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Review Article

A Critical Review of the Methods Used to Measure, Analyse and Interpret Kinetic Asymmetries During Cycling

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Abstract: The aim of this review was to critically assess the current methods of measuring, analysing and interpreting kinetic asymmetries during cycling. Although it has been conjectured that cycling asymmetrically may increase the risk of developing overuse injuries, and could compromise performance due to premature fatigue, there is a lack of evidence to support these claims. Many research studies in this field demonstrate conflicting findings which could be attributed to the heterogeneity of the research study characteristics. This review showed there is currently no consistent definition to classify cyclists' pedalling as (a)symmetrical, and the magnitude of the measured asymmetry can be affected by methodological factors including: the location of the power meter on the bicycle, the cycling metric assessed for asymmetry and, the calculation used to quantify interlimb differences. The participants' knowledge of the intent to investigate asymmetry may also result in less innate cycling techniques. Future research study designs in this field require standardisation to develop a clearer understanding of potential causes and/or effects of asymmetries during cycling.

Keywords: Asymmetry, Bilateral, Power Meter, Cycling.

1. Introduction

The concept of interlimb asymmetries is well established, with recognition that humans preferentially use one side of the body in voluntary motor acts (Carpes et al., 2010; McGrath et al., 2016). Although cycling does not inherently favor one side, kinetic asymmetries can be assessed by measuring bilateral force or torque at various components of a bicycle (Clarsen et al., 2010; Passfield et al., 2017). These asymmetries typically range between 5-20% in uninjured cyclists (Carpes et al., 2010). In the last decade, advancements in power meter technology have led to the production of more affordable and commercially available devices that measure and present a range of live data, including metrics on cycling asymmetry (Passfield et al., 2017).

1.1. Asymmetry and injury

Significant asymmetries have been observed during cycling in participants with existing injuries. For example, participants with an anterior cruciate ligament (ACL) injury exhibited significantly larger cycling kinetic asymmetries compared to healthy controls, where the non-injured limb contributed up to 50% more of the required power output than the ACL-deficient limb (Hunt et al., 2004). An assessment of individuals with knee osteoarthritis also detected significant asymmetries during cycling (Buddhadev et al., 2018). However, in this instance the more affected limb generated significantly more power than the less affected limb during cycling (Buddhadev et al., 2018).

Overuse injuries are common in cycling, with knee pain reported to affect 40-60% of recreational cyclists and 36-62% of professional cyclists (Clarsen et al., 2010). High training volumes, cycling with high gear ratios and low cadences, and hill climbing induce repetitive or heavy patellofemoral joint loads, which may increase the likelihood of overuse injury (Faria et al., 2005). It has been suggested that pedalling with equal forces delivered by each leg (symmetry) may reduce the risk of overuse injuries (Carpes et al., 2007; Smak et al., 1999) ; however, there is a lack of evidence to support this theory. A review investigating bilateral asymmetries across sporting disciplines found no direct evidence from either observational or interventional studies to support the claim that interlimb asymmetries increase injury occurrence (Afonso et al., 2022).

1.2. Asymmetries and performance

It has also been hypothesized that asymmetries might compromise cycling performance (Bini et al., 2017; Carpes et al., 2007), but results are inconsistent. For example, Bini et al., (2016), found no significant association between performance and peak pedal force asymmetries during a 20 km time trial, but larger asymmetries in effective force were linked with better 4 km time trial performances amongst competitive cyclists (Bini & Hume, 2015).

In an earlier review, Carpes et al. (2010) concluded that cyclists exhibit greater asymmetries during low to moderate intensity exercise, whereas maximal exercise intensities tend to be more symmetric. This has further been supported by (Farrell et al., 2021) whose research showed that power output asymmetries were greater at the intensity corresponding to a 2 mmol/L blood lactate concentration (-11.5%) compared to peak power output intensity (-1.7%) during an incremental cycling test. However, a positive association between asymmetry and intensity has been reported during incremental cycling, with peak torque asymmetries increasing from 6% at the initial 100 W stage to 27% at 350 W (Bini & Hume., 2014). Furthermore, asymmetries have been observed during supramaximal cycling (Diefenthaeler et al., 2016), therefore the relationship between intensity and asymmetry remains unclear.

During low intensity cycling, propulsive force asymmetries appear to be exacerbated when increasing cadence (Sanderson, 1990), an effect that is not present at higher intensities. Increasing cadence has also resulted in decreased asymmetry indices in negative power output, which resists the propulsive power of the contralateral limb in the power phase (Smak et al., 1999). However, a multi-visit study reported high variability both within and between days when assessing asymmetries at varied cycling cadences (Daly & Cavanagh, 1976).

1.3. Aims

The literature on cycling asymmetry is highly conflicting, with studies often presenting diverging findings. Most studies assessing asymmetries during cycling utilize a between-participants research design. Given the various participant characteristics that can influence cycling performance, including physiological attributes and training status, a within-participant study design may be more suitable for assessing the relationship between asymmetries and performance during cycling. Consequently, little is fully understood about the underlying causes or the potential effects of asymmetry during cycling. Similar challenges were reported by Heil et al., (2020) in their review of the influence of exercise-induced fatigue on interlimb asymmetry. They noted that the heterogeneity of research characteristics in their field makes it difficult to compare studies and draw definitive conclusions, leading them to recommend a more systematic approach to research design.

Researchers in the field of cycling asymmetry have also highlighted the need to identify an optimal method for the assessment of bilateral asymmetries (Bini & Hume, 2015), as this may help to explain the varied and inconsistent findings in the existing literature. Therefore, the first aim of this review was to describe the variance in methodological approaches to measuring, analysing and interpreting kinetic asymmetries during cycling. Secondly, we aim to critically review these methods to determine a best practice for measuring and interpreting kinetic asymmetries during cycling.

2. Materials and Methods

The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Page et al., 2021). A diagram of the study selection process is shown in Figure 1. A literature search was performed in PubMed, Google Scholar, Scopus and Medline databases up to February 2024. The search was conducted using a Boolean search strategy with the operators ‘AND’ and ‘OR’ and combinations of the following keywords: (‘cycling’ OR ‘bicycle’) AND ‘bilateral’ AND (‘asymmetry’ OR ‘symmetry’) AND ‘sport’ AND (‘torque’ OR ‘force’ OR ‘power’ OR ‘performance’ OR ‘injury’).

2.1. Inclusion criteria

Studies were included (Figure 1) if they 1) investigated kinetic parameters of cycling for the analysis of bilateral asymmetry, 2) included healthy, non-injured participants, 3) were peer reviewed articles or conference proceedings, and 4) were written in English.

2.2. Data extraction

From the included studies, the following descriptive data were extracted to investigate methods used to quantify asymmetry during cycling (Table 1): 1) the location of the power meter on the bicycle, 2) the criteria for determining a dominant limb, 3) the metric assessed for asymmetry, 4) the duration of data sampling, 5) the calculation used to quantify interlimb difference, and 6) the magnitude of interlimb difference required to be considered asymmetrical.

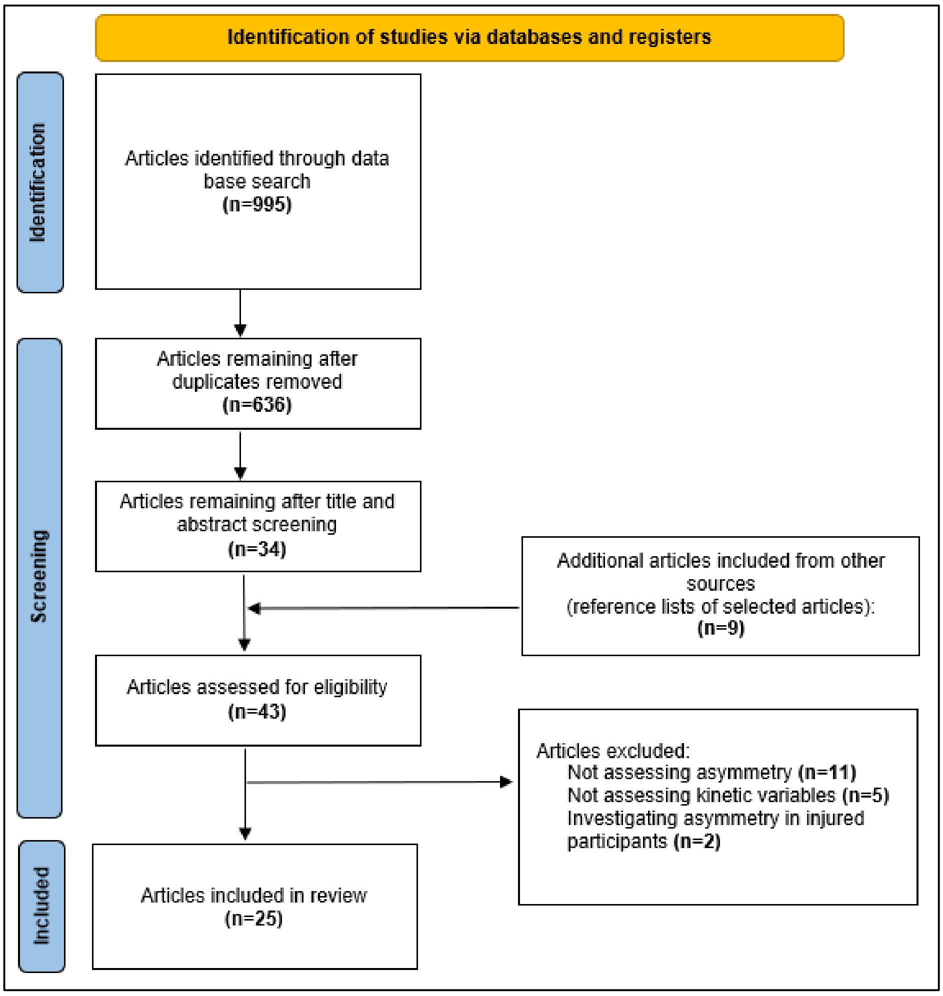

Figure 1. A flow diagram of the study selection process for methodological review.

3. Results

The initial search provided six hundred and thirty-six articles after the removal of duplicates. The titles and abstracts of those articles were screened, producing thirty-four articles for further full-text evaluation. To ensure all available articles were included, reference lists within those considered for evaluation were also assessed for inclusion, providing an additional nine articles. A diagram of the study selection process is shown in Figure 1. Of these forty-three articles identified for review. Eleven studies were excluded because they were not assessing asymmetry. A further seven were excluded for the following reasons: five studies because they were not measuring kinetic metrics during cycling, and two studies because they were investigating asymmetries in injured participants.

Figure 2 illustrates the varied methods reported across the n=25 studies included in the present review. Table 1 provides a detailed description of the methods used to assess bilateral asymmetries during cycling, by study.

To measure kinetic metrics of cycling, twelve studies used power meters located at the crank. Of these twelve studies, six studies used the Lode Excalibur cycle ergometer with integrated strain gauges in the crank. Four studies used SRM (Schoberer Rad Messtecnik, Jülich, Welldorf, Germany) and one study used Power2Max cranks. One study used a custom device with strain gauges bonded to each crank arm. Thirteen studies used power meters located at the pedal, ten studies using custom devices and three studies using commercially available devices including the Garmin Vector pedals (GVPs) and Polar Keo pedals. One study used a Wattbike ergometer.

When analysing asymmetries during cycling, five studies compared left and right limbs. Alternatively, twenty studies identified the participants' dominant or preferred limb using varied methods. Six studies determined dominance using the Waterloo Inventory. Ten studies identified dominance as the kicking limb and one study used a test of strength. Five studies determined dominance as the limb producing the highest torque, force, or power during cycling.

To assess the magnitude of asymmetries during cycling, sixteen studies conducted statistical analyses to determine whether the magnitude of asymmetry was significant. Eighteen studies determined the magnitude of asymmetry by calculating asymmetry indices.

A variety of pedalling metrics have been assessed for the asymmetries during cycling. Eleven studies used torque as the pedalling metric to compare limbs during cycling. Ten studies assessed asymmetries in power output, three studies assessed asymmetries in force, three studies assessed asymmetries in work and two studies assessed asymmetries in impulse. One study assessed asymmetries in the index of effectiveness and two studies assessed asymmetries in pedalling smoothness.

When assessing asymmetry at timepoints throughout cycling protocols, eleven studies analysed kinetic data for durations of 30 s to 300 s, eleven studies measured 5 to 30 complete crank revolutions. One study measured asymmetries continuously throughout a cycling event.

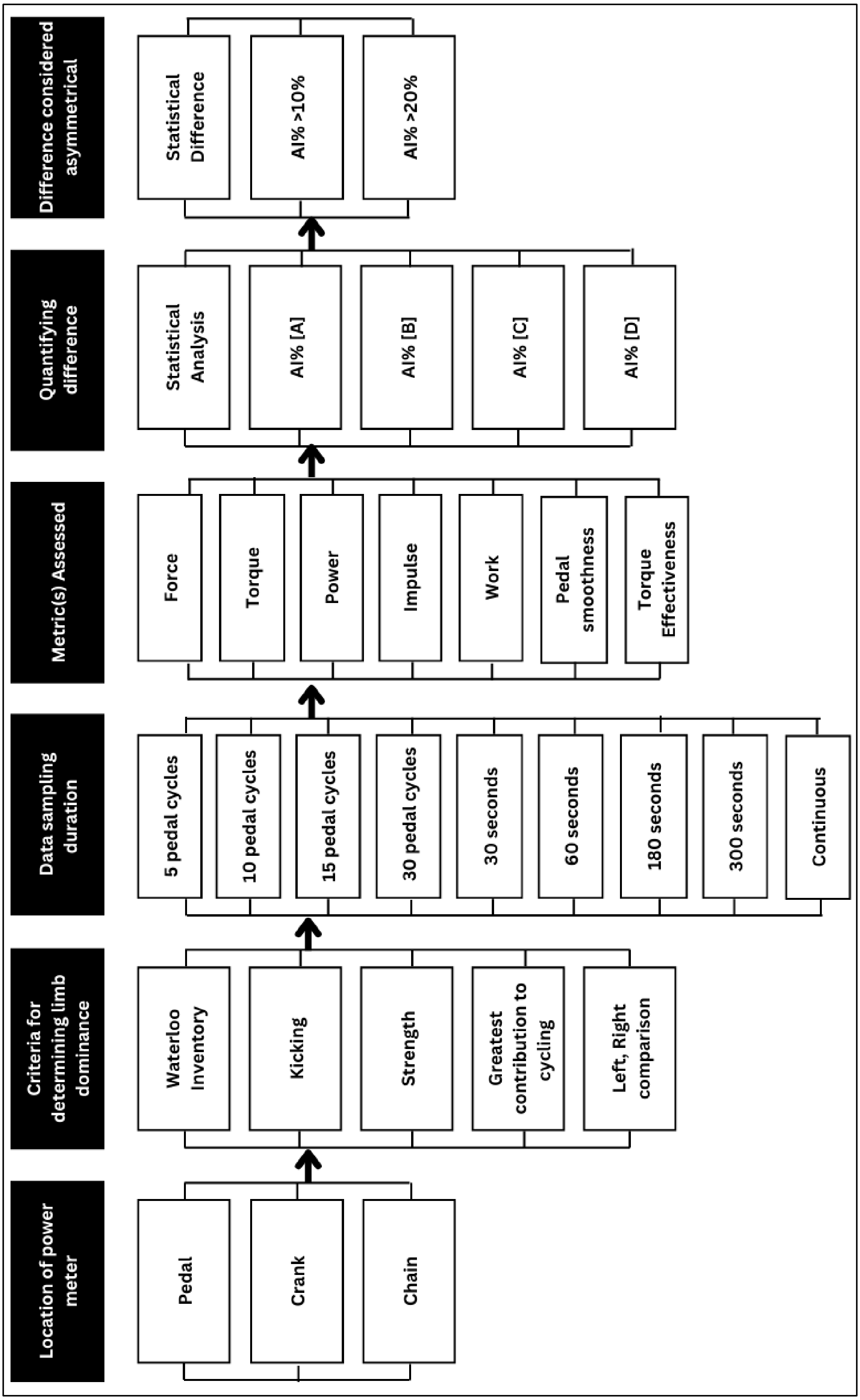

Figure 2 A schematic overview of the varied methods used to measure, analyse, and interpret asymmetries during cycling.

Table 1. A summary of methods used within studies assessing bilateral asymmetries during cycling.

Reference	Location of the power meter	Criteria for determining limb dominance	Data sampling duration	Metric(s) assessed	AI% Calculation and/or statistical analysis	Difference considered asymmetrical
(Bertucci et al., 2012)	Crank [SRM]	Greatest torque	30 s per stage	Peak torque	((D - ND) / D) x 100 [A] Paired Wilcoxon	Asymmetry index >10%
(Bini & Hume, 2014)	Crank [SRM], Pedal [Custom]	Waterloo inventory	5 pedal cycles per stage	Peak torque	((D - ND) / (D + ND / 2)) x 100 [C]	Asymmetry index >20%
(Bini & Hume, 2015)	Pedal [Custom]	Waterloo inventory	5 pedal cycles every 500 m	Average force, effective force, index of effectiveness	((D - ND) / (D + ND) / 2) x 100 [C] ANOVA	Asymmetry index >10%
(Bini et al., 2017)	Pedal [Custom]	Waterloo inventory	15 pedal cycles per interval	Total peak force	((D - ND) / (D + ND) / 2) x 100 [C]	Asymmetry index >20%
(Bini et al., 2007)	Pedal [Custom]	Comparison between left and right limbs	15 pedal cycles per intensity	Mean torque, external work	ANOVA	Statistically significant difference
(Bini et al., 2016)	Pedal [Custom]	Waterloo inventory	5 pedal cycles every 5 km	Peak total force	((D - ND) / (D + ND / 2)) x 100 [C] T Test	Statistically significant difference
(Carpes et al., 2007)	Crank [SRM]	Kicking	10 cycles every 5 min	Peak torque (propulsive)	((D - ND) / D) x 100 [A]	Asymmetry index >10%
(Carpes et al., 2008)	Crank [SRM]	Kicking	10 pedal cycles per min	Peak propulsive torque	ANOVA	Statistically significant difference
(Chen et al., 2016)	Pedal [Custom]	Comparison between left and right limbs	60 s per trial	Maximal torque, work	[R - L] / 0.5 (R + L) x 100 [C]	Asymmetry index >10%
(da Silva Soares et al., 2021)	Crank [LODE Excalibur]	Kicking	10 pedal cycles	Peak torque, torque curve	ANOVA, FANOVA	Statistically significant difference
(Daly & Cavanagh, 1976)	Crank [Custom]	Kicking, strength		Work	(D / ND) x 100 [B]	
(Diefenthaeler et al., 2016)	Crank [LODE Excalibur]	Waterloo Inventory		Peak torque	((P - NP) / P) x 100 [A] ANOVA	Statistically significant difference
(Farrell et al., 2021)	Crank [LODE Excalibur]	Kicking	60 s	Peak torque, average torque, power	((D – ND) / (D + ND) / 2) x 100 [C] Absolute: D - ND	
(Farrell & Neira, 2023)	Crank [LODE Excalibur]	Kicking	180 s	Power	((D – ND) / (D + ND) / 2) x 100 [C]	

Table 1. A summary of methods used within studies assessing bilateral asymmetries during cycling. (continued)

Reference	Location of the power meter	Criteria for determining limb dominance	Data sampling duration	Metric(s) assessed	AI% Calculation and/or statistical analysis	Difference considered asymmetrical
(Garcia-Lopez et al., 2015)	Crank [LODE Excalibur]	Kicking	300 s	Mean torque, peak torque, minimum torque, positive	ANOVA	Statistically significant difference
(González-Sánchez et al., 2019)	Pedal [Polar Keo]	Waterloo Inventory	180 – 300 s	Power	((D - ND) / D) x 100 [A] T test	Statistically significant difference
(Hunt et al., 2004)	Pedal [Custom]	Comparison between left and right limbs	15 pedal cycles	Power	(R - L) -1 ANOVA	Statistically significant difference
(Javaloyes et al., 2021)	Crank [Power2Max]	Greatest power	Continuous	Power	(D - ND) [percentage difference, calculation not specified]	Statistically significant difference
(Kell & Greer, 2017)	Wattbike	Greatest torque	300 s	Power	((D - ND) / D) x 100 [A] ANOVA	Asymmetry index >20%
(Rannama et al., 2017)	Pedal [Garmin Vector]	Comparison between left and right limbs	30 s	Power, pedal smoothness	((D - ND) / (D + ND) / 2) x 100 [C]	
(Rannama & Port, 2018)	Pedal [Garmin Vector]	Kicking	30 seconds	Power, pedal smoothness	((D - ND) / (D + ND) / 2) x 100 [C] T test	Statistically significant difference
(Sanderson, 1990)	Pedal [Custom]	Comparison between left and right limbs	30 seconds per trial	Total impulse, positive angular impulse	1- (left / right) ANOVA	
(Smak et al., 1999)	Pedal [Custom]	Greatest torque, kicking	5 pedal cycles per trial	Average total power, average positive power, average negative power	((D - ND) / (D + ND)) [D] T test	Statistically significant difference
(Stefanov et al., 2020)	Pedal [Custom]	Kicking	30 seconds at intervals	Peak power	((D - ND) / D) x 100 [A] Kruskal-Wallis	Statistically significant difference
(Trecroci et al., 2018)	Crank [LODE Excalibur]	Greatest torque	30 pedal cycles at initial and final stages	Peak torque	((D - ND) / D) x 100 [A] ANOVA	Statistically significant difference

D, dominant limb; L, left limb; ND, non-dominant limb; R, right limb.
The information within squared brackets in the 'location of the power meter' column refers to the specific power meter used in each study. The letter in squared brackets in the 'AI% calculation' column is an identifier to demonstrate studies which utilised the same AI% calculation. These are referred to in Table 3.

4. Discussion

The initial aim of this review was to assess cycling asymmetry literature to determine variance in the methodological approaches to measuring, analysing and interpreting kinetic asymmetries during cycling. Figure 2 shows the variety of methods used to measure, analyse, and interpret asymmetries during cycling amongst the existing literature. This schematic illustrates that there are >14,000 possible methodological combinations amongst research in the field which suggests that a consensus on the design of cycling asymmetry research is needed. The secondary aim of this review was to critically assess the varied methods to determine a best practice for measuring and interpreting kinetic asymmetries during cycling.

4.1. The location of the power meter on the bicycle

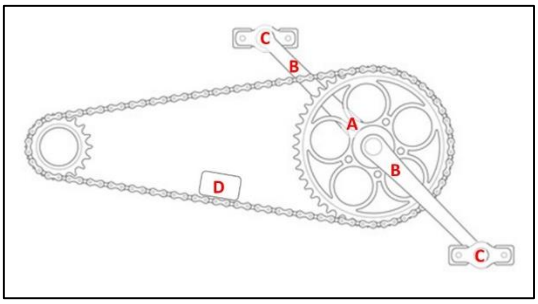

Figure 3. Anatomy of the drive train and location of power meters used to measure cycling kinetics. A: spider of the crank arm (SRM device). B: crank arms (all crank based power meters). C: pedal (all pedal based power meters). D: chain (Wattbike loadcell).

The location of power meters varies between studies (Table 1, Figure 3). A review by Bini *et al*. (2014) described the evolution of technologies used to determine force and power in cycling (Bini et al., 2014). Torque can be measured at many locations on the propulsive transmission system of a bicycle including the pedal, crank, bottom bracket, chain and rear hub (Passfield et al., 2017). The measurement of torque or power is affected by the location of the power meter on the bicycle (Passfield et al., 2017). Frictional losses through components of the bicycle's drive train (pedals, cranks, chainrings, chain, cassette, derailleur), dissipate some of the energy input (Bouillod et al., 2022; Passfield et al., 2017). These frictional losses are thought to be proportionate to the total power output and have been suggested to be ~2.4% (Passfield et al., 2017).

Many of the cycling asymmetry studies reviewed use crank spider-based power meters, such as SRM and Power2Max devices (Table 1). These devices cannot accurately measure the contribution of each limb separately because they are positioned on a component influenced by the net torque of both lower limbs (Bini et al., 2011, 2014; Bini & Hume, 2014; Javaloyes et al., 2021). These technologies attribute torque generated in each 180° of the crank cycle to the limb that is in the power phase or downstroke. However, resistive forces can occur during the recovery phase of the pedal cycle (Daly & Cavanagh, 1976; Smak et al., 1999). Using these power meters, negative torque applied by the contralateral limb diminishes torque of the ipsilateral limb (Bini & Hume, 2014), which could affect the calculated asymmetries. Additionally, cyclists using cleats or toe clips can generate propulsive forces during the upstroke, which would overestimate the torque of the limb in the power phase. This limitation is also true of the one study that used a Wattbike ergometer to assess asymmetry (Kell & Greer, 2017), as this equipment measures power output via a load cell located near the chain (Hopker et al., 2010). During a maximal incremental cycling test performed on a cycle ergometer equipped with both types of power meter, larger asymmetries in peak torque were detected using the pedal power meter compared to the crank spider (Bini & Hume, 2014). Significant asymmetries, defined as a >20% difference between limbs, were observed at intensities >150 W using pedal power meters but only at intensities >350 W using crank spider power meters (Bini & Hume, 2014). Considerable asymmetries at low intensities were not detected by the crank spider-based power meter which questions the validity of this equipment for assessing asymmetries during cycling (Bini & Hume, 2014).

Other crank based devices, such as the LODE Excalibur, measure left and right torque separately via strain gauges located at each crank's axis, making them suitable for the assessment of asymmetries during cycling. Previous studies have recommended pedals to be the preferred power meter for the assessment of bilateral asymmetries during cycling (Bini et al., 2011, 2014; Bini & Hume, 2014). Pedals measure forces directly at their application by the cyclist, before any frictional losses through the bicycle's drivetrain (Passfield et al., 2017). Additionally, pedals measure forces at a location on the bicycle with minimal left and right limb interaction. Some pedal power meters can be purchased as unilateral devices, reducing the cost to the consumer. The unilateral pedal power meters double the power measured at one limb to estimate net power output. Valenzuela *et al.* (2022) assessed the validity of net power output measured by unilateral and bilateral versions of the Favero Assioma (FA) pedal power meter and found that while the unilateral power meter provided a valid estimate of net power, its validity decreased in the presence of asymmetry (Valenzuela et al., 2022). This finding further justifies the use of bilateral pedal power meters for assessing asymmetries during cycling.

It is worth noting that commercial pedal power meters typically sample at low frequencies (1 Hz), which has been shown to reduce the validity of net power measured during sprint cycling at high cadences (Bouillord et al., 2017; Novak & Dascombe, 2016).

4.2 The criteria for determining a dominant or preferred limb

In a clinical setting, comparing injured and non-injured limbs allows for the quantification of asymmetry, which is useful for monitoring rehabilitation. The goal in this context is to reduce the deficit of the injured limb, using the performance of the non-injured limb as a reference. However, determining a 'reference' limb in healthy populations presents a greater challenge. A reference limb could be selected based on limb preference or limb dominance. These terms are often used interchangeably, but the limb that is subjectively preferred is not necessarily objectively dominant (Virgile & Bishop, 2021). For example, a participants preferred limb for kicking tasks may not be the strongest limb in a test of maximal strength.

Within cycling asymmetry literature, some studies assessed limb preference to determine a reference limb. Of the studies reviewed, six used the Waterloo Inventory to determine limb preference (Table 1). The Waterloo Inventory is a questionnaire that assesses preferences for tasks where the foot manipulates an object (e.g., kicking a ball) and tasks where the foot provides support (e.g., standing on one foot) (Elias et al., 1998). While these questions do not specifically address cycling actions, they indicated the preferred limb for daily activities. Alternatively, ten studies determined limb preference based on the limb used for kicking tasks (Table 1).

Other studies determined a reference limb by assessing limb dominance. Five studies defined dominance as the limb producing the highest torque, force or power during cycling (Table 1).

One study used a cycling-specific strength test to assess dominance (Daly & Cavanagh, 1976). This test, which measured force at the pedal spindle with the crank horizontal at 90°, required participants to apply maximum force to the pedal for ten consecutive trials per leg over two visits. Only thirteen of the twenty participants showed consistent dominance with the same leg on both days, leading to the conclusion that this test was unreliable for measuring limb dominance (Daly & Cavanagh, 1976).

A consistent approach to defining dominance or preference is needed within the literature, as different methods may classify the same cyclist as dominant in either limb. For example, a cyclist might use their right limb to kick a ball but produce higher torque with their left limb during cycling. Asymmetry should be reported as a vector quantity, expressing both magnitude and direction (Bailey et al., 2021). Focusing solely on magnitude may suggest consistent asymmetry (e.g., 20% difference between limbs), but direction analysis could reveal a switch from 20% in favour of the left limb to 20% in favour of the right limb. When dominance is defined as the limb producing the highest force, torque or power, the calculated asymmetry indices will always reflect a positive value favouring the dominant limb (Bishop et al., 2016). Using this method, it would not be apparent if there was a switch in the limb contributing most greatly, which has been observed during cycling (Daly & Cavanagh, 1976; Diefenthaeler et al., 2016; Smak et al., 1999). Using this method during longitudinal analyses may mask considerable changes in asymmetry (Bishop et al., 2016).

Positive or negative asymmetry indices indicate the direction of asymmetry, enabling the analysis of whether asymmetry is related to dominance. Of the twenty-five studies in this review, nine reported that cycling asymmetry is associated with limb dominance, as defined by the Waterloo Inventory (Bini & Hume, 2014a, 2015; Diefenthaeler et al., 2016) or the kicking limb (Carpes et al., 2007, 2008; Garcia-Lopez et al., 2015; Rannama & Port, 2018; Smak et al., 1999; Stefanov et al., 2020). Conversely, six studies found no association between cycling asymmetry and limb preference or dominance when assessed by the Waterloo Inventory (Bini et al., 2016, 2017; González-Sánchez et al., 2019), the kicking limb (da Silva Soares et al., 2021; Daly & Cavanagh, 1976; Farrell et al., 2021) or a test of strength (Daly & Cavanagh, 1976). Therefore, it appears that cycling asymmetries are not consistently related to limb preference or dominance.

Three studies in this review conducted simple comparisons of left and right limbs which might be the best approach for longitudinal analysis of cycling asymmetries. This method allows for a clear identification of which limb is contributing most and whether the direction of asymmetry changes. In group analyses, there could favouring of both left and right limbs among participants. Therefore, for such analyses, it is necessary to convert all calculated asymmetries into positive values, reflecting magnitude only. Additionally, statistical methods such as Kappa Coefficients could be employed to quantify the consistency in the direction of asymmetry to account for changes in the limb contributing most to cycling performance metrics.

4.3 The metric assessed for asymmetry and duration of data sampling

Asymmetries are task and metric specific (Bishop et al., 2021; Patterson et al., 2010). Asymmetries have been calculated for a range of metrics in cycling research, including torque, power, force, work, impulse, index of effectiveness (also known as torque effectiveness) and pedal smoothness (Table 1). Within the included studies, these metrics have been assessed as peak, average, total, positive and/or negative values. A description of the metrics used within the included studies is presented in Table 2.

Table 2. Description of metrics in relation to cycling.

Metric (S.I. Unit)	Definition
Force (N)	A push or a pull acting on a component of the bicycle.
Impulse (N.s)	Net force applied to a component of the bicycle, over a period of time.
Torque (N.m)	A measure of force that causes rotation of a component of the bicycle.
Power (J.s, W)	A product of torque and cadence.
Work (J or kJ)	A summation of power for the duration it is produced.
Pedal smoothness (%)	A measure of how evenly power is applied around the pedal cycle. A percentage, calculated by dividing average power by peak power, for each crank cycle.
Torque effectiveness or Index of effectiveness (%)	A percentage of the total force that is perpendicular to the crank.

Evaluating specific sections of the crank cycle, such as peak torque, may not adequately capture each limb's contribution. Many studies reviewed typically used discrete parameters such as peak values in the analysis of asymmetries. The bilateral differences presented in the studies cited in this review neglect the temporal information in the torque waveforms, thus a) the timing of the peak is missed and b) the two curves of left and right limbs may have similar peaks, but the waveforms differ. A similar discussion is present within gait research, questioning the methods with which to analyse gait cycle asymmetries (Viteckova et al., 2018).

Functional data analysis has been proposed as a method to establish symmetry over the whole waveform (Ramsay & Dalzell, 1991) and is represented by a mathematical function that spans the whole torque cycle revolution. This has been extended to the functional analysis of variance (FANOVA) (Helwig et al., 2016). Da Silva Soares *et al.* (2021) analysed asymmetries using this approach for the full torque curve, and subsequently in peak torque during sub-maximal cycling trials (da Silva Soares et al., 2021). They observed significant asymmetries in torque curves from 0° to 50°, 130° to 180° and 320° to 330° of the crank cycle, but reported no significant difference in the peak torque produced by each limb (da Silva Soares et al., 2021). Analysing the torque curve provides a thorough analysis of the contributions of each limb and provides a useful insight into pedalling technique (da Silva Soares et al., 2021). However, few commercially available power meters will provide the user with the full torque profile and this process would require additional and advanced analysis. Unless this data processing is integrated within commercial power meter software in an accessible format, it is likely that the use of discreet values in this analysis is likely to remain the norm.

Measuring bilateral power enables a comparison of the energy each limb is producing that will propel the bicycle. Calculating the work done by each limb could offer a valuable measure of 'asymmetrical load' describing each limb's contribution for the duration of a ride. Additional metrics such as torque effectiveness and pedal smoothness could compliment this data by offering insights into pedalling technique, specifically the proportion of total force that is effective, or propulsive.

The studies reviewed employed various data sampling methods: some collected data over a fixed duration (30 to 300 seconds), while others sampled data over several complete crank revolutions (5 to 30 revolutions) (Table 1). Studies which sampled data for several crank cycles used a range of 5 to 30 complete crank revolutions. Collecting small data samples at specific time points during cycling may not accurately reflect the participant's asymmetry. For example, Bini and Hume (2015) and Bini et al. (2016) assessed the impact of bilateral asymmetry on time trial performance over 4 km and 20 km, respectively. They analysed data from 5 complete crank cycles at 500 m and 5 km segments of the respective time trials. For the reported cycling cadences of between 90 to 105 rpm, 5 crank revolutions take approximately 3 seconds, resulting in data sampling periods of around 27 seconds for the 4 km time trial and 13 seconds for the 20 km trial, which for the latter is less than 1% of the mean performance duration of 30 ± 3.7 minutes. Continuous asymmetry analysis during trials, training or competitions, as employed by Javaloyes *et al.* (2020), may provide a more accurate representation of limb differences throughout these trials.

4.4 The calculation used to quantify asymmetry

Of the studies included in this review, eighteen reported interlimb differences as a relative asymmetry index (Table 1). However, these studies used four different asymmetry index calculations to quantify limb differences. To illustrate the impact of different calculations, we used simulated data to compute relative asymmetries for each method. The results are shown in Table 3. The simulated data revealed notable variability in the magnitude of asymmetry depending on the calculation method used, with values ranging from 10% to 22.2%. If arbitrary thresholds, such as a >20% difference are used to classify asymmetry, the same data could lead to participant's being classified as either symmetrical or asymmetrical depending on the chosen calculation method. This highlights the need for a standardized approach to quantifying asymmetries, to ensure consistency across studies and accurate interpretation by cyclists, coaches and practitioners.

Furthermore, the data in Table 3 illustrates how defining limb dominance affects asymmetry calculations. For example, using the simulated data, if dominance is defined as the limb producing the highest power (110 W from the left limb, representing 55% of the net power of 200 W), the left limb is considered dominant. However, if dominance is defined based on the kicking limb, the right limb would be deemed dominant. This discrepancy highlights a limitation of calculations [A] and [B], as the magnitude of asymmetry varies depending on which limb is defined as dominant (Table 3). For these calculations, the dominant limb serves as the reference, which can introduce variability in asymmetry outcomes. In healthy, non-injured cyclists, there is no clear reference limb. For these reasons, we would not recommend using calculation [A] or [B] for the assessment of bilateral asymmetries during cycling.

Table 3. A demonstration, using simulated data, of the effect of the chosen asymmetry calculation on the asymmetry outcome.

Identifier and number of studies using this calculation	Calculation	Dominance = limb producing more power [Left]	Dominance = limb preferred for kicking tasks [Right]
[A] (n=7)	((D-ND)/D) x 100	18.2%	-22.2%
[B] (n=1)	(D/ND) x 100 [100=symmetry]	22.2%	18.2%
[C] (n=8)	((D-ND)/(D+ND/2)) x 100 or ((D-ND)/0.5(D+ND)) x 100	20%	-20%
[D] (n=1)	((D-ND)/(D+ND) x 100	10%	-10%

Simulated data: Net power output =200 W, left limb = 110 W (55% of the net power), right limb = 90 W (45% of the net power), kicking limb = right.

Calculations [C] and [D] do not use the dominant limb as a reference for comparison. Instead, Calculation [D] assessed the interlimb difference relative to the net power of both limbs, while Calculation [C] compares the interlimb difference relative to half of the net power of both limbs.

Using the simulated data (Table 3), at a net power output of 200 W, perfect symmetry would result in each limb contributing 100 W. However, in our example, the left limb contributes 110 W and the right limb 90 W, representing a 10 W deviation from symmetry for each limb. Calculation [C] evaluates the combined deviation from symmetry (20 W) relative to the symmetrical power of one limb (100 W), resulting in an inflated asymmetry measure that is twice as high compared to Calculation [D]. Therefore, Calculation [D] is recommended as the more appropriate method for quantifying relative asymmetry during cycling.

There are limitations to presenting asymmetry as a relative measure, which can be illustrated by the simulated data in Table 3. For example, using Calculation [D], an absolute difference of 20 W at a power output of 200 W results in a 10% difference between limbs. If the intensity increases to 400 W and the relative difference remains at 10%, this suggests no change in asymmetry. However, in absolute terms, the difference between limbs has doubled to 40 W. This indicates that as intensity increases, the same absolute difference appears relatively smaller potentially masking significant changes in asymmetry.

Calculation [D]:

((D-ND)/(D+ND) X 100

At 200 W:

$$\frac{(110\,W - 90\,W)}{(110\,W + 90\,W)} \times 100 = 10\%$$

$$(20\,W\ absolute\ asymmetry)$$

At 400 W:

$$\frac{(220\,W - 180\,W)}{(220\,W + 180\,W)} \times 100 = 10\%$$

$$(40\,W\ absolute\ asymmetry)$$

We recommend calculating absolute asymmetries during cycling. This would require further investigations to provide normative data and a meaningful difference to be able to classify results as symmetrical or asymmetrical, this providing a stronger rationale for the chosen cut-off.

4.5 The magnitude of interlimb difference required to be considered asymmetrical

Many researchers utilise statistical analyses to determine whether the magnitude of asymmetry during cycling is significant. Alternatively, other studies use arbitrary thresholds of >10% or >20% to classify interlimb differences as asymmetrical (Table 1). The use of these arbitrary thresholds enables the analysis of group and individual data. However, the magnitude of asymmetry can be vastly different depending on the metric assessed (Bini & Hume, 2015; Bishop, 2021; Patterson et al., 2010) and the calculation used to quantify asymmetry (Parkinson et al., 2021) therefore the use of arbitrary thresholds should be questioned (Bini & Hume, 2015).

Earlier, we used simulated data to demonstrate the effects of the calculation used to quantify the magnitude of asymmetry. This data is presented in Table 3 and shows that the magnitude of asymmetry varies considerably (in this case 10% to 22.2%) depending on the calculation chosen. These limitations suggest that the use of a single threshold in all circumstances should be discouraged (Bishop, 2021). Alternatively, Exell *et al*. (2012) suggested that inter-limb differences should be greater than intra-limb variability to be considered asymmetrical (Exell et al., 2012). There appears to be considerable inter- and intra-participant variation in asymmetry indices during cycling, with reports of some participants demonstrating a reversal of the limb contributing most greatly (Daly & Cavanagh, 1976; Diefenthaeler et al., 2016; Smak et al., 1999). However, most cycling asymmetry studies assessed participants on a single occasion, with only one study assessing participants under the same conditions on multiple visits (Daly & Cavanagh, 1976).

It is plausible that due to the considerable variation in the magnitude of asymmetry between participants, a more individualised approach to assessing asymmetry may be necessary, accounting for individual variability (Parkinson et al., 2021). Future research should aim to define a range of acceptable asymmetries in uninjured cyclists (Bini & Hume, 2015). Inter limb differences should be assessed relative to variability in the measures (Bishop et al., 2021), therefore further research is needed to understand the day-to-day variability of asymmetries during cycling.

4.6 Other considerations

Only two studies included within this review described in their methods that participants were blinded to the analysis of pedalling asymmetry (Carpes et al., 2007, 2008), preventing this knowledge influencing their pedalling mechanics. One additional study stated that they blinded the participants to the power measurements during the protocol (González-Sánchez et al., 2019).

Two studies have investigated whether the provision of feedback enables cyclists to reduce the magnitude of asymmetry during sub-maximal cycling (Bini et al., 2017; Kell & Greer, 2017). Both studies report that participants who presented with initially considerable asymmetries were able to significantly reduce the magnitude of interlimb differences with verbal (Bini et al., 2017) and visual feedback (Bini et al., 2017;

Kell & Greer, 2017) demonstrating that cyclists can adjust their pedalling technique on an acute basis to ameliorate the magnitude of asymmetry. For this reason, when assessing asymmetries during cycling, participants should not be informed of the intention to assess bilateral contributions or receive any feedback on their asymmetry.

5. Conclusion and Practical Applications

This review highlights the variation in the methods amongst research assessing bilateral asymmetries during cycling. After critically reviewing the methods of the included studies, we can make the following recommendations for measuring, analysing and interpreting asymmetries in this field:

- The equipment used to assess asymmetries must measure left and right contributions separately, such as with technologies including pedal power meters or bilateral crank devices. Pedal devices have the additional advantage of measuring force directly at its application by the cyclist, before any losses through the bicycles drive train. Although, it should be noted that the validity of these pedal power meters decreased during supramaximal sprint cycling due to their low sampling frequency.

- Comparing left and right limbs (rather than assigning dominance) in uninjured cyclists is more appropriate for longitudinal analysis of cyclists' asymmetries as this enables clear identification of which limb is contributing most and whether the direction of asymmetry changes. For group analysis using left and right comparisons, it is necessary to convert all calculated asymmetries into positive values, expressing magnitude only. This data should then be analysed in conjunction with directionality using percentage agreement statistics such as the Kappa Coefficient.

- We recommend analysing asymmetries throughout the full torque curve/waveform. If this is not possible, we suggest analysing variables such as power output, which consider the full contribution of each limb, as opposed to sections of the crank cycle with metrics such as peak torque. Additionally, measuring the power output of each limb enables the calculation of asymmetrical load for the full duration of a cycling trial or event, which is important as small differences over prolonged durations could result in considerable differences in the work conducted by each limb. This analysis is also useful for the investigation of the effects of fatigue on asymmetry and the association between asymmetry and overuse injury in cycling.

- We recommend calculating absolute asymmetries rather than relative percentage differences between limbs during cycling, as relative values can result in misleading findings when reviewing asymmetries at varied intensities.

- Asymmetries should be defined relative to the variance in these measurements. Therefore, further research is needed to understand the typical day-to-day variability in asymmetries during cycling.

- Furthermore, as cyclists can adjust their pedalling technique with feedback or instruction, investigators should take caution when describing the purpose of the analysis to prevent cyclists performing less innate techniques. Ideally, participants should be blinded to the investigation of asymmetry.

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