included in this review, twelve distinct types of calculation were identified for five different limb comparisons (Table 3). Index-1, more commonly known as the Limb Symmetry Index, was the most used index (N = 20) and was applied across all five of the identified limb comparisons. Despite its widespread use, this index was identified by several other names, demonstrating inconsistency within the literature. This was also apparent for other more commonly used indices (Index-7 and -9). This potentially creates confusion when trying to interpret the published literature, especially when indices referred to by the same name produce inherently different scores. For example, in addition to Index-1, Index-9 (Menzel et al., 2013) and Index-4 (Almeida et al., 2019) were also referred to as the Limb Symmetry Index, despite fundamental differences in their arithmetic derivation. Furthermore, in some cases the naming of the index was inappropriate for the score produced, such as Index-10 which was referred to as the Symmetry Index (Suchomel et al., 2016), despite the calculation producing a score indicative of asymmetry rather than symmetry. Moreover, the Symmetry Index has been more generally described as the absolute difference between two sides divided by a reference value (Zifchock et al., 2008), where this value may be a single value or statistic of both sides. Thus, the Symmetry Index acts as an umbrella-term for a variety of calculations which produce a range of outcome scores. Therefore, careful consideration should be given when interpreting indices identified by the same name in the literature.

Index-1 requires the selection of a reference limb which is expected to be the stronger or better performing of the two, and the weaker limb is described as a percentage of the reference limb. Several other indices also provide either the contralateral limb or the difference between two limb values, as a measure of the reference limb. Despite widespread use of this type of index, selecting one limb as a reference may be problematic, particularly when the selection of a reference limb is arbitrary. When investigating injured groups or individuals following surgery, the reference limb choice is clearer and so the uninjured limb often serves as the reference value. However, increasing uncertainty is introduced when differentiating between dominant and nondominant limbs as although the dominant or uninjured limb is often stronger (Chmielewski et al., 2014; Hadzic et al., 2014; Dos'Santos et al., 2017a, 2018; Miles et al., 2019), this is not always the case (Fort-Vanmeerhaeghe et al., 2015, 2016; Fältström et al., 2017).

Table 4. Analysis of asymmetry indices for each identified limb comparison.

Index Calculation	Limb Comparison				
	Involved/ Uninvolved	Dominant/ Nondominant	Right/ Left	Stronger/ Weaker	Stance/Skill
$Index\ 1 = \frac{B}{A} \cdot 100$				✓	
$Index\ 2 = \frac{A}{B} \cdot 100$				✓	
$Index\ 3 = \left[1 - \left(\frac{B}{A}\right)\right] \cdot 100$				✓	
$Index\ 4 = 100 - \left[\left(\frac{B}{A}\right) \cdot 100\right]$				✓	
$Index\ 5 = \frac{100}{A} \cdot B \cdot -1 + 100$				✓	
$Index\ 6 = \frac{A}{B}$				✓	
$Index\ 7 = \frac{(A-B)}{A} \cdot 100$				✓	
$Index\ 8 = \frac{(B-A)}{A} \cdot 100$				✓	
$Index\ 9 = \frac{(A-B)}{Max(A,B)} \cdot 100$	✓	✓	✓	✓	✓
$Index\ 10 = \frac{(A-B)}{(A+B)} \cdot 100$	✓	✓	✓	✓	✓
$Index\ 11 = \frac{\left[45 - arctan\left(\frac{B}{A}\right)\right]}{90} \cdot 100$	✓	✓	✓	✓	✓
$Index\ 12 = \ln\left(\frac{B}{A}\right) \cdot 100$	✓	✓	✓	✓	✓

A = uninvolved, dominant, right, stronger, or stance/support limb value, and B = involved, nondominant, left, weaker, or skill/kicking limb value. Cells marked with a tick indicate that the calculation produces the same magnitude (ignoring direction) of asymmetry for scenario 2, when value A>B, as in scenario 3, when value A<B (i.e. the index works independent of which limb performs better). Blank cells indicate that the calculation produces different magnitudes (ignoring direction) of asymmetry for scenarios 2 and 3.

Table 5. Strength asymmetry thresholds used by the included articles (N = 53) and the evidence level of each threshold applied in the methodology of the study.

Article	Strength Asymmetry Threshold	Applied in methods? (Y/N)	Evidence Tier
Bourne et al., (2015)	Investigated asymmetries above and below 10%, 15% and 20%	Y	1
Dos'Santos et al., (2017a)	Threshold: mean + (0.2 SD of the mean) Above the threshold = abnormal Below the threshold = normal	Y	1
Dos'Santos et al., (2018)	Threshold: mean + (0.2 SD of the mean) Above the threshold = abnormal Below the threshold = normal	Y	1
Lockie et al., (2014)	Threshold: mean + (0.2 SD of the mean). Above the threshold = greater asymmetry group Below the threshold = lesser asymmetry group	Y	1

Y = Yes, N = No, n/a = not applicable, 1 = article provides the origin of the evidence for the threshold, 2 = article directly cites the origin of the evidence, 3 = article indirectly cites the origin of the evidence, 4 = article fails to provide or cite the origin of the evidence

Table 5. Continue…

Article	Strength Asymmetry Threshold	Applied in methods? (Y/N)	Evidence Tier
Opar et al., (2015)	Investigated asymmetries above and below 10%, 15% and 20%	Y	1
Holsgaard-Larsen et al., (2014)	Symmetry <85% and >115%=abnormal	Y	2
Fältström et al., (2017)	Symmetry <90% and >110% = abnormal	Y	3
Guney-Deniz et al., (2020)	Symmetry ≥90% = normal	Y	3
Menzel et al., (2013)	Asymmetry >15% = abnormal	Y	3
Abourezk et al., (2017)	Symmetry ≥90% = normal Symmetry <85% = abnormal	Y	4
Almeida et al., (2019)	Symmetry >10% = abnormal	Y	4
Ardern et al., (2015)	Presence of deficits on at least 2 of the following criteria: - Bilateral concentric hamstring peak torque ratio of 0.86 - Bilateral eccentric hamstring peak torque ratio of 0.86 - Concentric hamstring-quadriceps ratio of 0.47 - Mixed ratio of 0.80	Y	4
Batty et al., (2019)	Symmetry ≥90% = normal	Y	4
Clark &Mullally, (2019)	Asymmetry >10% = abnormal	Y	4
de Lira et al., (2017)	Asymmetry >15% = abnormal	Y	4
Hadzic et al., (2014)	Asymmetry >15% = abnormal	Y	4
Welling et al., (2019)	Symmetry >90% normal	Y	4
Zwolski et al., (2015)	Symmetry ≥90% = High quadriceps strength group Symmetry <90% = Low quadriceps strength group	Y	4
Chmielewski et al., (2014)	Symmetry ≥85-90% = normal	N	n/a
Costa Silva et al., (2015)	Asymmetry <15% = normal	N	n/a
Dai et al., (2019)	Asymmetry <10% = normal	N	n/a
Fort-Vanmeerhaeghe et al., (2015)	Asymmetry >10-15% = abnormal	N	n/a
Fort-Vanmeerhaeghe et al., (2016)	Asymmetry ≤10-15% = normal	N	n/a
Harput et al., (2018)	Symmetry ≥90% = normal	N	n/a
Lisee et al., (2019)	Symmetry ≥90% = normal	N	n/a
Lockie et al., (2012)	Asymmetry ≥15% = abnormal	N	n/a
Lockie et al., (2016)	Asymmetry >15% = abnormal	N	n/a
Miles et al., (2019)	Asymmetry <10-15% = normal	N	n/a
Xergia et al., (2013)	Symmetry ≥90% = normal	N	n/a
Zwolski et al., (2016)	Symmetry >90% = normal	N	n/a
Ageberg & Roos, (2016)	-	n/a	n/a
Benjanuvatra et al., (2013)	-	n/a	n/a
Bishop et al., (2019c)	-	n/a	n/a
Bishop et al., (2019d)	-	n/a	n/a
Bookbinder et al., (2020)	-	n/a	n/a
Carabello et al., (2010)	-	n/a	n/a
Coratella et al., (2018)	-	n/a	n/a
Hart et al., (2014)	-	n/a	n/a
Hiemstra et al., (2008)	-	n/a	n/a
Hubbard et al., (2007)	-	n/a	n/a
Hughes et al., (2019)	-	n/a	n/a
Kaminska et al., (2015)	-	n/a	n/a
Lloyd et al., (2020)	-	n/a	n/a
Lockie et al., (2013)	-	n/a	n/a
Madruga-Parera et al., (2019)	-	n/a	n/a
Madruga-Perera et al., (2020)	-	n/a	n/a
Maloney et al., (2017)	-	n/a	n/a
Peebles et al., (2019)	-	n/a	n/a
Redden et al., (2018)	-	n/a	n/a
Reid et al., (2007)	-	n/a	n/a
Riemann & Davies, (2019)	-	n/a	n/a
Suchomel et al., (2016)	-	n/a	n/a
Vanderstukken et al., (2019)	-	n/a	n/a

Y = Yes, N = No, n/a = not applicable, 1 = article provides the origin of the evidence for the threshold, 2 = article directly cites the origin of the evidence, 3 = article indirectly cites the origin of the evidence, 4 = article fails to provide or cite the origin of the evidence

Furthermore, irregular values may be produced if the reference limb fails to produce the larger values. Index analyses using hypothetical scores demonstrated this, as Index-1 failed to produce the same magnitude of asymmetry (ignoring direction) for scenario 3, when the contralateral limb was stronger, as in scenario 2, when the reference limb was stronger (Table 4). Index-2, -3, -4, -5, -6, -7, and -8 are similarly limited due to the need to select a reference limb. Therefore, indices which require the selection of a reference limb may be inappropriate for describing inter-limb imbalances and, at the very least, should be applied and interpreted with caution. It is also important to consider similarities and differences in the numerical derivation of each index which may be reflected in the score produced (Supplementary Material Table S1). Firstly, Index-1 and -2 both compute symmetry as a linear ratio between two limbs, where one limb is expressed as a percentage of the other. Index-3, -4 and -5 compute the score in a similar way, but convert a score of symmetry to a score of asymmetry by subtracting the score from 1 before multiplying it by 100% (Index-3), by subtracting the percentage score from 100 (Index-4), or by multiplying the score by -1 and then adding 100 (Index-5). More simply, Index-6 used by Ardern et al., (2015) and Riemann and Davies, (2019) provides the reference limb as a ratio of the contralateral limb, whereas Index-7 and -8 divide the absolute difference between two limb values by a reference limb. Thus, researchers and practitioners are encouraged to ensure appropriate understanding of an asymmetry calculation before implementation and interpretation of scores.

Although eight of the identified indices were unable to consistently produce the same magnitude of asymmetry across limb comparisons irrespective of which limb was stronger; they were able to produce the same magnitude of asymmetry when using the stronger/weaker limb comparison (Table 4, Supplementary Material Table S1). This indicates the stronger/weaker limb comparison can be used when selecting a reference limb without the associated limitations, as the asymmetry score is consistently normalised to the larger value produced by the two limbs. However, issues may arise for studies which assess reliability if the stronger limb fails to remain stronger in repeated measures, resulting in a lack of clarity in the results. This is also an important consideration for longitudinal studies. An additional limitation of the stronger/weaker limb comparison is that it fails to identify the direction of asymmetry, such that the context of asymmetry may be lost. Nevertheless, these limitations may be overcome by utilising a logical 'IF' function to identify the direction of asymmetry without compromising the magnitude of the score (Bishop et al., 2019c, 2019d). Using this method, the asymmetry score can be converted to a negative value when a specified limb produces the higher value. It may therefore be argued that any of the twelve indices identified in this review may be selected when using the stronger/weaker limb comparison however, this limits the versatility of asymmetry computation. It should also be noted that many of these indices rely on the use of a reference value, which has been reported to be problematic for resolution in some cases, when the difference between two limb values is large compared to the absolute values (Herzog et al., 1989).

Of the twelve identified calculations used to assess asymmetry, only four (Index-9, -10, -11 and -12) worked independent of which limb performed better (Table 4, Supplementary Material Table S1). These indices independently produce the same magnitude of asymmetry for scenario 2 and 3, which is important when the reference limb is not the stronger limb or when it is challenging to discern between sides. However, each of the four indices produce different scores which poses the question; which one to choose? Recent evidence suggests that the index should reflect the nature of the task therefore, Index-9 has been recommended when assessing asymmetry from unilateral tests, as it involves normalisation of the absolute difference to the stronger limb value (Bishop et al., 2018a). This index avoids arbitrary selection of a reference limb and can be used in conjunction with an 'IF' function to identify the direction of asymmetry. However, this approach requires normalisation to a reference value which can lead to artificial inflation of asymmetry scores (Herzog et al., 1989). Alternatively, when implementing bilateral tasks, it has been argued that asymmetry should be computed as the absolute difference relative to the summed limb values (Index-10), in order to account for the contribution from both limbs (Bishop et al., 2018a). Despite this, Index-10 has also been used for single leg isokinetic assessments (Costa Silva et al., 2015) yet, its use for unilateral tasks would not be recommended as it requires the use of data from separate trials, which is subject to variability. Moreover, Index-10 is more likely to deflate asymmetry scores, as it divides the absolute difference by the sum of both limb values, inhibiting resolution when making comparisons between test types and other indices (Supplementary Material Table S1). Thus, test-specific indices may not be appropriate for the calculation of inter-limb asymmetry, especially when a combination of both unilateral and bilateral tasks is implemented.

Alternatively, Index-11 does not rely on the selection of a reference limb or value. Also known as the Symmetry Angle (Maloney et al., 2017; Redden et al., 2018), the index has been proposed as a robust alternative, which defines an angle formed when a right-side value is plotted against a left-side value (Zifchock et al., 2008). Symmetry is achieved when two identical values create a 45° angle in relation to the x-axis. Index-12 similarly avoids the limitations associated with normalisation to a reference limb or value. Referred to as the Bilateral Limb Imbalance in the included articles (Opar et al., 2015; Bourne et al., 2015), the index is based upon the method proposed by Impellizzeri et al., (2008) which involves log-transformation of the ratio between two limbs. The log-transformed ratio can then be converted to a percentage by multiplying by 100. However, it was concluded by the authors that the bilateral ratios, as used to produce the index, have poor relative reliability and are more suitable for detecting large changes (Impellizzeri et al., 2008). Therefore, imbalance ratios may be useful when assessing inter-limb differences in injured groups but not so much in healthy individuals. It should also be noted that unlike the other indices identified by this review, Index-11 and -12 produce non-linear outputs, such that one-unit changes in asymmetry are magnitude-specific. As a result, identical magnitudes of changes to asymmetry scores are unlikely to be associated with identical changes of magnitude of the raw input values. This may make this index difficult to interpret. It may also be argued that both Index-11 and -12 are inappropriate for the calculation of asymmetry as they fail to recognise the nature of the task (Bishop et al., 2018a) however, as previously described, test-specific indices have other limitations. A paucity in the literature using both indices necessitates that further investigation be undertaken to determine their suitability as compared to other commonly used indices, considering both their precision and resolution.

To summarise, Index-9, -10, -11 and -12 are recommended over the other indices identified by this review. This is based on their ability to express the magnitude and direction of asymmetry, thereby overcoming the limitations associated with selecting a reference limb. However, they fundamentally differ in computation, which is reflected in the magnitude of asymmetry and this limits their relatability. Each index is also associated with other limitations as described in this review, which poses challenges when attempting to select an optimal approach. Therefore, in lieu of the literature adopting a standard unified index, it is recommended that investigators publish the raw data associated with their research, such that equivalent asymmetry scores can be calculated by the reader for the purpose of comparison using their personally preferred index. Researchers and practitioners are also encouraged to fully understand and interrogate their index of choice to ensure appropriate interpretation and comparison of asymmetry scores.

Asymmetry Thresholds

Thirty of the fifty-three articles in this review referred to an asymmetry threshold to indicate the point at which inter-limb difference in strength might be considered abnormal (Table 5). Amongst these articles, a threshold of 10-15% was most common, with a total of 27 articles referring to a threshold between these magnitudes. In support of this threshold, asymmetries larger than 10-15% have been associated with increased injury risk (Croisier et al., 2008; Fousekis et al., 2011; Brumitt et al., 2013) and reduced performance (Bishop et al., 2021b). Such evidence may explain the widespread use of a 10-15% threshold. However, no present consensus exists regarding the magnitude of asymmetry amongst specific groups and its effects. Recent evidence even indicates that athletes with inter-limb jump height asymmetries as low as 5% are susceptible to deficits in jumping, sprinting, and change of direction performance (Bishop et al., 2019a). Disparities in the literature may be partly explained by the use of various asymmetry indices that have the potential to produce largely different outcomes, as discussed above. Findings also highlight the sensitivity of asymmetry to methodology and sample characteristics, such that no single asymmetry threshold can be identified across the task, variable or population that is assessed (Read et al., 2021). In addition, recent reports indicate asymmetries rarely favour the same limb across tests (Bishop et al., 2019c, 2021a; Madruga-Parera et al., 2020). This suggests that an individualised approach to asymmetry assessment, considering the task, variables and population characteristics, may be necessary to avoid inappropriate use of generalised thresholds to identify abnormal asymmetry. Furthermore, thresholds should be supported by credible evidence if they are to be able to appropriately distinguish normal from abnormal asymmetry.

To overcome the limitations of using an arbitrary threshold, some investigators have determined group differences in strength asymmetry using the mean + 0.2 standard deviations (Lockie et al., 2014; Dos'Santos et al., 2017a, 2018). It has been suggested that for elite team sport athletes multiplying the between-subjects standard deviation by 0.2 produces the smallest worthwhile change (Hopkins, 2004). This is based on Cohen's *d* effect size, whereby 0.2 corresponds to a small, but not trivial effect (Sullivan and Feinn, 2012). Using this calculation, participants above and below the threshold were classified accordingly, based on small but meaningful differences in asymmetry. This provides a method for interpreting inter-limb differences without reliance on pre-determined thresholds that may not be suitable for the sample under investigation. When defining groups using 0.2 standard deviations of the mean, as done by several articles in this review (Lockie et al., 2014; Dos'Santos et al., 2017a, 2018), the threshold between groups lies on the 58th centile of the entire sample. Alternative calculations have also been proposed, such as the mean ± 1.0 standard deviations (Graham-Smith et al., 2016) which shifts the threshold to the 84th centile. Therefore, research is warranted to determine an appropriate magnitude for the smallest worthwhile change to identify the presence of meaningful differences in asymmetry between groups. However, in the absence of objective evidence linking cause and effect, any threshold, including those based on Cohen's *d* effect size, becomes arbitrary, simply describing the proportion of the population expected to fall within a group, rather than describing risk. Thus, when using such methods, researchers are encouraged to explore the effects of asymmetry on injury and performance within specific groups.

It is also important to consider that strength tests are likely to incur error due to noise introduced by factors such as nutrition, environmental conditions, testing equipment and athlete preparation. Therefore, careful measurement protocols should be implemented to limit the noise associated with any given test so that it does not exceed the magnitude of the smallest worthwhile change. Exell et al., (2012) proposed that for inter-limb asymmetry to be considered meaningful, it must be larger than the intra-limb variability, which can be calculated using the coefficient of variation (Dos'Santos et al., 2017a, 2018; Bishop et al., 2019d; 2019c; Vanderstukken et al., 2019; Madruga-Parera et al., 2020). Thus, only participants who display inter-limb differences greater than the sample-specific threshold and their individual variability may be interpreted as having meaningful asymmetry within the context of the sample, metric, and test. It should be noted that this approach does not lend itself to the idea of, or investigation of, 'generic' asymmetry, thereby inhibiting comparison of individuals. Yet, such an individualised approach to assessment of asymmetry is likely necessary in the future.

Retrospective analysis of the references revealed six of the eighteen articles that applied a threshold to original research had provided appropriate evidence, where the origin of the threshold was evidenced within the included article (Tier 1) or within its direct citations (Tier 2) (Figure 4). A study by Barber et al. (1990) was the oldest article to provide the origin of the evidence for a given threshold and appeared once in direct citations and twice more in indirect citations. In this study, a series of functional tests were implemented and thresholds of 80%, 85% and 90% were applied to assess normative symmetry in healthy controls. Of the three criteria investigated, 85% symmetry was identified in over 90% of the healthy controls under investigation during 2 of 3 functional tests, thus asymmetry larger than 15% was considered abnormal. Large deficits were observed between healthy and ACL-deficient knees during the three one-legged tests, such that only 50-58% achieved 85% symmetry and were classed as 'symmetrical'. Statistically significant relationships were also observed among abnormal scores (>15%) on the one-legged hop tests and self-assessed limitations for pivoting, cutting and twisting, quadriceps weakness and patellofemoral compression pain. This indicates functional limitations in individuals assessed by functional hop tests with asymmetries larger than 15%. As such, the authors concluded that 85% symmetry was sufficient to identify abnormal symmetry based on normative data in knee-healthy controls and functional outcomes in patients and controls. More recent evidence supports the use of this threshold, reporting increased risk of injury with asymmetries greater than or equal to 15% (Bourne et al., 2015). However, contradictory findings using the same index (Index-12) demonstrated no increase in hamstring strain injury risk for asymmetries of 10%, 15% or 20% (Opar et al., 2015). Evidence demonstrating the individual nature of asymmetry further undermines the use of arbitrary thresholds to determine abnormal asymmetry (Dos'Santos et al., 2017b; Bishop et al., 2019b; 2019c; Read et al., 2021). Therefore, evidence for the justification of an asymmetry threshold of 15% remains unclear.

Retrospective analysis of the articles that applied a threshold in the methodology of their study, revealed 67% provided Tier 3 or 4 evidence, as they failed to provide or directly cite the origin of the evidence (Figure 4). Although Tier 3 articles provided the origin of the evidence in the indirect citations, Tier 4 articles failed to signpost the reader to appropriate evidence at all. Instead, Tier 4 articles often provided supporting references that failed to apply the threshold to original research (e.g. in a review or clinical commentary), could not be accessed in English and Full-Text, or failed to clearly evidence the threshold applied in the included article. For example, one article (Welling et al., 2019) applied a threshold of 90% symmetry based upon a consensus agreement achieved through survey responses (Lynch et al., 2015) rather than original research, and was classified as Tier 4 evidence as a result. Lower Tiered evidence provides limited traceability and transparency and as such, Tier 3 and 4 articles were deemed weak evidence on which to base a given threshold. These observations suggest that some research studies are underpinned by poor referencing, and in some cases, the threshold in use may lack a robust scientific foundation.

In summary, retrospective assessment of asymmetry thresholds from this review demonstrates the need for more appropriate referencing within the scientific literature, where direct citations signpost the reader to the origin of the evidence. Furthermore, it should be noted that the quality of each evidence source was not interrogated beyond the application of asymmetry thresholds. Therefore, the quality of the research underpinning each threshold would require further investigation before application of pre-determined thresholds. In addition to the limitations of comparing asymmetry scores from different indices, the lack of appropriate referencing suggests that the use of specific, pre-determined asymmetry thresholds may be flawed. This is particularly important for the use of thresholds between 10-15%, as they are often applied within asymmetry literature, yet they may lack the solid evidence-base necessary to rationalise their application to identify abnormal asymmetry. A lack of consensus within the literature further suggests that pre-determined thresholds should be avoided. Instead, an individualised approach to the interpretation of asymmetry should be adopted, which may be based on sample-specific thresholds and individual variability.

Normative asymmetry and subsequent effects: Athletes

Athletes were well researched within the included articles (N = 33), but the definition of 'athlete' varied largely between articles. Therefore, participants that were described as 'athletes' or 'players' were considered as athletes in this review, which resulted in the inclusion of individuals participating at various levels of activity and competition. As such, strength asymmetry in athletes as reported in the literature, is likely to reflect diversity in the athletic population. Bilateral force asymmetries generally less than 10% have been reported amongst individual and team-sport collegiate athletes during a series of tests, including a countermovement jump and push up test (Dai et al., 2019). However, normative jump height asymmetries of 10-15% have been reported in male and female basketball and volleyball players (Fort-Vanmeerhaeghe et al., 2016). Furthermore, asymmetries up to 13% and 15% in isometric strength and hopping tasks have been reported amongst National Collegiate Athletic Association athletes without performance deficits (Dos'Santos et al., 2017a, 2018), undermining the commonly used threshold of 10%. Individual and group mean peak torque asymmetries in excess of 15% have also been reported amongst team sport athletes (Lockie et al., 2013; de Lira et al., 2017). This suggests that the presence of asymmetries of larger than 15% may not be uncommon. When interpreting these findings, the effect of index selection should also be considered as Dai et al., (2019) utilised Index-9, whereas Index-7 was used for the other investigations (Lockie et al., 2013; Fort-Vanmeerhaeghe et al., 2016; Dos'Santos et al., 2017a, 2018; de Lira et al., 2017). Although both indices produce the same magnitude of asymmetry for scenario 1, Index-7 produces inappropriate scores if the reference limb fails to perform better which would have implications for study comparisons (Supplementary Material Table S1).

When interpreting normative asymmetry in athletes, it is also important to consider that sport and activity level may affect the limb imbalance observed. Group differences have been observed in absolute values for isokinetic torque (de Lira et al., 2017), jumping and push-up force (Dai et al., 2019) between athletes from different sports. However, no sport effect for strength asymmetry was observed (de Lira et al., 2017; Dai et al., 2019). Others have similarly reported no significant difference between activity level for symmetry in isokinetic and isometric peak torque, average power and hop distance (Lisee et al., 2019). Therefore, asymmetries appear less performance-level and sport-specific, and more individualistic. However, the general consensus is that healthy athletes from recreational to elite level present inter-limb differences in strength of some magnitude. Therefore, perfect symmetry between limbs may not be an appropriate goal, nor an appropriate threshold against which to judge asymmetry. Additional sample characteristics should also be considered, as asymmetries in jumping and isokinetic torque reportedly vary as a function of maturation status (Madruga-Parera et al., 2019) and team-sport playing position (Costa Silva et al., 2015). Thus, sample characteristics should be considered when prescribing training interventions based on asymmetry assessments.

The presence of asymmetry in athletes indicates that it may not always cause dysfunction, however researchers have reported detriments to performance resulting from asymmetry. Hart et al., (2014) assessed the effect of isometric strength and lean mass asymmetry on kicking accuracy in sub-elite Australian footballers. Inaccurate kickers had significant asymmetry in lean mass, which translated to significant imbalance due to strength deficits in the support leg. However, the wider literature points to variability in the direction of asymmetry between the skill and support limb, as strength adaptations in favour of the support limb have been documented (Bishop et al., 2020). It is often recommended that athletes work to achieve greater symmetry to improve technical proficiency and performance outcomes. In support of this, detriments to speed and performance in change of direction tasks have been associated with strength asymmetry, such that athletes with larger asymmetries in isokinetic peak torque and some jump tests, performed worse (Bishop et al., 2019d; Coratella et al., 2018; Lockie et al., 2016; Madruga-Parera et al., 2020). Not only has strength asymmetry been associated with detriments to performance, but findings also indicate improved function amongst injured athletes with reduced post-surgery inter-limb asymmetry in isometric peak torque (Zwolski et al., 2015). Similar findings have also been reported in non-athletes with a history of ACLR (Harput et al., 2018; Bookbinder et al., 2020) however, this association does not demonstrate whether reduced asymmetry is the cause or effect of functional improvements.

Based on the association between strength asymmetry and reduced performance, it is often assumed that action should be taken to minimise asymmetry wherever possible. However, this notion is undermined by reports of asymmetries up to 13% in isometric strength and up to 15% in functional performance amongst collegiate athletes without detriment to change of direction speed (Dos'Santos et al., 2018; Dos'Santos et al., 2017). Furthermore, the direction of dominance was not always consistent between isometric strength or hopping and speed tests. Additionally, findings from Lockie et al., (2012) demonstrate better multi-directional speed performance in athletes with larger concentric torque and work differences between limbs. However, it is important to consider that the authors may have sampled a largely symmetrical group of athletes, which might lead to generally better speed performance. Furthermore, reports indicate a task specific nature of asymmetry, such that correlations have been observed for some tasks but not others (Bishop et al., 2019d). Therefore, although some studies may demonstrate a lack of association between asymmetry and performance, and even beneficial associations in some cases, it should be considered that detrimental relationships may exist when the same sample is assessed using different methods.

Investigation into the effects of strength asymmetry on injury risk in athletes has become a well-researched topic as it is advocated that better competitive performance comes from minimising the time an athlete spends away from training through injury. One study assessed eccentric hamstring strength in 194 rugby players using the Nordic hamstring exercise and reported that between limb force asymmetries of ≥15% and ≥20% increased the risk of prospective hamstring strain injury by 2.4-fold and 3.4-fold, respectively (Bourne et al., 2015). However, a similar study (Opar et al., 2015) observed contradictory findings, reporting no statistically significant increase in relative risk of future hamstring strain injuries in professional Australian rules footballer's with Nordic strength imbalances of 10%, 15% or 20%. An explanation for this is a difference between the activity level of athletes, as one study recruited athletes from elite, sub-elite and U19 premier-grade teams (Bourne et al., 2015) whereas, the other recruited elite athletes only (Opar et al., 2015). Furthermore, the first study took measurements during pre-season only (Bourne et al., 2015), whereas Opar et al., (2015) assessed asymmetry at three time-points throughout the season. Hence, differences in findings between studies may be partly explained by changes in strength due to physiological adaptations to muscle architecture over-time in response to training (Nimphius et al., 2012). Although training for single-limb dominant sports may be expected to increase asymmetry between limbs due to increased exposure to one-sided tasks, asymmetry has been found to reduce over the course of a season in a sample of male youth soccer players (Lloyd et al., 2020). Therefore, lack of consensus in the literature might be associated with differences in the definition of an athletic population or the timepoint of testing in relation to the season.

Normative asymmetry and subsequent effects: Females

Females were also well researched by the studies examined in this review (N = 25) however, some studies presented male and female data combined, which poses challenges when attempting to understand asymmetry in females independent of their male counterparts. Several studies also failed to provide the sex of their participants, which has implications when attempting to understand the effect of sex on asymmetry. Furthermore, differences in sample characteristics and methodological practices between studies pose limitations when attempting to compare results to male-only studies. Only ten of the fifty-three included articles report strength asymmetry in female-only groups, suggesting that research investigating females separately from males is warranted.

One study investigated male and female National Collegiate Athletic Association Division I athletes and non-athletes across various sports and assessed the effect of sex on limb symmetry (Lisee et al., 2019). As expected, males demonstrated greater peak torque and power and outperformed their female counterparts during the single and triple hop for distance. However, no sex differences were observed in limb symmetry scores, with scores close to 95% limb symmetry on all hop-for-distance tests for both groups (Lisee et al., 2019). Close to perfect symmetry has also been reported during the single-leg hop for distance in healthy female athletes performing in both high- (Zwolski et al., 2016) and low-level sport (Fältström et al., 2017). However, Fort-Vanmeerhaeghe et al., (2016) found larger inter-limb asymmetries in females than males during a vertical countermovement jump. Similarly large magnitudes of jump height asymmetry have been reported in physically active (19.3%), competitive (22.2 %) and elite female athletes (14.1%) (Benjanuvatra et al., 2013; Bishop et al., 2019d; Fort-Vanmeerhaeghe et al., 2015) which may indicate that the vertical countermovement jump has greater sensitivity to detect asymmetry between limbs. In support of this, Clark and Mullally, (2019) reported large individual asymmetries in female netball players during a unilateral vertical jump, such that over half of the participants were identified as having clinically significant asymmetry between limbs (>10%), which was expected to increase risk of injury. This was in comparison to less than 9% of participants classified as asymmetrical for the triple hop and single leg hop for distance. Therefore, disparities in the literature regarding sex-differences are likely to reflect the task-specific nature of asymmetry. Anthropometric characteristics may also need to be considered when interpreting asymmetry between sexes, as non-normalised scores from a unilateral seated shot-put test were found to reflect differences in body size (Chmielewski et al., 2014).

When females were included in investigations, their data were rarely separated from the male data which makes it difficult to understand asymmetry in the female population. Nevertheless, findings from combined-sex data suggests the presence of inter-limb strength deficits in both males and females who are who are injured (Hubbard et al., 2007) or following surgery (Hiemstra et al., 2008; Batty et al., 2019; Bookbinder et al., 2020; Guney-Deniz et al., 2020), and these deficits are larger than for healthy controls (Hubbard et al., 2007; Bookbinder et al., 2020; Guney-Deniz et al., 2020). However, asymmetries following ACLR may be reduced over time through rehabilitation and functional knee bracing (Peebles et al., 2019). Furthermore, reduction in inter-limb asymmetry may be necessary to enhance performance during walking and jogging (Abourezk et al., 2017), and to improve knee function (Zwolski et al., 2015) and confidence post-surgery (Ageberg and Roos, 2016).

Normative asymmetry and subsequent effects: Injured/post-surgery

Twenty-three of the included articles recruited individuals who were injured or post-surgery. The literature generally indicates that injured individuals and those post-surgery experience greater between-limb strength deficits than uninjured controls. One study reported greater isokinetic knee extension torque deficits at speeds of 120°/sec, 180°/sec and 300°/sec, as well as greater hop asymmetry for individuals following ACLR compared to controls (Xergia et al., 2013). When averaged across speeds and hop tests, ACLR patients failed to reach the recommended asymmetry of less than 10-15% asymmetry (Index-1) in isokinetic strength (76.9%) and hop distance (82.4%), compared to controls (98.2% and 100.8%, respectively). Similarly, ACLR patients in a study by Holsgaard-Larsen et al., (2014) averaged 77.4% symmetry (Index-1) in involved versus uninvolved isometric hamstring peak torque. However, the task-specific nature of asymmetry is demonstrated by this research, as patients reached the recommended guidelines during the single-leg hop for distance, achieving 92.9%. Therefore, a battery of tests may be necessary to detect functionally relevant strength asymmetries, to overcome the limitations associated with task sensitivity.

Despite reports of patients achieving the recommended asymmetry of less than 10-15%, statistical significance has been found between the ACLR and control groups (Holsgaard-Larsen et al., 2014). This suggests that even when the 10-15% threshold is achieved post-surgery; individual's still experience strength deficits compared to their healthy counterparts. Furthermore, research investigating the magnitude of asymmetry immediately following exercise demonstrates that patients following ACLR experienced improved limb symmetry in the single-leg hop for distance, such that scores improved from 4% less than controls pre-exercise, to 1.5% less than controls post-exercise (Bookbinder et al., 2020). This indicates differences in fatiguability between post-surgery and healthy groups, which may be the result of altered muscle architecture after ACLR (Noehren et al., 2016). Significant group differences have also been reported between controls and participants with chronic ankle instability for asymmetries in isometric hip abduction force, ankle eversion average power and plantarflexion average power (Hubbard et al., 2007). However, no group differences were observed for any other ankle or hip strength and power outcomes, which indicates that asymmetry should also be interpreted in relation to the outcome variable that is assessed, as indicated previously (Dos'Santos et al., 2017b; Bishop et al., 2019c; b; Read et al., 2021). Nevertheless, absolute values should be examined in addition to symmetry scores, as they may reflect effects on asymmetry that would be otherwise overlooked (Reid et al., 2007)

In addition to group differences between injured and control groups, differences have also been identified between injury types. For example, in one study non-athletes following combined anterior and posterior cruciate ligament injury demonstrated less knee extension torque and work symmetry between limbs than those with an isolated injury to the anterior cruciate ligament (Kaminska et al., 2015). Group differences have also been identified in response to treatment type and rehabilitation. Improved limb symmetry in hamstrings and quadriceps peak torque was observed in soccer players from 4- to 10-months following ACLR and completion of a strength training protocol (Welling et al., 2019). At 10 months post-surgery, 65.8% of patients achieved limb symmetry greater than 90% for quadriceps strength and 76.3% for hamstring strength. Improvements in knee function were also observed at each time point post-surgery, demonstrating rehabilitation of limb symmetry to pre-injury levels when strength training is implemented. However, at 7- and 10-months following ACLR, the authors observed significantly greater quadriceps strength symmetry in soccer players treated with a hamstring tendon graft, compared to those treated with a bone-patellar tendon graft (Welling et al., 2019). In another study, patients treated with a bone-patellar tendon autograft similarly demonstrated greater symmetry in quadriceps peak torque at 5 to 8 months post-surgery compared to patients treated with a quadriceps tendon autograft (Hughes et al., 2019). This resulted in more patients with a bone-patellar bone autograft meeting criteria for return to running and return to play. These findings confirm the potential effect of surgical intervention type on rehabilitation of strength asymmetry following surgery, as previously reported (Machado et al., 2018; Welling et al., 2018).

Normative asymmetry and subsequent effects: Older adults

Individuals over the age of 45 years were rarely investigated in the included articles (N = 1) which indicates a paucity of research on older individuals within the asymmetry literature. The article in question reported similar relative asymmetry in 1-Repetion Maximum for healthy middle-aged adults (40-55yrs), healthy older adults (70-85yrs) and older mobility-limited adults (70-85yrs), however the older mobility-limited group had significantly larger asymmetries in power (Carabello et al., 2010). They also consistently displayed asymmetries larger than the frequently cited 15% threshold and presented larger group standard deviations when compared to the healthy groups who demonstrated asymmetry magnitudes similar to those of young non-athletes for similar tasks and metrics (Lisee et al., 2019). However, it should also be considered that Carabello et al., (2010) quantified asymmetry using Index-8, which is prone to inflation of scores when the reference limb fails to produce the larger value (Supplementary Material Table S1). Nevertheless, findings indicate that strength asymmetry increases with age, which may be explained by a decline in muscle mass and quality (Goodpaster et al., 2006). Although the data indicates that older adults with mobility limitations have larger asymmetries in strength, it is unclear whether mobility limitations are the product of asymmetry or whether asymmetry is simply exacerbated by existing mobility limitations. Therefore, further research is warranted in adults over the age of 45 years to better understand the effect of age on asymmetry.

Limitations

There are some limitations to this review. Firstly, the search strategy limited results to articles available in English which may introduce language bias. Similarly, articles were required to be readily available in Full-Text which may have led to the exclusion of otherwise relevant studies. The use of filters as part of the search process means some citations may have been excluded if the indexing process of the relevant database was incomplete. Although article quality assessment is important to reduce the risk of bias and ensure the quality of a review (Shamseer et al., 2015), there is a lack of consensus in the literature regarding selection of an appropriate tool that can be used across study designs as required by this review. Therefore, a modified article quality tool originally designed for the assessment of non-randomised studies (Peters et al., 2010) was used in this review. Thus, it should be noted that quality scores generated in this review and by other studies in the literature may not be comparable to scores generated by alternative methods. The use of the article quality tool in this review demonstrates poor quality amongst many articles within the Sport and Exercise Science field. In particular, articles within this area failed to utilise *a priori* sample size calculations to justify their samples which may introduce sample size bias. It is recommended that future studies justify their sample size prior to investigation. In scenarios where this is not feasible, the authors should be able to appropriately justify the sample size and identify it as a limitation where relevant. Additionally, evaluation of the five article quality items selected based on their importance to this review, demonstrated weak quality of reporting for study protocol and main findings in this area of research. Improper protocol reporting poses challenges when attempting to replicate research, which draws into question whether results are valid and reliable when they cannot be fairly interrogated by the scientific community. To be included in this review, articles were required to report their results as the mean, standard deviation and *P* value where appropriate, to ensure fair comparison between studies. Therefore, it is possible that some otherwise high-quality articles that utilised alternative statistical reporting methods were excluded.

Conclusion

In conclusion, this review demonstrates disparate practice with regards to the quantification and interpretation of inter-limb strength asymmetry using threshold boundaries. Index-9, -10, -11 and -12 were the only indices able to overcome the limitations associated with selection of a reference limb or value. However, other challenges should be considered when calculating inter-limb asymmetry by any of these methods. Further investigation is also necessary to determine whether they are capable of achieving sufficient precision and resolution when computing asymmetry across tasks and metrics. The use of pre-determined, arbitrary thresholds to determine what is “normal” should be avoided, especially as commonly used thresholds, such as between 10-15% are not robustly supported by the literature. Such methodological limitations are likely to contribute to the lack of consensus regarding the magnitude of inter-limb differences in strength and the subsequent implications for injury and performance. Therefore, practitioners should interpret asymmetries in strength with caution due to inherent limitations associated with methodlogical practices, and the interchangeable use of various indices in the literature. Going forward, an individualised approach to asymmetry assessment may be necessary, which considers the use of sample-specific thresholds and individual variability. It is also vital that various participant groups are investigated, including older adults, females, and individuals from different sports.

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References

Abourezk, M.N., Ithurburn, M.P., McNally, M.P., Thoma, L.M., Briggs, M.S., Hewett, T.E., et al. (2017) Hamstring Strength Asymmetry at 3 Years After Anterior Cruciate Ligament Reconstruction Alters Knee Mechanics During Gait and Jogging. *The American Journal of Sports Medicine* **45**, 97–105. http://doi.org/:10.1177/0363546516664705.

Ageberg, E. and Roos, E.M. (2016) The Association Between Knee Confidence and Muscle Power, Hop Performance, and Postural Orientation in People With Anterior Cruciate Ligament Injury. *The Journal of Orthopaedic and Sports Physical Therapy* **46**, 477–482. http://doi.org/:10.2519/jospt.2016.6374.

Almeida, G.P.L.L., Albano, T.R. and Melo, A.K.P. (2019) Hand-held dynamometer identifies asymmetries in torque of the quadriceps muscle after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy* **27**, 2494–2501. http://doi.org/:10.1007/s00167-018-5245-3.

Ardern, C.L., Pizzari, T., Wollin, M.R. and Webster, K.E. (2015) Hamstrings strength imbalance in professional football (soccer) players in Australia. *Journal of Strength and Conditioning Research* **29**, 997–1002. http://doi.org/:10.1519/JSC.0000000000000747.

Bailey, C.A., Sato, K., Burnett, A. and Stone, M.H. (2015) Force-Production Asymmetry in Male and Female Athletes of Differing Strength Levels. *International Journal of Sports Physiology and Performance* **10**, 504–508. http://doi.org/:10.1123/ijspp.2014-0379.

Baltzopoulos, P.B., King, M., Gleeson, N., De, M. and Croix, S. (2012) *The BASES Expert Statement on Measurement of Muscle Strength with Isokinetic Dynamometry*.

Barber, S.D., Noyes, F., Mangine, R.E. and DeMaio, M. (1992) Rehabilitation after ACL reconstruction: Function Testing. *Orthopedics* **15**, 969–974. Available from https://www.researchgate.net/publication/21646496

Barber, S.D., Noyes, F.R., Mangine, R.E., McCloskey, J.W. and Hartman, W. (1990) Quantitative Assessment of Functional Limitations in Normal and Anterior Cruciate Ligament-Deficient Knees. *Clinical Orthopaedics and Related Research* **255**, 204–214. http://doi.org/:10.1097/00003086-199006000-00028.

Batty, L.M., Feller, J.A., Hartwig, T., Devitt, B.M. and Webster, K.E. (2019) Single-Leg Squat Performance and Its Relationship to Extensor Mechanism Strength After Anterior Cruciate Ligament Reconstruction. *The American Journal of Sports Medicine* **47**, 3423–3428. http://doi.org/:10.1177/0363546519878432.

Bell, D.R., Sanfilippo, J.L., Binkley, N. and Heiderscheit, B.C. (2014) Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. *Journal of Strength and Conditioning Research* **28**, 884–891. http://doi.org/:10.1519/JSC.0000000000000367.

Benjanuvatra, N., Lay, B.S., Alderson, J.A. and Blanksby, B.A. (2013) Comparison of ground reaction force asymmetry in one- and two-legged countermovement jumps. *Journal of Strength and Conditioning Research* **27**, 2700–2707. http://doi.org/:10.1519/JSC.0b013e318280d28e.

Bishop, C. (2021) Interlimb Asymmetries: Are Thresholds a Usable Concept? *Strength and Conditioning Journal* **43**, 32–36. http://doi.org/:10.1519/SSC.0000000000000554.

Bishop, C., Brashill, C., Abbott, W., Read, P., Lake, J.P. and Turner, A. (2019a) Jumping Asymmetries are Associated with Speed, Change of Direction Speed, and Jump Performance in Elite Academy Soccer Players. *Journal of Strength and Conditioning Research,* in press. Available from http://eprints.chi.ac.uk/id/eprint/4293/

Bishop, C., Lake, J., Loturco, I., Papadopoulos, K., Turner, A. and Read, P. (2021a) Interlimb asymmetries: The need for an individual approach to data analysis. *Journal of Strength and Conditioning Research* **35**, 695–701. http://doi.org/:10.1519/JSC.0000000000002729.

Bishop, C., Pereira, L.A., Reis, V.P., Read, P., Turner, A.N. and Loturco, I. (2020) Comparing the magnitude and direction of asymmetry during the squat, countermovement and drop jump tests in elite youth female soccer players. *Journal of Sports Sciences* **38**, 1296–1303. http://doi.org/:10.1080/02640414.2019.1649525.

Bishop, C., Read, P., Brazier, J., Jarvis, P., Chavda, S., Bromley, T., et al. (2019b) Effects of Interlimb Asymmetries on Acceleration and Change of Direction Speed: A Between-Sport Comparison of Professional Soccer and Cricket Athletes. *Journal of Strength and Conditioning Research*, in press. Available from https://uhra.herts.ac.uk/bitstream/handle/2299/21810/Effects_of_Inter_limb_Asymmetries.pdf?sequence=1&isAllowed=y

Bishop, C., Read, P., Chavda, S., Jarvis, P. and Turner, A. (2019c) Using Unilateral Strength, Power and Reactive Strength Tests to Detect the Magnitude and Direction of Asymmetry: A Test-Retest Design. *Sports* **7**, 58. http://doi.org/:10.3390/sports7030058.

Bishop, C., Read, P., Chavda, S. and Turner, A. (2016) Asymmetries of the Lower Limb: The Calculation Conundrum in Strength Training and Conditioning. *Strength and Conditioning Journal* **38**, 27–32. http://doi.org/:10.1519/SSC.0000000000000264.

Bishop, C., Read, P., Lake, J., Chavda, S. and Turner, A. (2018a) Interlimb asymmetries: understanding how to calculate differences from bilateral and unilateral tests. *Strength and Conditioning Journal* **40**, 1–6. http://doi.org/:10.1519/SSC.0000000000000371.

Bishop, C., Read, P., McCubbine, J. and Turner, A. (2021b) Vertical and Horizontal Asymmetries Are Related to Slower Sprinting and Jump Performance in Elite Youth Female Soccer Players. *Journal of Strength and Conditioning Research* **35**, 56–63. http://doi.org/:10.1519/JSC.0000000000002544.

Bishop, C., Turner, A., Jarvis, P., Chavda, S. and Read, P. (2017) Considerations for Selecting Field-Based Strength and Power Fitness Tests to Measure Asymmetries. *Journal of Strength and Conditioning Research* **31**, 2635–2644. http://doi.org/:10.1519/JSC.0000000000002023.

Bishop, C., Turner, A., Maloney, S., Lake, J., Loturco, I., Bromley, T., et al. (2019d) Drop Jump Asymmetry is Associated with Reduced Sprint and Change-of-Direction Speed Performance in Adult Female Soccer Players. *Sports* **7**, 29. http://doi.org/:10.3390/sports7010029.

Bishop, C., Turner, A. and Read, P. (2018b) Effects of inter-limb asymmetries on physical and sports performance: a systematic review. *Journal of Sports Sciences* **36**, 1135–1144. http://doi.org/:10.1080/02640414.2017.1361894.

Bookbinder, H., Slater V., L., Simpson, A., Hertel, J. and Hart, J.M. (2020) Single-Leg Jump Performance Before and After Exercise in Healthy and Anterior Cruciate Ligament Reconstructed Individuals. *Journal of Sport Rehabilitation* **29**, 879–885. http://doi.org/:10.1123/jsr.2019-0159.

Bourne, M.N., Opar, D.A., Williams, M.D. and Shield, A.J. (2015) Eccentric knee flexor strength and risk of hamstring injuries in rugby union: A prospective cohort study. *American Journal of Sports Medicine* **43**, 2663–2670. http://doi.org/:10.1177/0363546515599633.

Brumitt, J., Heiderscheit, B.C., Manske, R.C., Niemuth, P.E. and Rauh, M.J. (2013) Lower extremity functional tests and risk of injury in division III collegiate athletes. *International Journal of Sports Physical Therapy* **8**, 216–227. Available from http://www.ncbi.nlm.nih.gov/pubmed/23772338.

Carabello, R.J., Reid, K.F., Clark, D.J., Phillips, E.M. and Fielding, R.A. (2010) Lower extremity strength and power asymmetry assessment in healthy and mobility-limited populations: reliability and association with physical functioning. *Aging clinical and experimental research* **22**, 324–329. http://doi.org/:10.3275/6676.

Ceroni, D., Martin, X.E., Delhumeau, C. and Farpour-Lambert, N.J. (2012) Bilateral and Gender Differences During Single-Legged Vertical Jump Performance in Healthy Teenagers. *Journal of Strength and Conditioning Research* **26**, 452–457. http://doi.org/:10.1519/JSC.0b013e31822600c9.

Ceyssens, L., Vanelderen, R., Barton, C., Malliaras, P. and Dingenen, B. (2019) Biomechanical risk factors associated with running-related injuries: a systematic review. *Sports Medicine* **49**, 1095–1115. http://doi.org/:10.1007/s40279-019-01110-z.

Chmielewski, T.L., Martin, C., Lentz, T.A., Tillman, S.M., Moser, M.W., Farmer, K.W., et al. (2014) Normalization Considerations for Using the Unilateral Seated Shot Put Test in Rehabilitation. *Journal of Orthopaedic & Sports Physical Therapy* **44**, 518–524. http://doi.org/:10.2519/jospt.2014.5004.

Clark, N.C. and Mullally, E.M. (2019) Prevalence and magnitude of preseason clinically-significant single-leg balance and hop test asymmetries in an English adult netball club. *Physical Therapy in Sport* **40**, 44–52. http://doi.org/:10.1016/j.ptsp.2019.08.008.

Coratella, G., Beato, M. and Schena, F. (2018) Correlation between quadriceps and hamstrings inter-limb strength asymmetry with change of direction and sprint in U21 elite soccer-players. *Human Movement Science* **59**, 81–87. http://doi.org/:10.1016/j.humov.2018.03.016.

Costa Silva, J.R.L., Detanico, D., Dal Pupo, J. and Freitas, C. de la R. (2015) Bilateral asymmetry of knee and ankle isokinetic torque in soccer players u20 category. *Revista Brasileira de Cineantropometria e Desempenho Humano* **17**, 195–204. http://doi.org/:10.5007/1980-0037.2015v17n2p195.

Croisier, J.-L., Forthomme, B., Namurois, M.-H., Vanderthommen, M. and Crielaard, J.-M. (2002) Hamstring muscle strain recurrence and strength performance disorders. *The American Journal of Sports Medicine* **30**, 199–203. http://doi.org/:10.1177/03635465020300020901.

Croisier, J.-L., Ganteaume, S., Binet, J., Genty, M. and Ferret, J.M. (2008) Strength imbalances and prevention of hamstring injury in professional soccer players: A prospective study. *The American Journal of Sports Medicine* **36**, 1469–1475. http://doi.org/:10.1177/0363546508316764.

Dai, B., Layer, J., Vertz, C., Hinshaw, T., Cook, R., Li, Y., et al. (2019) Baseline Assessments of Strength and Balance Performance and Bilateral Asymmetries in Collegiate Athletes. *Journal of Strength and Conditioning Research* **33**, 3015–3029. http://doi.org/:10.1519/JSC.0000000000002687.

Dos'Santos, T., Thomas, C., A. Jones, P., Comfort, P., Dos'Santos, T., Thomas, C., et al. (2017a) Asymmetries in single and triple hop are not detrimental to change of direction speed. *Journal of Trainology* **6**, 35–41. http://doi.org/:10.17338/trainology.6.2_35.

Dos'Santos, T., Thomas, C. and Jones, P.A. (2021) Assessing Interlimb Asymmetries: Are We Heading in the Right Direction? *Strength and Conditioning Journal* **43**, 91–100. http://doi.org/:10.1519/SSC.0000000000000590.

Dos'Santos, T., Thomas, C., Jones, P.A. and Comfort, P. (2017b) Assessing Muscle-Strength Asymmetry via a Unilateral-Stance Isometric Midthigh Pull. *International Journal of Sports Physiology and Performance* **12**, 505–511. http://doi.org/:10.1123/ijspp.2016-0179.

Dos'Santos, T., Thomas, C., Jones, P.A. and Comfort, P. (2018) Asymmetries in Isometric Force-Time Characteristics Are Not Detrimental to Change of Direction Speed. *Journal of Strength and Conditioning Research* **32**, 520–527. http://doi.org/:10.1519/JSC.0000000000002327.

Ebert, J.R., Edwards, P., Yi, L., Joss, B., Ackland, T., Carey-Smith, R., et al. (2018) Strength and functional symmetry is associated with post-operative rehabilitation in patients following anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy* **26**, 2353–2361. http://doi.org/:10.1007/s00167-017-4712-6.

Eitzen, I., Eitzen, T.J., Holm, I., Snyder-Mackler, L., Risberg, M.A., Arna Risberg, M., et al. (2010) Anterior Cruciate Ligament-Deficient Potential Coper's and Noncopers Reveal Different Isokinetic Quadriceps Strength Profiles in the Early Stage After Injury. *The American Journal of Sports Medicine* **38**, 586–593. http://doi.org/:10.1177/0363546509349492.

Exell, T.A., Irwin, G., Gittoes, M.J.R. and Kerwin, D.G. (2012) Implications of intra-limb variability on asymmetry analyses. *Journal of Sports Sciences* **30**, 403–409. http://doi.org/:10.1080/02640414.2011.647047.

Fältström, A., Hägglund, M., Kvist, J., Faltstrom, A., Hagglund, M. and Kvist, J. (2017) Functional Performance Among Active Female Soccer Players After Unilateral Primary Anterior Cruciate Ligament Reconstruction Compared With Knee-Healthy Controls. *The American Journal of Sports Medicine* **45**, 377–385. http://doi.org/:10.1177/0363546516667266.

Ferreira, J.C., Araujo, S.R.S., Pimenta, E.M., Menzel, H.-J.K., Medeiros, F.B., de Andrade, A.G.P., et al. (2018) Impact of competitive level and age on the strength and asymmetry of young soccer players. *Revista Brasileira de Medicina do Esporte* **24**, 357–360. http://doi.org/:10.1590/1517-869220184985.

Fort-Vanmeerhaeghe, A., Gual, G., Romero-Rodriguez, D. and Unnitha, V. (2016) Lower Limb Neuromuscular Asymmetry in Volleyball and Basketball Players. *Journal of Human Kinetics* **50**, 135–143. http://doi.org/:10.1515/hukin-2015-0150.

Fort-Vanmeerhaeghe, A., Montalvo, A.M., Sitja-Rabert, M., Kiefer, A.W. and Myer, G.D. (2015) Neuromuscular asymmetries in the lower limbs of elite female youth basketball players and the application of the skillful limb model of comparison. *Physical Therapy in Sport* **16**, 317–323. http://doi.org/:10.1016/j.ptsp.2015.01.003.

Fousekis, K., Tsepis, E., Poulmedis, P., Athanasopoulos, S. and Vagenas, G. (2011) Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: A prospective study of 100 professional players. *British Journal of Sports Medicine* **45**, 709–714. http://doi.org/:10.1136/bjsm.2010.077560.

Goodpaster, B.H., Park, S.W., Harris, T.B., Kritchevsky, S.B., Nevitt, M., Schwartz, A.V., et al. (2006) The Loss of Skeletal Muscle Strength, Mass, and Quality in Older Adults: The Health, Aging and Body Composition Study. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* **61**, 1059–1064. http://doi.org/:10.1093/gerona/61.10.1059.

Graham-Smith, P., Al-Dukhail, A. and Jones, P. (2016) Agreement between attributes associated with bilateral jump asymmetry. *ISBS-Conference Proceedings Archive* 926–929. Available from https://ojs.ub.uni-konstanz.de/cpa/article/view/6555

Guney-Deniz, H., Harput, G., Kaya, D., Nyland, J. and Doral, M.N. (2020) Quadriceps tendon autograft ACL reconstructed subjects overshoot target knee extension angle during active proprioception testing. *Knee Surgery, Sports Traumatology, Arthroscopy* **28**, 645–652. http://doi.org/:10.1007/s00167-019-05795-7.

Hadzic, V., Sattler, T., Veselko, M.M., Markovic, G. and Dervisevic, E. (2014) Strength asymmetry of the shoulders in elite volleyball players. *Journal of Athletic Training* **49**, 338–344. http://doi.org/:10.4085/1062-6050-49.2.05.

Harput, G., Ozer, H., Baltaci, G. and Richards, J. (2018) Self-reported outcomes are associated with knee strength and functional symmetry in individuals who have undergone anterior cruciate ligament reconstruction with hamstring tendon autograft. *The Knee* **25**, 757–764. http://doi.org/:10.1016/j.knee.2018.06.007.

Hart, N.H., Nimphius, S., Spiteri, T. and Newton, R.U. (2014) Leg Strength and Lean Mass Symmetry Influences Kicking Performance in Australian Football. *Journal of Sports Science & Medicine* **13**, 157–165. Available from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3918553/.

Herzog, W., Nigg, B.M., Read, L.J. and Olsson, E. (1989) Asymmetries in ground reaction force patterns in normal human gait. *Medicine & Science in Sports & Exercise* **21**, 110–114. http://doi.org/:10.1249/00005768-198902000-00020.

Hiemstra, L.A., Sasyniuk, T.M., Mohtadi, N.G.H.H. and Fick, G.H. (2008) Shoulder strength after open versus arthroscopic stabilization. *The American Journal of Sports Medicine* **36**, 861–867. http://doi.org/:10.1177/0363546508314429.

Holsgaard-Larsen, A., Jensen, C., Mortensen, N.H.M.H.M. and Aagaard, P. (2014) Concurrent assessments of lower limb loading patterns, mechanical muscle strength and functional performance in ACL-patients--a cross-sectional study. *The Knee* **21**, 66–73. http://doi.org/:10.1016/j.knee.2013.06.002.

Hoogeslag, R.A.G.G., Brouwer, R.W., Boer, B.C., de Vries, A.J., in 't Veld, R. and Huis in 't Veld, R. (2019) Acute Anterior Cruciate Ligament Rupture: Repair or Reconstruction? Two-Year Results of a Randomized Controlled Clinical Trial. *The American Journal of Sports Medicine* **47**, 567–577. http://doi.org/:10.1177/0363546519825878.

Hopkins, W.G. (2004) How to Interpret Changes in an Athletic Performance Test. Sport Science. Available from URL: http://sportsci.org/jour/04/wghtests.htm

Hubbard, T.J., Kramer, L.C., Denegar, C.R. and Hertel, J. (2007) Contributing factors to chronic ankle instability. *Foot and Ankle International* **28**, 343–354. http://doi.org/:10.3113/FAI.2007.0343.

Hughes, J.D., Burnham, J.M., Hirsh, A., Musahl, V., Fu, F.H., Irrgang, J.J., et al. (2019) Comparison of Short-term Biodex Results After

Anatomic Anterior Cruciate Ligament Reconstruction Among 3 Autografts. *Orthopaedic Journal of Sports Medicine* **7**, 2325967119847630. http://doi.org/:10.1177/2325967119847630.

Impellizzeri, F.M., Bizzini, M., Rampinini, E., Cereda, F. and Maffiuletti, N.A. (2008) Reliability of isokinetic strength imbalance ratios measured using the Cybex NORM dynamometer. *Clinical Physiology and Functional Imaging* **28**, 113–119. http://doi.org/:10.1111/j.1475-097X.2007.00786.x.

Impellizzeri, F.M., Rampinini, E., Maffiuletti, N. and Marcora, S.M. (2007) A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Medicine and Science in Sports and Exercise* **39**, 2044–2050. http://doi.org/:10.1249/mss.0b013e31814fb55c.

Jones, P.A. and Bampouras, T.M. (2010) A comparison of isokinetic and functional methods of assessing bilateral strength imbalance. *Journal of Strength and Conditioning Research* **24**, 1553–1558. http://doi.org/:10.1519/JSC.0b013e3181dc4392.

Kaminska, E., Piontek, T., Wiernicka, M., Cywinska-Wasilewska, G., Lewandowski, J. and Lochynski, D. (2015) Differences in Isokinetic Strength of the Knee Extensors and Flexors in Men With Isolated and Combined Cruciate-Ligament Knee Injury. *Journal of Sport Rehabilitation* **24**, 268–277. http://doi.org/:10.1123/jsr.2014-0157.

Kyritsis, P., Bahr, R., Landreau, P., Miladi, R. and Witvrouw, E. (2016) Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *British Journal of Sports Medicine* **50**, 946–951. http://doi.org/:10.1136/bjsports-2016-096410.

Laroche, D.P., Cook, S.B. and Mackala, K. (2012) Strength asymmetry increases gait asymmetry and variability in older women. *Medicine and Science in Sports and Exercise* **44**, 2172–2181. http://doi.org/:10.1249/MSS.0b013e31825e1d31.

Leister, I., Mattiassich, G., Kindermann, H., Ortmaier, R., Barthofer, J., Vasvary, I., et al. (2018) Reference values for fatigued versus non-fatigued limb symmetry index measured by a newly designed single-leg hop test battery in healthy subjects: a pilot study. *Sport Sciences for Health* **14**, 105–113. http://doi.org/:10.1007/s11332-017-0410-5.

Liberati, A., Altman, D.G., Tetzlaff, J., Mulrow, C., Gøtzsche, P.C., Ioannidis, J.P.A., et al. (2009) The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *BMJ* **339;** b2700. https://doi.org/10.1136/bmj.b2700

de Lira, C.A.B., Mascarin, N.C., Vargas, V.Z., Vancini, R.L. and Andrade, M.S. (2017) Isokinetic knee muscle strength profile in Brazilian male soccer, futsal, and beach soccer players: a cross-sectional study. *International Journal of Sports Physical Therapy* **12**, 1103–1110. http://doi.org/:10.26603/ijspt20171103.

Lisee, C., Slater, L., Hertel, J. and Hart, J.M. (2019) Effect of sex and level of activity on lower-extremity strength, functional performance, and limb symmetry. *Journal of Sport Rehabilitation* **28**, 413–420. http://doi.org/:10.1123/jsr.2017-0132.

Lloyd, R.S., Oliver, J.L., Myer, G.D., Croix, M.D.S. and Read, P.J. (2020) Seasonal variation in neuromuscular control in young male soccer players. *Physical Therapy in Sport* **42**, 33–39. http://doi.org/:10.1016/j.ptsp.2019.12.006.

Lockie, R.G., Callaghan, S.J., Berry, S.P., Cooke, E.R.A., Jordan, C.A., Luczo, T.M., et al. (2014) Relationship between unilateral jumping ability and asymmetry on multidirectional speed in team-sport athletes. *Journal of Strength and Conditioning Research* **28**, 3557–3566. http://doi.org/:10.1519/JSC.0000000000000588.

Lockie, R.G., Schultz, A.B., Callaghan, S.J. and Jeffriess, M.D. (2013) The effects of isokinetic knee extensor and flexor strength on dynamic stability as measured by functional reaching. *Isokinetics and Exercise Science* **21**, 301–309. http://doi.org/:10.3233/IES-130501.

Lockie, R.G., Schultz, A.B., Jeffriess, M.D. and Callaghan, S.J. (2012) The relationship between bilateral differences of knee flexor and extensor isokinetic strength and multi-directional speed. *Isokinetics and Exercise Science* **20**, 211–219. http://doi.org/:10.3233/IES-2012-0461.

Lockie, R.G., Stage, A.A., Stokes, J.J., Orjalo, A.J., Davis, D.L., Giuliano, D.V., et al. (2016) Relationships and Predictive Capabilities of Jump Assessments to Soccer-Specific Field Test Performance in Division I Collegiate Players. *Sports* **4**, 56. http://doi.org/10.3390/sports4040056.

Lynch, A.D., Logerstedt, D.S., Grindem, H., Eitzen, I., Hicks, G.E., Axe, M.J., et al. (2015) Consensus criteria for defining "successful outcome" after ACL injury and reconstruction: A Delaware-Oslo ACL cohort investigation. *British Journal of Sports Medicine* **49**, 335–342. http://doi.org/:10.1136/bjsports-2013-092299.

Machado, F., Debieux, P., Kaleka, C.C., Astur, D., Peccin, M.S. and Cohen, M. (2018) Knee isokinetic performance following anterior cruciate ligament reconstruction: patellar tendon versus hamstrings graft. *Physician and Sportsmedicine* **46**, 30–35. http://doi.org/:10.1080/00913847.2018.1418592.

Madruga-Parera, M., Bishop, C., Read, P., Lake, J., Brazier, J. and Romero-Rodriguez, D. (2020) Jumping-based Asymmetries are Negatively Associated with Jump, Change of Direction, and Repeated Sprint Performance, but not Linear Speed, in Adolescent Handball Athletes. *Journal of Human Kinetics* **71**, 47–58. http://doi.org/:10.2478/hukin-2019-0095.

Madruga-Parera, M., Romero-Rodríguez, D., Bishop, C., Beltran-Valls, M.R., Latinjak, A.T., Beato, M., et al. (2019) Effects of Maturation on Lower Limb Neuromuscular Asymmetries in Elite Youth Tennis Players. *Sports* **7**, 106. http://doi.org/:10.3390/sports7050106.

Maffiuletti, N.A., Bizzini, M., Desbrosses, K., Babault, N. and Munzinger, U. (2007) Reliability of knee extension and flexion measurements using the Con-Trex isokinetic dynamometer. *Clinical Physiology and Functional Imaging* **27**, 346–353. http://doi.org/:10.1111/j.1475-097X.2007.00758.x.

Maloney, S.J., Richards, J., Nixon, D.G.D., Harvey, L.J. and Fletcher, I.M. (2017) Do stiffness and asymmetries predict change of direction performance? *Journal of Sports Sciences* **35**, 547–556. http://doi.org/:10.1080/02640414.2016.1179775.

Maulder, P. and Cronin, J. (2005) Horizontal and vertical jump assessment: Reliability, symmetry, discriminative and predictive ability. *Physical Therapy in Sport* **6**, 74–82. http://doi.org/:10.1016/j.ptsp.2005.01.001.

Menzel, H.-J.J., Chagas, M.H., Szmuchrowski, L.A., Araujo, S.R.S., De Andrade, A.G.P. and De Jesus-Moraleida, F.R. (2013) Analysis of lower limb asymmetries by isokinetic and vertical jump tests in soccer players. *Journal of Strength and Conditioning Research* **27**, 1370–1377. http://doi.org/:10.1519/JSC.0b013e318265a3c8.

Michailidis, Y., Savvakis, C., Pirounakis, V., Mikikis, D., Margonis, K. and Mataxas, T. (2020) Association between jump asymmetry and reduced performance in the change of direction tests of youth soccer players. *Journal of Physical Education and Sport* **20**, 1362–1368. http://doi.org/:10.7752/jpes.2020.03188.

Miles, J.J., King, E., Falvey, E.C., Daniels, K.A.J., Falvey, É.C., Daniels, K.A.J., et al. (2019) Patellar and hamstring autografts are associated with different jump task loading asymmetries after ACL reconstruction. *Scandinavian Journal of Medicine & Science in Sports* **29**, 1212–1222. http://doi.org/:10.1111/sms.13441.

Moher, D., Liberati, A., Tetzlaff, J. and Altman, D.G. (2009) Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Medicine* **6**, e1000097–e1000097. http://doi.org/:10.1371/journal.pmed.1000097.

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., et al. (2015) Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic Reviews* **4**, 1. http://doi.org/:10.1186/2046-4053-4-1.

Nimphius, S., McGuigan, M.R. and Newton, R.U. (2012) Changes in Muscle Architecture and Performance During a Competitive Season in Female Softball Players. *Journal of Strength and Conditioning Research* **26**, 2655–2666. http://doi.org/:10.1519/JSC.0b013e318269f81e.

Noehren, B., Andersen, A., Hardy, P., Johnson, D.L., Ireland, M.L., Thompson, K.L., et al. (2016) Cellular and Morphological Alterations in the Vastus Lateralis Muscle as the Result of ACL Injury and Reconstruction. *The Journal of Bone and Joint Surgery. American volume* **98**, 1541–1547. http://doi.org/:10.2106/JBJS.16.00035.

Nugent, F.J., Vinther, A., McGregor, A., Thornton, J.S., Wilkie, K. and Wilson, F. (2021) The relationship between rowing-related low back pain and rowing biomechanics: a systematic review. *British*

Journal of Sports Medicine **55**, 616–630. http://doi.org/:10.1136/bjsports-2020-102533.

O'Malley, E., Richter, C., King, E., Strike, S.S., Moran, K., Franklyn-Miller, A., et al. (2018) Countermovement Jump and Isokinetic Dynamometry as Measures of Rehabilitation Status After Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training* **53**, 687–695. http://doi.org/:10.4085/1062-6050-480-16.

Opar, D.A., Williams, M.D., Timmins, R.G., Hickey, J., Duhig, S.J. and Shield, A.J. (2015) Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine and Science in Sports and Exercise* **47**, 857–865. http://doi.org/:10.1249/MSS.0000000000000465.

Palmieri-Smith, R.M. and Lepley, L.K. (2015) Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. *The American Journal of Sports Medicine* **43**, 1662–1669. http://doi.org/:10.1177/0363546515578252.

Peebles, A.T., Miller, T.K., Moskal, J.T. and Queen, R.M. (2019) Hop testing symmetry improves with time and while wearing a functional knee brace in anterior cruciate ligament reconstructed athletes. *Clinical Biomechanics* **70**, 66–71. http://doi.org/:10.1016/j.clinbiomech.2019.08.002.

Pérez-Castilla, A., García-Ramos, A., Janicijevic, D., Miras-Moreno, S., De la Cruz, J.C., Rojas, F.J., et al. (2021) Unilateral or Bilateral Standing Broad Jumps: Which Jump Type Provides Inter-Limb Asymmetries with a Higher Reliability? *Journal of Sports Science and Medicine* **20**, 317–327. http://doi.org/:10.52082/jssm.2021.317.

Peters, A., Galna, B., Sangeux, M., Morris, M. and Baker, R. (2010) Quantification of soft tissue artifact in lower limb human motion analysis: A systematic review. *Gait & Posture* **31**, 1–8. http://doi.org/:10.1016/j.gaitpost.2009.09.004.

Read, P.J., McAuliffe, S., Bishop, C., Oliver, J.L., Graham-Smith, P. and Farooq, M.A. (2021) Asymmetry Thresholds for Common Screening Tests and Their Effects on Jump Performance in Professional Soccer Players. *Journal of Athletic Training* **56**, 46–53. http://doi.org/:10.4085/1062-6050-0013.20.

Redden, J., Stokes, K. and Williams, S. (2018) Establishing the Reliability and Limits of Meaningful Change of Lower Limb Strength and Power Measures during Seated Leg Press in Elite Soccer Players. *Journal of Sports Science & Medicine* **17**, 539–546. Available from URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6243620/

Reid, A., Birmingham, T.B., Stratford, P.W., Alcock, G.K. and Giffin, J.R. (2007) Hop Testing Provides a Reliable and Valid Outcome Measure During Rehabilitation After Anterior Cruciate Ligament Reconstruction. *Physical Therapy* **87**, 337–349. http://doi.org/:10.2522/ptj.20060143.

Riemann, B.L. and Davies, G.J. (2019) Association Between the Seated Single-Arm Shot-Put Test With Isokinetic Pushing Force. *Journal of Sport Rehabilitation* **29**, 689–692. http://doi.org/:10.1123/jsr.2019-0140.

Rohman, E., Steubs, J.T. and Tompkins, M. (2015) Changes in Involved and Uninvolved Limb Function During Rehabilitation After Anterior Cruciate Ligament Reconstruction: Implications for Limb Symmetry Index Measures. *The American Journal of Sports Medicine* **43**, 1391–1398. http://doi.org/:10.1177/0363546515576127.

Ruas, C.V., Brown, L.E. and Pinto, R.S. (2015) Lower-extremity side-to-side strength asymmetry of professional soccer players according to playing position. *Kinesiology* **47**, 188–192.

Schmitt, L.C., Paterno, M.V., Ford, K.R., Myer, G.D. and Hewett, T.E. (2015) Strength Asymmetry and Landing Mechanics at Return to Sport after ACL Reconstruction. *Medicine & Science in Sports & Exercise* **47**, 1426–1434. http://doi.org/:10.1249/MSS.0000000000000560.

Shamseer, L., Moher, D., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., et al. (2015) Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: elaboration and explanation. *BMJ* **349**, g7647. http://doi.org/:10.1136/bmj.g7647.

Suchomel, T.J., Sato, K., DeWeese, B.H., Ebben, W.P. and Stone, M.H. (2016) Relationships between potentiation effects after ballistic half-squats and bilateral symmetry. *International Journal of Sports Physiology and Performance* **11**, 448–454. http://doi.org/:10.1123/ijspp.2015-0321.

Sullivan, G.M. and Feinn, R. (2012) Using Effect Size—or Why the P Value Is Not Enough. *Journal of Graduate Medical Education* **4**, 279–282. http://doi.org/:10.4300/jgme-d-12-00156.1.

Tsiros, M.D., Grimshaw, P.N., Shield, A.J. and Buckley, J.D. (2011) Test-Retest Reliability of the Biodex System 4 Isokinetic Dynamometer for Knee Strength Assessment in Paediatric Populations. *Journal of Allied Health* **40**, 115–119.

Vanderstukken, F., Jansen, N., Mertens, T. and Cools, A.M. (2019) Elite male field hockey players have symmetric isokinetic glenohumeral strength profiles, but show asymmetry in scapular muscle strength. *Journal of Sports Sciences* **37**, 484–491. http://doi.org/:10.1080/02640414.2018.1507238.

Welling, W., Benjaminse, A., Lemmink, K.A.P.M., Dingenen, B., Gokeler, A., Lemmink, K.A.P.M., et al. (2019) Progressive strength training restores quadriceps and hamstring muscle strength within 7 months after ACL reconstruction in amateur male soccer players. *Physical Therapy in Sport* **40**, 10–18. http://doi.org/:10.1016/j.ptsp.2019.08.004.

Welling, W., Benjaminse, A., Seil, R., Lemmink, K., Zaffagnini, S. and Gokeler, A. (2018) Low rates of patients meeting return to sport criteria 9 months after anterior cruciate ligament reconstruction: a prospective longitudinal study. *Knee Surgery, Sports Traumatology, Arthroscopy* **26**, 3636–3644. http://doi.org/:10.1007/s00167-018-4916-4.

Xergia, S.A., Pappas, E., Zampeli, F., Georgiou, S. and Georgoulis, A.D. (2013) Asymmetries in functional hop tests, lower extremity kinematics, and isokinetic strength persist 6 to 9 months following anterior cruciate ligament reconstruction. *The Journal of Orthopaedic and Sports Physical Therapy* **43**, 154–162. http://doi.org/:10.2519/jospt.2013.3967.

Zifchock, R.A., Davis, I., Higginson, J. and Royer, T. (2008) The symmetry angle: A novel, robust method of quantifying asymmetry. *Gait & Posture* **27**, 622–627. http://doi.org/:10.1016/j.gaitpost.2007.08.006.

Zwolski, C., Schmitt, L.C., Quatman-Yates, C., Thomas, S., Hewett, T.E. and Paterno, M.V. (2015) The influence of quadriceps strength asymmetry on patient-reported function at time of return to sport after anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine* **43**, 2242–2249. http://doi.org/:10.1177/0363546515591258.

Zwolski, C., Schmitt, L.C., Thomas, S., Hewett, T.E. and Paterno, M.V. (2016) The Utility of Limb Symmetry Indices in Return-to-Sport Assessment in Patients With Bilateral Anterior Cruciate Ligament Reconstruction. *The American Journal of Sports Medicine* **44**, 2030–2038. http://doi.org/:10.1177/0363546516645084.

Key points

- Only four of the twelve identified asymmetry indices were able to overcome the limitations associated with selecting a reference limb or value
- Interpretation of asymmetry scores using pre-determined thresholds, such as 10-15%, may be unfounded as many lack a solid evidence base
- The magnitude of inter-limb strength asymmetry varies from approximate symmetry to greater than 15% asymmetry, however there are inconsistent findings regarding the magnitude of asymmetry in similar participant groups and the subsequent effects of asymmetry on injury and performance
- Disparate findings can be attributed to differences in methodology, including asymmetry calculation and threshold application
- Going forward, an individualised approach to asymmetry may be necessary, which considers the use of sample-specific thresholds and individual variability

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Supplementary Material

Table S1. Worked examples of hypothetical asymmetry scores for each index calculation across three scenarios: 1) limb symmetry, where A=B, 2) limb asymmetry, where A>B, or 3) limb asymmetry where A<B. Hypothetical peak torque values of 1.0Nm.kg^{-1}, 1.2Nm.kg^{-1} and 0.8Nm.kg^{-1} were used.

Index no.	Index Calculation	Scenario	Limb Comparison				
			Involved/Uninvolved	Dominant/Nondominant	Right/Left	Stronger/Weaker	Stance/Skill
1	$\frac{B}{A} \cdot 100$	1	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$
		2	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$
		3	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$
2	$\frac{A}{B} \cdot 100$	1	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$
		2	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$
		3	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$
3	$\left[1 - \left(\frac{B}{A}\right)\right] \cdot 100$	1	$\left[1 - \left(\frac{1.0}{1.0}\right)\right] \cdot 100 = 0\%$	$\left[1 - \left(\frac{1.0}{1.0}\right)\right] \cdot 100 = 0\%$	$\left[1 - \left(\frac{1.0}{1.0}\right)\right] \cdot 100 = 0\%$	$\left[1 - \left(\frac{1.0}{1.0}\right)\right] \cdot 100 = 0\%$	$\left[1 - \left(\frac{1.0}{1.0}\right)\right] \cdot 100 = 0\%$
		2	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$
		3	$\left[1 - \left(\frac{1.2}{0.8}\right)\right] \cdot 100 = -50\%$	$\left[1 - \left(\frac{1.2}{0.8}\right)\right] \cdot 100 = -50\%$	$\left[1 - \left(\frac{1.2}{0.8}\right)\right] \cdot 100 = -50\%$	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$	$\left[1 - \left(\frac{1.2}{0.8}\right)\right] \cdot 100 = -50\%$
4	$100 - \left[\left(\frac{B}{A}\right) \cdot 100\right]$	1	$100 - \left[\left(\frac{1.0}{1.0}\right) \cdot 100\right] = 0\%$	$100 - \left[\left(\frac{1.0}{1.0}\right) \cdot 100\right] = 0\%$	$100 - \left[\left(\frac{1.0}{1.0}\right) \cdot 100\right] = 0\%$	$100 - \left[\left(\frac{1.0}{1.0}\right) \cdot 100\right] = 0\%$	$100 - \left[\left(\frac{1.0}{1.0}\right) \cdot 100\right] = 0\%$
		2	$100 - \left[\left(\frac{0.8}{1.2}\right) \cdot 100\right] = 33.3\%$	$100 - \left[\left(\frac{0.8}{1.2}\right) \cdot 100\right] = 33.3\%$	$100 - \left[\left(\frac{0.8}{1.2}\right) \cdot 100\right] = 33.3\%$	$100 - \left[\left(\frac{0.8}{1.2}\right) \cdot 100\right] = 33.3\%$	$100 - \left[\left(\frac{0.8}{1.2}\right) \cdot 100\right] = 33.3\%$
		3	$100 - \left[\left(\frac{1.2}{0.8}\right) \cdot 100\right] = -50\%$	$100 - \left[\left(\frac{1.2}{0.8}\right) \cdot 100\right] = -50\%$	$100 - \left[\left(\frac{1.2}{0.8}\right) \cdot 100\right] = -50\%$	$100 - \left[\left(\frac{0.8}{1.2}\right) \cdot 100\right] = 33.3\%$	$100 - \left[\left(\frac{1.2}{0.8}\right) \cdot 100\right] = -50\%$
5	$\frac{100}{A} \cdot B \cdot (-1) + 100$	1	$\frac{100}{1.0} \cdot 1.0 \cdot (-1) + 100 = 0\%$	$\frac{100}{1.0} \cdot 1.0 \cdot (-1) + 100 = 0\%$	$\frac{100}{1.0} \cdot 1.0 \cdot (-1) + 100 = 0\%$	$\frac{100}{1.0} \cdot 1.0 \cdot (-1) + 100 = 0\%$	$\frac{100}{1.0} \cdot 1.0 \cdot (-1) + 100 = 0\%$
		2	$\frac{100}{1.2} \cdot 0.8 \cdot (-1) + 100 = 33.3\%$	$\frac{100}{1.2} \cdot 0.8 \cdot (-1) + 100 = 33.3\%$	$\frac{100}{1.2} \cdot 0.8 \cdot (-1) + 100 = 33.3\%$	$\frac{100}{1.2} \cdot 0.8 \cdot (-1) + 100 = 33.3\%$	$\frac{100}{1.2} \cdot 0.8 \cdot (-1) + 100 = 33.3\%$
		3	$\frac{100}{0.8} \cdot 1.2 \cdot (-1) + 100 = -50\%$	$\frac{100}{0.8} \cdot 1.2 \cdot (-1) + 100 = -50\%$	$\frac{100}{0.8} \cdot 1.2 \cdot (-1) + 100 = -50\%$	$\frac{100}{1.2} \cdot 0.8 \cdot (-1) + 100 = 33.3\%$	$\frac{100}{0.8} \cdot 1.2 \cdot (-1) + 100 = -50\%$
6	$\frac{A}{B}$	1	$\frac{1.0}{1.0} = 1$	$\frac{1.0}{1.0} = 1$	$\frac{1.0}{1.0} = 1$	$\frac{1.0}{1.0} = 1$	$\frac{1.0}{1.0} = 1$
		2	$\frac{1.2}{0.8} = 1.5$	$\frac{1.2}{0.8} = 1.5$	$\frac{1.2}{0.8} = 1.5$	$\frac{1.2}{0.8} = 1.5$	$\frac{1.2}{0.8} = 1.5$
		3	$\frac{0.8}{1.2} = 0.7$	$\frac{0.8}{1.2} = 0.7$	$\frac{0.8}{1.2} = 0.7$	$\frac{1.2}{0.8} = 1.5$	$\frac{0.8}{1.2} = 0.7$

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7	$\frac{(A-B)}{A}\cdot 100$	1	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$
		2	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$
		3	$\frac{(0.8-1.2)}{0.8}\cdot 100 = -50\%$	$\frac{(0.8-1.2)}{0.8}\cdot 100 = -50\%$	$\frac{(0.8-1.2)}{0.8}\cdot 100 = -50\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(0.8-1.2)}{0.8}\cdot 100 = -50\%$
8	$\frac{(B-A)}{A}\cdot 100$	1	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$
		2	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$
		3	$\frac{(1.2-0.8)}{0.8}\cdot 100 = 50\%$	$\frac{(1.2-0.8)}{0.8}\cdot 100 = 50\%$	$\frac{(1.2-0.8)}{0.8}\cdot 100 = 50\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(1.2-0.8)}{0.8}\cdot 100 = 50\%$
9	$\frac{(A-B)}{Max(A,B)}\cdot 100$	1	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$
		2	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$
		3	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$
10	$\frac{(A-B)}{(A+B)}\cdot 100$	1	$\frac{(1.0-1.0)}{(1.0+1.0)}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{(1.0+1.0)}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{(1.0+1.0)}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{(1.0+1.0)}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{(1.0+1.0)}\cdot 100 = 0\%$
		2	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$
		3	$\frac{(0.8-1.2)}{(0.8+1.2)}\cdot 100 = -20\%$	$\frac{(0.8-1.2)}{(0.8+1.2)}\cdot 100 = -20\%$	$\frac{(0.8-1.2)}{(0.8+1.2)}\cdot 100 = -20\%$	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$	$\frac{(0.8-1.2)}{(0.8+1.2)}\cdot 100 = -20\%$
11	$\frac{[45-arctan(^{B}/_{A})]}{90}\cdot 100$	1	$\frac{[45-arctan(^{1.0}/_{1.0})]}{90}\cdot 100 = 0\%$	$\frac{[45-arctan(^{1.0}/_{1.0})]}{90}\cdot 100 = 0\%$	$\frac{[45-arctan(^{1.0}/_{1.0})]}{90}\cdot 100 = 0\%$	$\frac{[45-arctan(^{1.0}/_{1.0})]}{90}\cdot 100 = 0\%$	$\frac{[45-arctan(^{1.0}/_{1.0})]}{90}\cdot 100 = 0\%$
		2	$\frac{[45-arctan(^{0.8}/_{1.2})]}{90}\cdot 100 = 12.6\%$	$\frac{[45-arctan(^{0.8}/_{1.2})]}{90}\cdot 100 = 12.6\%$	$\frac{[45-arctan(^{0.8}/_{1.2})]}{90}\cdot 100 = 12.6\%$	$\frac{[45-arctan(^{0.8}/_{1.2})]}{90}\cdot 100 = 12.6\%$	$\frac{[45-arctan(^{0.8}/_{1.2})]}{90}\cdot 100 = 12.6\%$
		3	$\frac{[45-arctan(^{1.2}/_{0.8})]}{90}\cdot 100 = -12.6\%$	$\frac{[45-arctan(^{1.2}/_{0.8})]}{90}\cdot 100 = -12.6\%$	$\frac{[45-arctan(^{1.2}/_{0.8})]}{90}\cdot 100 = -12.6\%$	$\frac{[45-arctan(^{0.8}/_{1.2})]}{90}\cdot 100 = 12.6\%$	$\frac{[45-arctan(^{1.2}/_{0.8})]}{90}\cdot 100 = -12.6\%$
12	$\ln\left(\frac{B}{A}\right)\cdot 100$	1	$\ln\left(\frac{1.0}{1.0}\right)\cdot 100 = 0\%$	$\ln\left(\frac{1.0}{1.0}\right)\cdot 100 = 0\%$	$\ln\left(\frac{1.0}{1.0}\right)\cdot 100 = 0\%$	$\ln\left(\frac{1.0}{1.0}\right)\cdot 100 = 0\%$	$\ln\left(\frac{1.0}{1.0}\right)\cdot 100 = 0\%$
		2	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$
		3	$\ln\left(\frac{1.2}{0.8}\right)\cdot 100 = 40.5\%$	$\ln\left(\frac{1.2}{0.8}\right)\cdot 100 = 40.5\%$	$\ln\left(\frac{1.2}{0.8}\right)\cdot 100 = 40.5\%$	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$	$\ln\left(\frac{1.2}{0.8}\right)\cdot 100 = 40.5\%$

Limb A = uninvolved, dominant, right, stronger, or stance limb value, and Limb B = involved, nondominant, left, weaker, or skill limb value