An investigation of asymmetries in cycling: methods and performance implications

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ABSTRACT

Advancements in power meter technology have increased the availability of affordable, user-friendly power meters, resulting in a prevalence in their use amongst cyclists of all performance levels. Power meters present an array of live data, including cycling asymmetry metrics. Although cycling is a bilateral sport with no obvious lateral preference, asymmetries have been observed in uninjured cyclists, typically ranging between 5 to 20%.

Contradictory findings within the literature can be attributed to the heterogenous methodologies in this field in relation to measuring, analysing and interpreting kinetic pedalling metrics. We critically evaluated the current methods to determine a best practice for assessing bilateral asymmetries during cycling and identified further investigations required to inform the methodological recommendations for this field, including assessing the measurement error of asymmetries during cycling.

Comparing the torque measured by left and right Garmin Vector power pedals (GVPs) against a criterion measure during static load testing, we found that the GVPs were reliable and valid. By conducting a multiple visit study, we showed that the magnitude and direction of asymmetries during cycling are highly variable.

An earlier review noted that cyclists exhibit higher asymmetries during low to moderate intensity exercise, whilst bilateral contributions at maximal intensities were suggested to be symmetrical. We revisited this research questions, using our methodological recommendations and benefiting from advancements in technology, and found no clear and consistent effect of intensity on the magnitude of asymmetry during cycling.

Interestingly, asymmetries were negatively associatied with gross efficiency, a key determinant of cycling performance. Greater resistive forces generated by the limb contributing least to net power could have resulted in the ipsilateral limb generating greater

power to overcome the additional resistance, which could explain the increased oxygen cost of cycling with larger asymmetries. Further work is needed to understand the effect of technique on asymmetries in cycling.

COVID-19 IMPACT STATEMENT

The COVID-19 pandemic impacted upon the research presented in this thesis (**Chapters 5, 6 and 7**). In March 2020, the University of Essex suspended all face-to-face research in response to the pandemic. At this point in time, data collection for **Chapters 5** and **6** of this thesis were underway and nine participants of a targeted twelve were completed. These Chapters investigated the variance of asymmetries during cycling between visits and the effects of intensity on cycling asymmetries.

With the findings of **Chapter 5** suggesting that asymmetries are highly variant between days, we planned to further our research to conduct a within participant analysis of the effects of asymmetry on cycling performance during multiple visits to the laboratory. To conduct this investigation, we planned to assess a performance outcome variable, such as time to exhaustion, whilst cycling at a relative intensity of maximal aerobic power at a fixed cadence to analyse whether the magnitude of asymmetry effects time to exhaustion.

Utilising this study design, we also intended to investigate the effects of fatigue on the magnitude of asymmetry as the participants progressed through their time to exhaustion trial. With the ongoing and unknown end date for the suspension of face-to-face research, the decision was made to redesign **Chapter 7**. Due to the extensive data collected for **Chapters 5** and **6**, we were able to investigate the effects of asymmetry on a key performance indicator of cycling performance (gross efficiency) rather than a direct performance outcome. This provided an initial insight into the potential implications of asymmetry on cycling performance.

The original plans for our research now feature in the general discussion (**Chapter 8, section 8.4**) as potential future directions for research in the field.

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My thanks must also go to those keen cyclists who participated in my studies, for giving up their time in the name of science! This project stemmed from my applied practice in the University of Essex Human Performance Unit where I had many interactions with inquisitive cyclists with questions about power meter innovations and the data this equipment provides. Thank you for keeping me on my toes!

To my family (Mum, Dad and Hayley). I am lucky to have such a loving and supportive family. You have and continue to support me in my studies, work and life in general without pressure, judgement or expectation. You are proud without the need for achievement. These are the greatest gifts you could give, for which I'd like to take this opportunity to say I am incredibly thankful.

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Your role in this journey cannot be overstated and definitely earns the title of bonus supervisor. But beyond that, you've been by my side every step of the way, encouraging and empowering me to be the best I can be. I am forever grateful and super excited for our future adventures together!

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ABBREVIATIONS

ACL	Anterior cruciate ligament
AI%	Asymmetry index (percentage difference between limbs)
ANOVA	Analysis of variance
Bla	Blood lactate accumulation
CE	Cycling experience
CI	Confidence interval
cm	Centimetres
CM	Criterion measure
CV	Coefficient of variation
D	Dominant limb
DC	Direction consistent
DI	Direction inconsistent
EE	Energy expenditure
EMG	Electromyography
ES	Effect size
FA	Favero Assioma pedals
FANOVA	Functional analysis of variance
FTP	Functional threshold power
GE	Gross efficiency
GSI	Global symmetry index
GVPs	Garmin vector pedals
HR	Heart rate
HRR	Heart rate reserve
ICC	Intraclass correlation

J	Joules
J.s	Joules per second
kg	Kilograms
kJ	Kilojoules
km	Kilometres
L	Left
LKP	Look Keo pedals
l/min	Litres per minute
LoA	Limits of agreement
LP	Left pedal
MAP	Maximal aerobic power
MC	Magnitude consistent
ME	Mechanical efficiency
MI	Magnitude inconsistent
min	Minute
ml/kg/min	Millilitres per kilogram, per minute
MLM	Mixed linear model
mmol/L	Millimoles per litre
N	Newtons
NCE	No cycling experience
Nm	Newton meters
N.s	Newtons per second
NCE	No cycling experience
ND	Non dominant limb
OA	Osteoarthritis

OBLA	Onset of blood lactate accumulation
PPO	Peak power output
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
PT	PowerTap pedals
R	Right
RP	Right pedal
rpm	Revolutions per minutes
s	Seconds
SD	Standard deviation
SG	strain gauge
SRM	Schoberer Rad Messtecnik, crank based power meter
TE	Typical error
TEff	Torque effectiveness
$\dot{V}CO_2$	Volume of carbon dioxide
$\dot{V}O_2$	Volume of oxygen
$\dot{V}O_2$ max	Maximal oxygen uptake
$\dot{V}O_2$ peak	Peak oxygen uptake
W	Watts
W/min	Watts per minute
W/kg	Watts per kilogramme
UCI	Union Cycliste Internationale

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

It is well established that during voluntary motor acts, humans preferentially use one side of the body (2,3). Sporting asymmetries have been demonstrated for a wide range of populations, and the magnitude of asymmetry may depend upon the type of sport played (4). Guiard (1987) recommended grouping motor tasks in four categories: unilateral (e.g. long jump take off), bilateral asymmetric (e.g. golf swing), out-of-phase bilateral symmetric (e.g. cycling) and in phase bilateral symmetric (e.g. weight lifting) (5). The existence of asymmetry may be clear and obvious in unilateral or bilateral asymmetric tasks (4) and these could be considered ‘functional asymmetries’. However, asymmetries have also been observed during bilateral endurance sports such as running, swimming and cycling, where there is no obvious demand or benefit for lateral dominance.

As shown in **Figure 1.1**, numerous physiological characteristics underpin maximal and submaximal endurance performance, including maximal oxygen uptake, the fractional utilisation of maximum oxygen uptake, and efficiency (1). Enhancing these physiological characteristics enables the production and preservation of high maximal and relative aerobic power outputs during cycling.

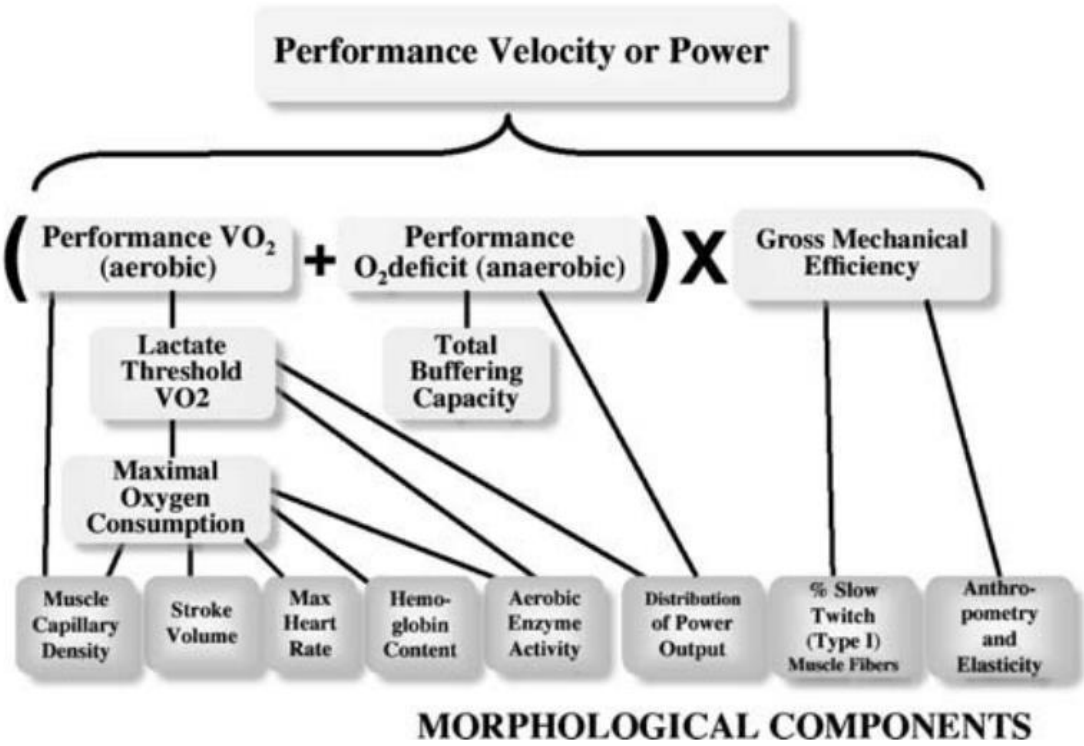


Figure 1.1 A schematic of the multiple physiological factors that interact as determinants of performance velocity or power output for endurance exercise performance

Source: Joyner and Coyle (2008) Endurance exercise performance: the physiology of champions (1)

Professional cyclists can be categorised as general classification contenders, sprinters, climbers, time trialists or all-rounders, depending upon their physiological traits and their role in the team dynamics (6). Grand tour cyclists typically accumulate annual volumes of 850 to 1000 hrs of cycling, covering 25,000 to 35,000 miles per year (7–10). At a more moderate performance level, trained male cyclists also accumulate a considerable training volume, on average 7.5 to 11.7 hrs per week (11). Road cycling events can be categorised as time trial or mass starts, with the latter performed on single or multiple day/stage formats. Race demands are dependent upon the event or stage duration/length, type (time trials, mass start), topography (mountainous, semi-mountainous, flat) and environmental conditions (altitude, temperature) (12–17). The varied profile of an event or stage, containing climbs, descents, flat sections and sprint segments results in power output being more stochastic in nature (10). Often, decisive or race winning efforts are performed after a period of sustained work and high performers are able to generate and maintain higher power outputs after a period of sustained work, when compared to less successful cyclists (18). This resistance to fatigue is also considered a key determinant for success in cycling (18).

In cycling, power output is commonly monitored to evaluate training and race performances (19). Torque and angular velocity can be measured at many locations on the propulsive transmission system of a bicycle including the pedal, crank, bottom bracket, chain and rear hub (19). Historically power meters were restricted to laboratories, were challenging to install and were only compatible with some bicycles. When linked to handlebar mounted cycling computers, modern power meters provide an array of live metrics which cyclists use to monitor training and event intensities. Notably, right/left balance is a common metric available to many cyclists in the field, which describes the percentage of the net power output produced by each limb. This facilitates the assessment of asymmetries during cycling.

It is hypothesised that asymmetries during cycling 1) present a risk for overuse (non-traumatic) injury and 2) could limit cycling performance (3). Overuse injuries are common in cycling, mostly effecting the knee (20–25). Knee pain is reported to affect 40 to 60% of recreational cyclists, and 36 to 62% of professional cyclists (21). Knee injuries were reported to affect between 24 to 62% of professional cyclists in a study of seven road cycling teams certified to participate in international competitions by the Union Cycliste Internationale (UCI) (23). Cyclists may present with knee pain for numerous reasons, including a sub-optimal bicycle set up or poor biomechanics. Furthermore, high training volumes, cycling with high gear ratios and low cadences, and hill climbing all induce repetitive or heavy patellofemoral joint loads which may increase the likelihood of overuse injury (26). However, there is little evidence to substantiate claims that cycling asymmetrically increases the likelihood for overuse injury. There is a need for longitudinal studies to determine whether those who cycle asymmetrically experience greater occurrence of injury in the limb contributing more to overall power output, compared to those who cycle with a symmetrical contribution.

With regards to cycling performance, there are logical reasons that might support the hypothesis that asymmetries are performance limiting. Firstly, power output is related to the cyclist's torque generating capacity. If one limb produces significantly less torque than the other, this might limit over all power output (key for cycling performance). Secondly, due to high training volumes and event demands, fatigue can impede cycling performance. If workload is not evenly distributed between limbs, the limb contributing more may fatigue and result is a subsequent decline in net power output.

Further work is required to establish whether asymmetries during cycling are performance limiting.

1.2 AIMS OF THE RESEARCH

Researchers justify the investigation of interlimb asymmetries during cycling due to the potential implications of overuse injury and performance limitation. However, these justifications are a matter of conjecture. This thesis aims to investigate whether interlimb asymmetries during cycling effect performance. Before these investigations can proceed, authors state that there is a need to identify a consistent approach to measuring and interpreting interlimb asymmetries during cycling (27). Current findings in the field are often conflicting, which could be due to the heterogenous study characteristics amongst the literature in this field.

1.3 THESIS STRUCTURE

From our initial scoping review (**Chapter 2**) and the future work recommended from authors in the field, we identified the need to determine an optimal method for assessing asymmetries during cycling.

In **Chapter 3**, we critically evaluated the methods used to assess bilateral asymmetries during cycling amongst existing literature and where possible, made recommendations for future best practice.

In **Chapters 4 and 5**, we investigated sources of measurement error in the assessment of bilateral asymmetries during cycling. Firstly (**Chapter 4**), we assessed the equipment error of a pedal-based power meter, an example of the equipment that we identified as the most suitable technology for the measurement of data to assess asymmetries during cycling (**Chapter 3)**. Secondly, we assessed the biological error, or variability of asymmetries over multiple trials and visits to the laboratory (**Chapter 5**).

In **Chapter 6,** we researched the effects of cycling intensity on asymmetries during cycling and finally, in **Chapter 7**, we investigated the effects of asymmetry on gross efficiency to determine whether asymmetries effect cycling performance.

A schematic of the thesis structure is provided in **Figure 1.2**.

	Chapter Title	Chapter Aim(s)
Literature Review	**Chapter 2:** Interlimb asymmetries during cycling: a scoping review.	**1.** Investigate whether asymmetries during cycling are associated with incidence of injury or with cycling performance. **2.** Examine the conditions under which asymmetries are most prevalent.
Literature Review	**Chapter 3:** A methodological review: the measurement, analysis, and interpretation of interlimb asymmetries during cycling.	**1.** Assess cycling asymmetry literature to determine variance in the methodological approaches to measuring and interpreting asymmetries during cycling. **2.** Critically assess the varied methods to determine a best practice for measuring and interpreting asymmetries during cycling.
Measurement Error	**Chapter 4:** The reliability and validity of the Garmin Vector pedals for the assessment of bilateral asymmetries.	**1.** Assess the reliability and validity of the left and right Garmin Vector pedals using repeated static load trials to assess their suitability for use in the assessment of bilateral asymmetries during cycling
Measurement Error	**Chapter 5:** The between day variability of interlimb asymmetries during cycling.	**1.** Assess variance in cycling asymmetry over multiple visits. **2.** Identify whether individual variance in asymmetry could be used as a threshold for defining interlimb asymmetries
Performance Trials	**Chapter 6:** The effects of intensity on asymmetry during cycling.	**1.** Assess bilateral asymmetry in power output during trials of different relative intensities to investigate the influence of intensity of the magnitude of asymmetry.
Performance Trials	**Chapter 7:** The effects of interlimb asymmetry on gross efficiency during cycling.	**1.** Investigate whether there is an association between interlimb asymmetry and gross efficiency during cycling.

Figure 1.2 An overview of the thesis structure and chapter aims.

1.4 RESEARCH QUESTIONS

- What is the best practice approach to measuring, analysing and interpreting interlimb asymmetries during cycling?
- How variable are interlimb asymmetries during cycling?
- Is there an association between exercise intensity and asymmetry during cycling?
- Do interlimb asymmetries effect cycling performance?

1.5 OVERVIEW OF EXPERIMENTAL CHAPTERS

1.5.1 Chapter 3 - A methodological review: the measurement, analysis, and interpretation of interlimb asymmetries during cycling.

This methodological review investigated the methods used to measure, analyse and interpret asymmetries during cycling within this field of research. We identified that variation in the methodologies existed amongst the 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.

Methods were critiqued, with supporting literature, and where possible a best practice for assessing asymmetries during cycling was recommended.

1.5.2 Chapter 4 – The reliability and validity of the Garmin Vector pedals for the assessment of bilateral asymmetries.

This study assessed the reliability and validity of the Garmin Vector pedals (GVPs). The GVPs are a commercially available pedal-based power meter which measure bilateral power output during cycling. In **Chapter 3**, we determined that pedal power meters are the most suitable equipment the assessment of bilateral asymmetries during cycling and although investigations of the reliability and validity of these devices had been conducted for the net power measures, it would be valuable to assess both left and right pedals for their measures of torque, independently.

During this study, static evaluations of the pedals were conducted by loading them with hook weights of 0 to 40 kg in mass at crank angles at 45° intervals (0, 45, 90, 135, 180, 225, 270, 315°).

Coefficient of variance (CV) for left and right pedals of 0.25% and 0.28% respectively demonstrated that the torque measured using this equipment had good reliability. Using crank length, crank angle and pedal load, known torque was calculated and used as a criterion measure. Limits of agreement between the criterion measure and left and right pedals were 0.14 Nm and 0.18 Nm, respectively, demonstrating that both the left and right pedals provide valid measurements of torque during static load trials. As the angular velocity measures of these pedals had already been validated (28,29), it was concluded that the GVPs are suitable for the assessment of bilateral asymmetries during cycling.

1.5.3 Chapter 5 - The between day variability of interlimb asymmetries during cycling.

In our scoping review (**Chapter 2**), we identified a single study that assessed participants' asymmetries on multiple days. Therefore, the aim of this study was to investigate the between day variability of asymmetries during cycling. Nine experienced male cyclists participated in 4 x 4 min cycling trials at 40, 60 75 and 90 % of their maximal aerobic power (MAP). All trials were repeated on three visits, conducted at the same time of day, each separated by one week.

The participant's mean CV for absolute interlimb differences in power output ranged between 12.87% to 186.22% between visits. Within trial CV in power output was 5.25% and 5.65% for left and right limb, respectively. Between visit Kappa coefficients from -0.17 to 1.00 demonstrated that the direction of asymmetry frequently changes from one limb to the other.

Our results showed that both magnitude and direction of asymmetry are highly variant within participants. This further added to our methodological recommendations that asymmetries should be assessed on multiple occasions.

1.5.4 Chapter 6 – The effects of intensity of asymmetries during cycling.

In this Chapter, we investigated the effects of cycling intensity on the magnitude of asymmetry using the methodological recommendations of **Chapter 3**. This research questions was the identified as the most commonly assessed in the field of cycling asymmetries (**Chapter 2**) with conflicting results that could be attributed in part to the variation in the methods (**Chapter 3**). Our aim was to evaluate the effects of intensity of asymmetry using the methodologies we recommended in **Chapter 3**, to shed light on this research question. Our results suggested that there was no clear effect of intensity on the magnitdue of asymmetry during cycling. When scrutinsing the data of individual participants, we observed that negative and positive associations between intensity and asymmetry were present amongst our participant group, and for most participants the effect of intensity on the magnitude of asymmetry varied day to day.

1.5.5 Chapter 7 – The effects of interlimb asymmetries on gross efficiency during cycling

The purpose of this study was to investigate whether there was an association between cycling asymmetry and gross efficiency (GE). Efficiency was determined during the final minute of 4 min cycling trials of 40, 60 and 75% of MAP. Seventy-three cases of data were collected and analysed to assess the effects of absolute interlimb asymmetries in power output on GE during cycling.

Pearson's correlation showed a negligible effect of absolute asymmetry in power output on GE ($r = 0.287$). However, linear mixed model analysis estimated that for every 1 W interlimb difference in power output, GE decreased by 0.04%. Tests of reliability report that the smallest detectable change in GE is 0.6% (30,31). Based upon the results of our study, an absolute asymmetry of 15 W would result in a 0.6% change in GE. These results imply that asymmetries may negatively affect cycling performance. This study also provides a minimum interlimb difference of 15 W that could have a measurable effect on a key determinant of cycling performance which could act as a meaningful threshold for defining asymmetry.

CHAPTER 2

Interlimb asymmetries during cycling: a scoping review.

2.1 INTRODUCTION

The concept of interlimb asymmetries is well established and it is recognised that humans preferentially use one side of the body in voluntary motor acts (2,3). Although cycling is not a sport with an obvious lateral preference, asymmetries can be assessed by measuring bilateral force or torque at various components of the bicycle (19,32).

Reviewing the literature in this field, Carpes *et al*. (2011) noted that asymmetries in cycling are common, with interlimb differences in uninjured cyclists typically ranging between 5 to 20% (3). In this review, it was concluded that cyclists exhibit higher asymmetry indices during low to moderate intensity exercise, whilst bilateral contributions at maximal intensities were suggested to be more symmetrical (3). Authors justify the investigation of asymmetries during cycling with the implication that they may lead to overuse injury or premature fatigue and performance limitation. With road cyclists performing a high proportion of their training and competition durations at low to moderate intensities (33–36), during which it has been suggested that asymmetries are greatest, cyclists may produce repeated asymmetrical loads (3) which may increase their risk for overuse injury or performance limitation.

In the last decade, advancements in power meter technology have resulted in manufacturers producing more affordable commercially available devices which present an array of live data, including cycling asymmetry metrics (19). With the use of these devices prevalent amongst both professional and amateur cyclists, it is appropriate to understand if cycling asymmetrically has implications to injury and/or performance.

Therefore, the primary aim of this review was to investigate whether asymmetries during cycling are associated with incidence of injury or with cycling performance. Furthermore, this review will examine the conditions under which asymmetries are most prevalent. Therefore, additional research questions within this review include:

- Is there an association between cycling intensity and asymmetry?
- Is there an association between cadence and asymmetry?
- Is there an association between bicycle configuration and asymmetry?
- Is there an association between cycling position and asymmetry?
- Is there an association between participants performance level and asymmetry?
- Are interventions effective at ameliorating asymmetries?

2.2 METHODS

2.2.1 Literature Review

A review of the literature was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (37). A diagram of the search process is shown in **Figure 2.1**. A literature search was performed in PubMed, Google Scholar, Scopus and Medline databases up to October 2022. 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’).

2.2.2 Inclusion Criteria

Studies were included 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 (**Figure 2.1**).

- To assess whether there is an association between cycling asymmetry on the incidence of injury, studies which measured asymmetry and assessed incidence of injury were selected.
- To assess whether there is an effect of asymmetry on cycling performance, studies which measured asymmetry during a performance trial, simulated time trial or cycling event were selected.
- To assess the association between cycling intensity and asymmetry, studies that assessed participants at more than one intensity were selected.
- To assess the association between cadence and asymmetry, studies that assessed participants at more than one cadence were selected.
- To assess the association between bicycle configuration and asymmetry, studies were selected if they assessed participants asymmetries during multiple trials for which the geometry of the bicycle was adjusted.
- To assess the association between cycling position and asymmetry, studies were selected if participants cycled at varied seated and standing positions, or handlebar grips.
- To assess the association between the participants' performance level and asymmetry, studies which had multiple participant groups of varied cycling abilities were selected.
- To assess whether cycling asymmetries can be ameliorated, studies which carried out an intervention to reduce asymmetry during cycling where selected.

2.2.3 Data Extraction

The following information was extracted from each included study: 1) sample size, sex and participant descriptor, 2) experimental protocol, 4) reported asymmetry indices, 4) whether the authors considered there to be an association between dependant and independent variables.

2.3 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 inclusion were also assessed for inclusion, providing an additional eight articles. A diagram of the search process is shown in **Figure 2.1**.

Of the forty-two articles identified for full-text review, eleven studies were excluded because they were not assessing asymmetry. A further eight were excluded for the following reasons: five studies because they were not measuring kinetic variables during cycling, and three studies because they were not investigating topics within the aim of this review.

For the aim of investigating the effects of asymmetry during cycling on injury or performance, of the articles that met the inclusion criteria for this review, no studies assessed the effects of cycling asymmetrically on the incidence of injury. Two studies assessed the effect of asymmetry on cycling performance (27,38). Information about these studies is presented in **Table 2.1** and **Figure 2.2**.

For the aim of investigating the conditions under which asymmetries are most prevalent, fifteen studies assessed the association between cycling intensity and asymmetry (39–53). Five studies assessed the association between cadence and asymmetry (46,47,51,54,55). Three studies assessed the effect of bicycle configuration or cycling position on asymmetry (50,54,56). Two studies assessed the effect of the participants' performance level on asymmetry (16,17) and two studies assessed whether cycling asymmetries can be ameliorated using interventions (57,58). Information about these studies are presented in **Table 2.2** and **Figure 2.3**.

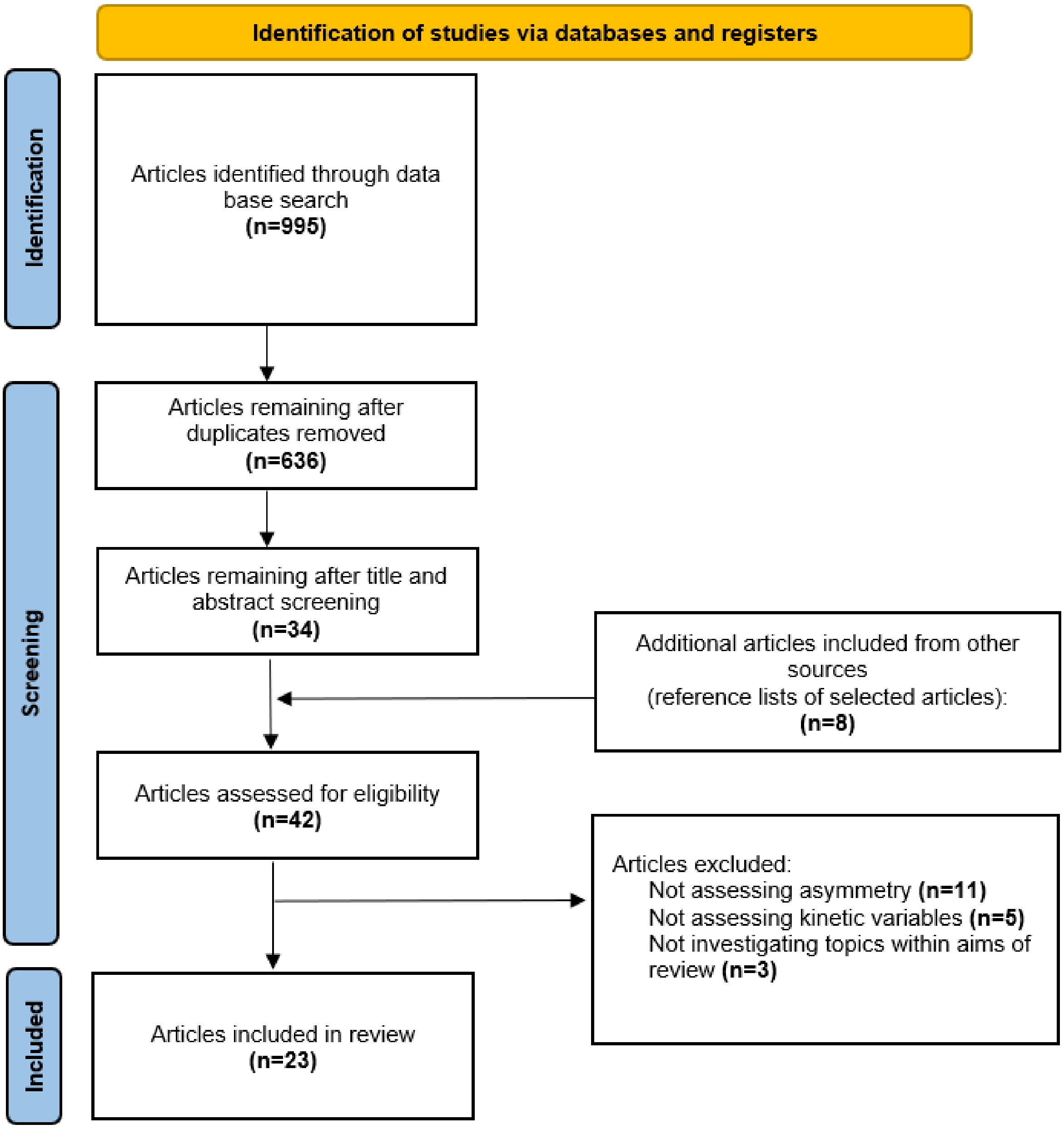


Figure 2.1 A flow diagram of the study selection process.

Table 2.1 A summary of studies investigating the effect of asymmetry on cycling performance.

Reference	Participants	Experimental protocol	Asymmetry Indices (AI%)	Association Observed (Y/N)
The effect of asymmetry on cycling performance				
Bini and Hume 2015 (27)	n=10, competitive cyclists or triathletes.	Laboratory time trial, 4 km.	AI% range: 36 to 54% (propulsive force), 11 to 21% (total force), 21 to 32% (index of effectiveness).	Y. Effective force: r=-0.72, resultant force: r=0.01, index of effectiveness: r=-0.29).
Bini et al 2016 (38)	n=15, 11 males, 4 females, cyclists or triathletes	Laboratory time trial, 20 km.	Mean AI%: -3 ± 20%, range 43% in favour of dominant limb to 34% in favour of non-dominant limb.	N. r=0.01

Figure 2.2 A summary of the association between asymmetry and cycling performance.

Donut Chart: central value is the number of studies investigating this question, data labels are the number of studies that reported that an association had or had not been observed between the dependant and independent variables. The people graph provides information on the combined participant numbers in studies that reported that an association had or had not been observed between the dependant and independent variables.

Table 2.2 A summary of studies investigating the effect of cycling conditions on asymmetry.

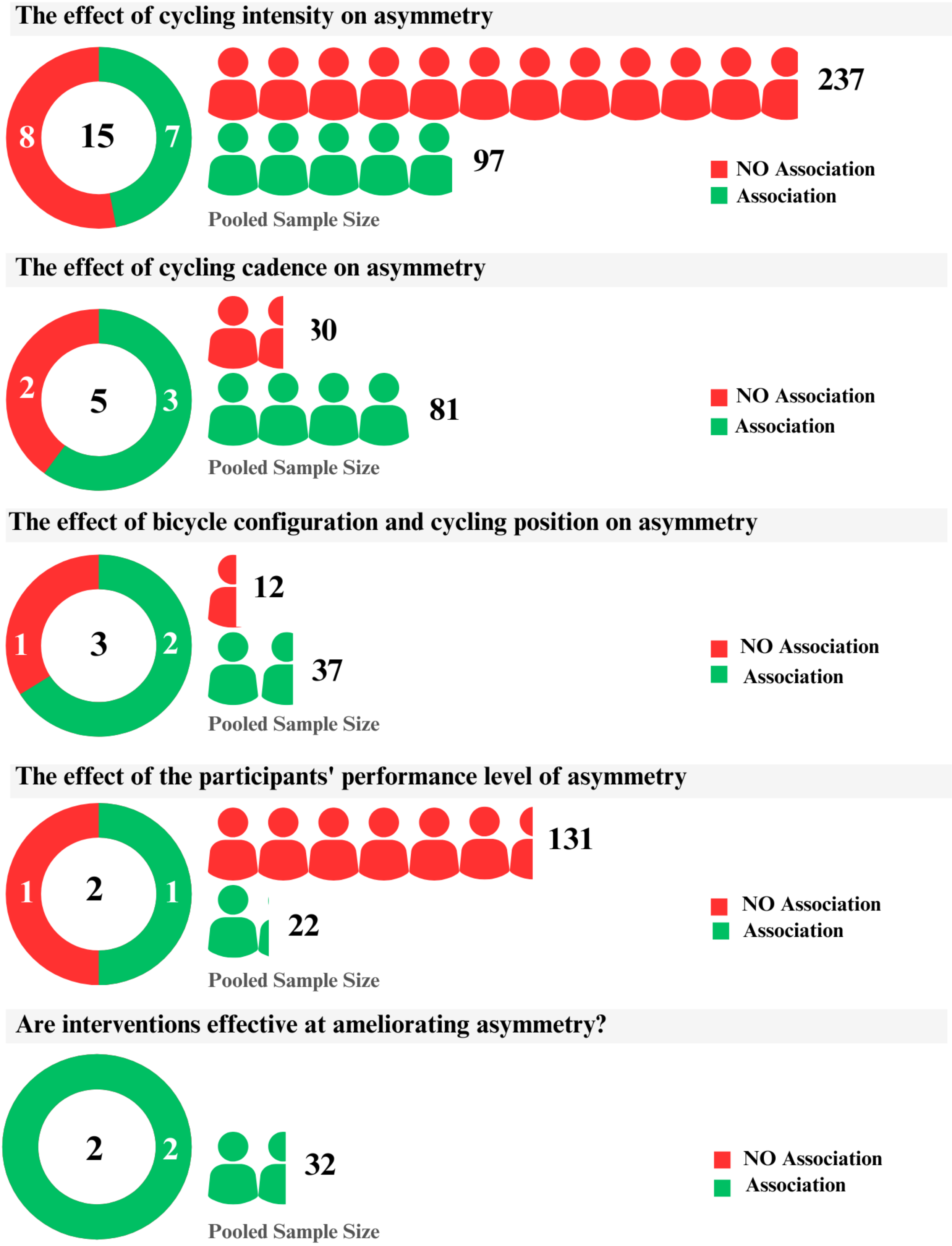
Reference	**Participants**	**Experimental protocol**	**Asymmetry Indices (AI%)**	**Association Observed (Y/N)**
The effect of cycling intensity on asymmetry				
Bertucci *et al.* 2012 (44)	n=11, masters cyclists.	Sub-maximal incremental test (100 to 250 W).	Mean AI%: 30 ± 8 (100 W), 23 ± 13 (250 W).	N.
Bini and Hume 2014 (43)	n=10, cyclists/triathletes [7 males, 3 females].	Maximal incremental test (150 W + 25 W/min).	Crank Mean AI%: 6 ± 17 (100 W), 4 ± 15 (150 W), 8 ± 17 (200 W), 5 ± 15 (250 W), 13 ± 20 (300 W), 27 ± 18 (350 W). Pedal Mean AI%: 11 ± 28 (100 W), 20 ± 33 (150 W), 22 ± 30 (200 W), 28 ± 31 (250 W), 36 ± 33 (300 W), 51 ± 36 (350 W).	Y.
Bini *et al.* 2007 (42)	n=11, male cyclists.	Maximal incremental test.	Highest AI% 3%.	N.
Carpes *et al*. 2007 (53)	n=6, male, competitive cyclists.	Laboratory time trial, 40 km. Analysed at four equal time segments.	Mean AI%: 8.91 ± 0.7% (segment 1), 13.51 ± 4.17% (segment 2), 17.28 ± 5.11% (segment 3), 0.32 ± 2.92% (segment 4).	Y.
Carpes *et al.* 2008 (41)	n=6, amateur and competitive cyclists.	Maximal incremental test (100 W + 25 W/min).	Mean AI% <10% (intensities <50% $\dot{V}O_2$ peak), Mean AI% >25% (intensities >90% $\dot{V}O_2$ peak).	Y.
Da Silva Soares 2017 (52)	n=20, amateur cyclists	Submaximal trials at 60, 80, 95% MAP.	No AI%. Significant differences between limbs in torque curves.	N.
Daly and Cavanagh 1976 (51)	n=20, males.	Nine trials at varied intensities and cadences.	AI% range: 44 to 74%, no significant difference between intensity conditions (p>0.05)	N.
Diefenthaeler *et al.* 2016 (50)	n=12, national and regional level cyclists.	Constant load trial (6 min) and 30 s Wingate.	Mean AI%: 6.68% (constant load test), 9.49% (Wingate).	N.
Farrell *et al.* 2021 (49)	n=22, 11 male, 11 female. 2 groups: Cycling experience (CE) or no cycling experience (NCE).	Maximal incremental test (1 W/kg + 0.5 W/kg every 3 min). Assessed at 2 mmol/L blood lactate concentration (BLa), 4 mmol/L BLa and peak power output (PPO).	CE Mean AI% for power: -11.5 ± 28.0 (2 mmol BLa), -4.5 ± 23.3% (4 mmol BLa), -1.7 ± 23.0% (PPO). NCE Mean AI% for power: 4.2 ± 11.0% (2 mmol/L BLa), 1.8 ± 6.8% (4 mmol/L BLa), 3.5 ± 5.1% (PPO).	N.
Garcia-Lopez 2015 (48)	n=131, n=47 professional cyclists, n=84 amateur cyclists.	3 x 5 min trials at 200, 250 and 300 W.	No AI% reported. Professional cyclists: significant difference between limbs for mean torque and positive impulse. Amateur cyclists: significant difference between limbs for mean torque and positive impulse.	N.

Hunt *et al.* 2004 (47)	n=10, uninjured people (5 male, 5 female).	Six trials at varied intensities and cadences.	Mean AI% in power output at 75 W: 13% (60 rpm), 18% (90 rpm). Mean AI% in power output at 125 W: 12% (60 rpm), 14% (90 rpm). Mean AI% in power output at 175 W: 8% (60 rpm), 11% (90 rpm).	N.
Javaloyes *et al.* 2020 (45)	n=12, professional cyclists (male)	Three week cycling event (Giro d'Italia).	Mean AI% flat stages: 4.21% (Z1), 3.93% (Z2), 3.41% (Z3), 3.22% (Z4), 3.03% (Z5), 2.84% (Z6), 2.70% (Z7). Mean AI% semi mountainous stages: 4.72% (Z1), 5.15% (Z2), 4.57% (Z3), 4.31% (Z4), 4.25% (Z5), 4.30% (Z6), 4.20% (Z7). Mean AI% mountainous stages: 4.58% (Z1), 4.30% (Z2), 3.77% (Z3), 3.66% (Z4), 3.69(Z5), 3.78%. (Z6), 3.59% (Z7).	Y.
Sanderson 1990 (46)	n=45.	Six trials at varied intensities and cadences.	Mean AI% in total force: 8.83% (100 W), 9.47% (235 W). Mean AI% in propulsive force: 12.33% (100 W), 7.87% (235 W).	Y.
Stefanov *et al.* 2020 (40)	n=8, male, student cyclists	Sub-maximal incremental stage (35, 55 and 85% HRR).	Mean AI%: 10.7% (55% HRR), 6.3% (85% HRR).	Y.
Trecoci *et al.* 2018 (39)	n=10, male, elite cyclists.	Maximal incremental test (100 W + 25 W/min).	Mean AI%: -2.12 ± 9.05% (first stage), 5.61 ± 6.62% (last stage).	Y.
The effect of cycling cadence on asymmetry				
Daly and Cavanagh 1976 (51)	n=20, males.	Nine trials at varied intensities and cadences.	AI% range: 44 to 74%, significant difference between cadence conditions ($p \leq 0.05$) varied between days.	N.
Gonsalez-Sanchez *et al.* 2019 (54)	n=25, indoor cycling instructors.	Indoor cycling session of varied intensities and cadences.	Mean AI%:12.6 ± 11% (75 rpm), 30.4 ± 39.2% (120 rpm).	Y.
Hunt *et al.* 2004 (47)	n=10, uninjured people (5 male, 5 female).	Six trials at varied intensities and cadences.	Mean AI% in power output at 60 rpm: 13% (75 W), 12% (125 W), 8% (175 W). Mean AI% in power output at 90 rpm: 18% (75 W), 14% (125 W), 11% (175 W).	N.
Sanderson 1990 (46)	n=45.	Six trials at varied intensities and cadences.	Mean AI% in total force at 100 W: 9.2% (60 rpm), 9.5% (80 rpm), 7.8% (100 rpm). Mean AI% in propulsive force at 100 W: 11.7% (60 rpm), 14.2% (80 rpm), 21.1% (100 rpm). Mean AI% in total force at 235 W: 9.8% (60 rpm), 9.6% (80 rpm), 9.0% (100 rpm). Mean AI% in propulsive force at 235 W: 8.9% (60 rpm), 7.2% (80 rpm), 7.5% (100 rpm).	Y.

Smak *et al.* 1999 (55)	n=11, male, competitive cyclists.	Five trials at 250 W, at randomised cadences of 60 - 120 rpm.	Mean AI% for negative power: 29.1% (60 rpm), 21.2% (75 rpm), 16.3% (90 rpm), 12.2% (105 rpm), 10.1% (120 rpm).	Y.
The effect of bicycle configuration and cycling position on asymmetry				
Chen 2016 (59)	n= 12, healthy cycling (9 male, 3 female)	4 x 2 min intervals at varied cycling positions.	Mean AI%: 19.25% (sitting positions), 7.55% (standing positions).	Y.
Diefenthaeler *et al.* 2016 (50)	n=12, national and regional level cyclists.	Constant load trial (6 min) and 30 s Wingate at three saddle height conditions.	Mean AI%: 8.28% (reference saddle height), 10.65% (saddle down), 5.33% (saddle up).	N.
Gonsalez-Sanchez *et al.* 2019 (54)	n=25, indoor cycling instructors.	Indoor cycling session of varied intensities and cadences.	Mean AI%: 52.2 ± 76.6% (standing), 12.4 ± 9% (seated).	Y.
The effect of the participants' performance level on asymmetry				
Farrell *et al.* 2021 (49)	n=22, 11 M, 11 F 2 groups: Cycling experience (CE) or no cycling experience (NCE).	Maximal incremental test (1 W/kg + 0.5 W/kg every 3 min).	AI% range, peak torque: -4.1 to 1.5% (CE), 3.0 to 11.2% (NCE). AI% range, mean torque: -0.7 to -4.5% (CE), 1.2 to 3.8% (NCE). AI% range, power: -1.7 to -11.5% (CE), 1.8 to 4.2% (NCE).	Y.
Garcia-Lopez 2015 (48)	n=131, n=47 professional cyclists, n=84 amateur cyclists.	3 x 5 min trials at 200, 250 and 300 W.	AI% <2% for all performance levels.	N.
Are interventions effective at ameliorating asymmetry?				
Bini *et al.* 2017 (57)	n=20, male, cyclists or triathletes.	3 x 1 min trials at 70% MAP, followed by 12 x 1 min trials at 70% MAP.	Mean AI%: -27 ± 14% (pre-intervention), -7 ± 9% (post intervention).	Y.
Kell and Greer 2017 (58)	n=12, 7 males, 5 females.	3 x 10 min trials at 60% $\dot{V}O_2$ peak, under 3 conditions.	Mean AI% all participants: 5.1 ± 4.8% (baseline), 4.3 ± 4.4% (conscious pedalling), 2.9 ± 2.0% (visual feedback). Mean AI% initially asymmetrical participants: 8.1 ± 4.1% (baseline), 6.1 ± 5.0% (conscious pedalling), 3.5 ± 2.3% (visual feedback).	Y.

Abbreviations; BLa: blood lactate accumulation, HRR: heart rate reserve, MAP: maximal aerobic power, PPO: peak power output, rpm: revolutions per minute, Z: training zone.

FIGURE 2.3 A summary of the association between cycling conditions and asymmetry.



Donut Chart: central value is the number of studies investigating this question, data labels are the number of studies that reported that an association had or had not been observed between the dependant and independent variables. The people graph provides information on the combined participant numbers in studies that reported that an association had or had not been observed between the dependant and independent variables.

2.4 DISCUSSION

The aims of this review were twofold. Firstly, to investigate whether asymmetries during cycling are associated with incidence of injury or with cycling performance. Secondly, this review aimed to examine the conditions under which asymmetries are most prevalent during cycling. This included reviewing studies which assessed the effects of manipulating intensity, cadence, bicycle configuration and cycling position on asymmetry. Furthermore, we reviewed studies which investigated the effects of participant performance level on asymmetry and whether interventions were effective at ameliorating the magnitude of asymmetry during cycling.

2.4.1 The effects of cycling asymmetry on the incidence of injury

To the best of our knowledge, there are no studies that specifically assess the effect of cycling asymmetrically on the occurrence of injury. There are a lack of longitudinal studies that assess the effects of cycling asymmetry on the development of overuse injuries during cycling.

Overuse injuries are common in cycling, mostly effecting the knee (20–25). Knee pain is reported to affect 40 to 60% of recreational cyclists and 36 to 62% of professional cyclists (21). Knee injuries are reported to affect between 24 to 62% of professional cyclists (23). In a study of seven road cycling teams certified to participate in international competitions by the UCI, of the one hundred and nine cyclists interviewed, knee injuries were reported as the most likely cause for time loss from cycling (23). Cyclists may present with knee pain for numerous reasons, including a sub-optimal bicycle set up or poor biomechanics. For example, medial projection of the knee is said to increase the lateral shear at the joint, which could trigger knee injury (60). Furthermore, high training volumes, cycling with high gear ratios and low cadences, and hill climbing all induce repetitive or heavy patellofemoral joint loads which may increase the likelihood of overuse injury (26). Therefore, asymmetries in kinetic and kinematic parameters of cycling may provide insight for lower limb injury risk.

It is well accepted that existing injuries could result in the presence of asymmetry during cycling. A study assessing the cycling kinetics of participants with an anterior cruciate ligament (ACL) injury observed significantly larger asymmetries in an injured participant group compared to the healthy controls (47). In those with a unilateral ACL deficiency, the non-injured limb contributed up to nearly 50% more of the power output required than the ACL deficient limb (47). The authors of this study describe that cycling exercise is frequently prescribed for ACL rehabilitation, but its effectiveness for building muscle strength may be lessened if the uninjured limb is compensating for the injured limb. They suggested that providing participants with feedback on their cycling asymmetry, or prescribing single leg cycling might encourage greater activation of the injured limb (47). In studies that investigated interventions to ameliorate asymmetries, cyclists who presented with initially considerable asymmetries were able to adjust their pedalling to significantly reduce the magnitude of interlimb difference with verbal and visual feedback (57,58), which might be a useful addition to cycling rehabilitation in those with ACL injuries.

In contrast to the previous study (47), an assessment of individuals with knee osteoarthritis (OA) saw that the more affected limb generated significantly more power than the less affected limb during cycling (61). When asked to exert effort to match a target force, participants with knee OA overshot the target force compared with healthy controls, suggesting there was an inability to gauge muscular effort in the injured cohort (61).

Whilst a known injury is likely to result in asymmetrical cycling, it is unknown whether regularly cycling with an asymmetrical load could result in the development of an overuse injury in otherwise healthy cyclists.

Bicycle configuration, cycling technique and/or training load are all suggested to affect the likelihood of developing overuse symptoms or injures (20,21,25). However, a systematic review of factors associated with overuse injuries in cyclists found no strong evidence of a relationship between any bike, body or load parameter and cycling overuse symptoms or injury (62). Additionally, a review investigating bilateral asymmetries across sporting disciplines found no direct evidence from either observational of interventional studies to sustain the claims that interlimb asymmetries increase injury occurrence (63).

The hypothesis that repetitive asymmetrical load of the lower limbs during high volumes of training is a risk for overuse injury, particularly of the limb contributing most, is logical but lacking evidence. There is a need for longitudinal studies investigating the frequency and severity of injury or symptoms in cyclists who present with an asymmetry during cycling, vs those who cycle with a more even bilateral contribution.

2.4.2 The effect of asymmetry on cycling performance

Cycling performance is associated with the ability to produce high maximal aerobic power and to sustain high relative power outputs for the duration of an event (64,65). Asymmetry during cycling could be interpreted as one limb performing sub-optimally and therefore limiting overall power output. Alternatively, it could be construed that the limb producing the highest power output is at risk of premature fatigue, which could also result in a decline in the power output that could be sustained during an event.

Two studies assessed the association between asymmetry and cycling performance during laboratory based simulated time-trials (27,38). However, the results of these studies are conflicting. In a group of fifteen male and female cyclists or triathletes, no clear association was observed between performance and peak pedal force asymmetries during a time-trial performed over a 20 km distance (38). Contrary to these findings, Bini and Hume (2015) did observe a negative association between asymmetry and performance (27). Larger asymmetries in effective force were related to better 4 km time trial performances in a group of ten competitive cyclists or triathletes, which is opposed to suggestions that asymmetries may be performance limiting. However, amongst the ten participants in this study, 4 km performance times and asymmetry indices varied considerably (27). Performance times varied by ~42% between participants and group mean effective force asymmetries varied between 36 to 54% throughout the time trial, with standard deviations of 26 to 36% (27). The considerable variation in both performance times and asymmetry indices during this study questions whether there is sufficient evidence to determine that asymmetries are negatively associated with cycling performance.

Although they did not specifically measure asymmetries during cycling, Rannama *et al.* (2015) measured the bilateral strength of male competitive road cyclists using isokinetic dynamometry. They observed that asymmetries in peak isokinetic torque of the knee extensors were negatively correlated with 5 s maximal power output during sprint cycling (66), suggesting that asymmetries in strength may be performance limiting to sprint cycling.

Bishop *et al.* (2017) conducted a systematic review investigating the effects of interlimb asymmetries on physical and sports performance and reported that findings in this field are often inconsistent (67). A critical review by Maloney (2019) agreed with this conclusion, stating the need for randomised control trials to differentiate between training induced improvements in performance and the direct reduction in sporting asymmetries (4).

As there are numerous participant factors that affect performance, including physiological parameters and training status, a within participant study design may be more appropriate for assessing the association between cycling asymmetry and cycling performance.

2.4.3 The effect of cycling intensity on asymmetry

Both maximal and sub-maximal intensity performance indicators, such as peak power output, power output at lactate threshold and power to weight ratio, are predictive of cycling performance (26). To increase cycling power output at a fixed angular velocity or cadence, cyclists might increase the gear on their bicycle which in turn requires the generation of larger muscular forces to rotate the cranks.

Fifteen studies assessed the effect of cycling intensity on the magnitude of asymmetry (39–53) using a range of protocols to assess this association. Eight studies, with a pooled sample size of two hundred and thirty seven participants, reported no effect of cycling intensity on the magnitude of asymmetry during protocols including constant load trials (47,48,50–52), incremental cycling tests (42,44,49) and supra maximal cycling (50). Alternatively, seven studies with a pooled sample size of ninety-seven participants did observe an effect of cycling intensity on asymmetry. However, the direction of the effect was varied. Assessed during incremental cycling tests, two studies reported a positive association between asymmetry and intensity, with larger asymmetries occurring during the higher intensity stages of the test (39,43). In contrast, two other studies assessing asymmetries during incremental cycling tests saw the opposite effect, reporting that asymmetries were greatest during the initial lower intensity stages and that asymmetries were negatively associated with intensity (40,41). Negative associations between asymmetry and intensity were also present during randomised controlled trials of varied intensities (46) and laboratory-based time trials (53). Javaloyes *et al.* (2020) also observed a negative association between cycling intensity and asymmetry, and were the only study to investigate this research questions using data collected from professional cyclists during a cycling event (45). They assessed the asymmetries of members of a UCI World-Tour professional cycling team during mass start stages of the Grand Tour event, the Giro d'Italia (45). They assessed asymmetries when cycling in different training zones, which were defined relative to each of the cyclist's functional threshold power (FTP). The magnitude of the calculated asymmetry indices in power output reduced as cycling intensity increased, suggesting that there was a negative association between intensity and asymmetry. However, when analysing the data by team role, this effect was observed in those cyclists considered 'helpers' and not those considered 'climbers', which the authors hypothesised was related to the helper role eliciting higher rates of fatigue during moments of a higher power output to lead the 'climbers' into a good position before they attack (45).

There is a larger weight of evidence demonstrating that there is no clear association between asymmetry and cycling intensity. Amongst the literature, significant asymmetries have been observed at low, moderate, maximal, and supramaximal intensities. Conversely, symmetry has also been observed across the intensity spectrum.

Reviewing the literature, varied definitions of asymmetry may affect the interpretation of the results between studies. To illustrate this, one study observed significant asymmetries during the final stage of an incremental test, that were not present at the initial workload (39). However, the observed mean interlimb differences at the final workload were 5.61 ± 6.62% (39), a difference that other studies would report as below the 10% threshold to be considered 'asymmetrical'.

The influence of fatigue is a potential limitation to the use of time-trials or maximal incremental cycling tests to assess the effect of intensity on asymmetry. The highest intensities occur towards the end of these protocols, when the participant is arguably most fatigued (43). In the study of professional cyclists during the Giro d'Italia, Javaloyes *et al.* acknowledged that the cumulative fatigue during the race stages was not accounted for in their data and likely had an effect on their data (45). Fatigue is reported to effect the coordinative patten of cycling (68). Asymmetries in power output were observed to decrease significantly throughout 30 s supramaximal cycling (69), suggesting a sensitivity to fatigue. However, decreases in cadence with fatigue during the supramaximal efforts in this study could also contribute towards changes in inter-limb asymmetry (69).

A review on the influence of exercise induced fatigue on interlimb asymmetries stated that it is not possible to derive explicit conclusions on this topic as inconsistent findings and heterogenous study characteristics make it difficult to systematically review the literature in this field (70). However, some studies have explored this interaction and reported an effect of fatigue on asymmetry. Melo *et al.* (71) assessed global symmetry index (GSI), a combined measure of symmetry in three planes of movement collected using accelerometers. They reported that GSI decreased in the final 20% of a 10km running trial suggesting that asymmetry is exacerbated by fatigue (71). Alternatively, during a set of eight barbell back squats performed at 90% of eight repetition maximum, asymmetries in bilateral ground reaction force decreased throughout the set in participants who presented with an initial asymmetry (72). However, in this study, later repetitions within the set were performed more slowly compared to earlier repetitions, therefore rate of movement could be a factor influencing asymmetry indices in this study (72).

To the best of our knowledge, the effects of fatigue on cycling specific asymmetries has not been investigated.

2.4.4 The effect of cadence on asymmetry

Power output during cycling is a product of torque and cadence. Optimal cadence has been defined as the pedalling rate which minimises energetic cost, muscular stress or perception of effort (73). However, different cadences are required to achieve each of these varied definitions of 'optimal', leading to conflicting opinions about which cadence should be selected to maximise performance (73). For a given power output, increasing pedalling cadence reduces the muscular forces required per pedal revolution and encourages recruitment of more energy efficient Type I muscle fibres (65). However, higher cadences require greater oxygen uptake and energy expenditure (65).

Five studies assessed the effect of cycling cadence on the magnitude of asymmetry (46,51,54,55). Four studies conducted randomised, fixed cadence trials (46,47,51,55) and one study assessed the asymmetries of cycling instructors during a planned continuous indoor cycling session consisting of intervals which varied in cadence (54).

Two studies, with a pooled sample size of thirty participants, reported no clear effect of cadence on the magnitude of asymmetry (47,51). During 2 min cycling trials of varied intensities and cadences, in an uninjured control group, Hunt *et al.* (2004) reported a trend towards greater asymmetries as cadence increased from 60 rpm to 90 rpm, however differences in asymmetry indices were not significant between conditions. Daly and Cavanagh (1976) observed significant differences in work asymmetry indices between cycling trials at cadences of 40, 70 and 100 rpm. In this study, all conditions were repeated trials during two visits to the laboratory and the authors reported the presence of large variability in asymmetries both within and between days, with no clear trend on the effect of cadence on cycling asymmetries (51).

Conversely, three studies with a pooled sample size of eighty one participants did observe an effect of cycling cadence on the magnitude of asymmetry (46,54,55). Two of these studies reported that asymmetries were greater at higher cadences (46,54). Power output asymmetries were greater at cadences of 120 rpm (30.4 ± 39.2%), compared to cadences of 75 rpm (12.6 ± 11%) in a group of indoor cycling instructors (54). In a study of male and female cyclists of varied experience levels, increasing cadence from 60 rpm to 100 rpm at low intensities (100 W), resulted in significantly larger asymmetries in propulsive force (46). However, this effect was not present when increasing cadence at higher power outputs (235 W) (46). Smak *et al.* (1999) assessed the effects of cadence on asymmetry in a group of competitive cyclists at a fixed intensity of 250 W (55). Although they did not see an effect of cadence on total or positive crank power, they did observe that as cadence increased from 60 to 120 rpm, there was a decrease in negative (resistive) power asymmetry (55). This was also evidenced by a smaller hip extensor torque in the non-dominant limb during the upstroke.

The alternating bilateral technique of cycling requires coordination and effective activation and deactivation (relaxation) dynamics to ensure the limb in the recovery phase (upstroke) is not impeding the work of the limb in the propulsive phase (downstroke) by producing excessing negative torque (74). At higher cadences, relatively more time is consumed by the activation and relaxation process (75). If at lower intensities one limb is conducting this process ineffectively and generating larger negative or resistance forces for the limb in the power phase to overcome, it is plausible that the magnitude of asymmetry may increase at faster cycling cadences.

There is a larger weight of evidence to suggest that there is an association between cycling cadence and asymmetry. However, this effect may be dependent upon cycling intensity, participant performance level and freely chosen cadence. Individual analyses may be required to understand case by case effects of cadence on asymmetry.

2.4.5 The effect of bicycle configuration and cycling position on asymmetry

The transfer of power from the human body to the drive train of the bicycle depends upon factors including crank length, foot position on the pedal, seat height and seat tube angle (65). Adjusting these components of a bicycle can affect muscle activation, pedal force application, lower limb kinematics and the energy cost of cycling.

One study by Diefenthaler *et al.* (2016) investigated the effect of saddle height on the magnitude of asymmetry (50). Participants visited the laboratory on three occasions to conduct cycling trials at three randomised saddle heights. These included the participants preferred saddle height and heights adjusted higher and lower by 2.5% of their inseam leg length. Asymmetries were present at all saddle heights and but were not significantly different between saddle height conditions during sub maximal or supra maximal cycling (50). Based upon this study (50), adjusting saddle height does not appear to affect the magnitude of asymmetry.

A review by Bini *et al*. (2011), which investigated the effects of saddle height on knee injury risk and performance in cycling, described that saddle height effects oxygen uptake and energy expenditure, power output, cycling economy and time to exhaustion in constant load trials (76). They also reported that a 5% change in saddle height affects force production and joint moments, joint angles and muscle length. Furthermore, the authors of this review described that cyclists self-selected saddle heights differ to that which minimise oxygen uptake and joint moments (76). It is justifiable that Diefenthaeler *et al*. (2016) chose the participants preferred saddle height as the reference, as this best reflects their typical cycling conditions (50). However, it is possible that the participants preferred saddle heights were sub optimal and that changes in saddle height were not sufficient to observe an effect.

Cycling can be performed in seated and standing positions and cyclists often transition from seated to standing positions during ascensions or periods of rapid acceleration (77). Two studies assessed asymmetry during cycling in seated and standing positions (54,59), however results are conflicting. A group of twenty five cycling instructors pedalled to the beat of music that matched a desired cadence (54). During low intensity intervals, the cycling instructors produced greater asymmetries in power output in the standing position compared to intervals performed in the seated position (54). However, intensities were not controlled, and power output was lower in the intervals performed in the standing position compared to standing.

In contrast, a group of twelve healthy cyclists produced greater asymmetries in power output in seated positions compared to standing positions, during laboratory based trials (59). Again, intensities were not controlled in this study and during the standing intervals torque produced was threefold of that produced during the seated positions. The cycling trials in this study were two minutes in duration with a 1:1 work to rest ratio. The standing intervals occurred after the seated intervals in a non-randomised order, therefore the results could have been affected by fatigue. Furthermore, the cycling trials were performed at low cadences of 50 rpm and the figures included in this research article depict participants cycling bare foot. These methods limit the ecological validity of these findings as cyclists typically cycle at cadences of 70 to 90 rpm and use cycling cleats which fix the shoe to the pedal.

2.4.6 The effect of the participants' performance level on asymmetry

The training and physiological characteristics of cyclists, such as maximum oxygen uptake, peak power output and training volume, vary depending on performance level (78,79).

Of the articles selected for review, two studies assessed the association between the performance level of participants and the magnitude of asymmetry (48,49). A study by Garcia-Lopez *et al.* (2015) reported no difference in the magnitude of asymmetry between cyclists of club level to professional, during incremental cycling (48). They reported asymmetry indices of <2% for cyclists of all performance levels. The authors of this study recognised that their findings are in contrast to many others that observe much larger asymmetries during cycling but support their findings with kinematic data that was also considered symmetrical. This article is presented as a conference proceeding with limited details to critically assess why asymmetries were not present in these cohorts.

Alternatively, Farrell *et al*. (2021) did report an effect of performance level on asymmetries during an incremental cycle test. The participants' performance level were determined using training volume with the completion of <10 hrs per week over the previous 6 months classified as 'non-experienced', or ≥10 hrs per week over the same period classified as 'experienced'. In this study greater asymmetries in peak crank torque were observed in the non-experienced cyclists when compared to experienced cyclists (49). They also observed significant differences between groups for the absolute asymmetries in power output, with larger asymmetries observed in the experienced cycling group. This difference was not observed between groups when asymmetries in power output were presented as relative asymmetry indices. The experienced cycling group produced significantly higher power outputs, which may explain why group effects were observed for absolute interlimb differences and not for relative interlimb differences. Furthermore, some participants presented large negative asymmetry indices, which may affect results when averaged across a participant group.

Questions remain about whether asymmetries differ between cyclists of different performance levels. If more experienced cyclists do present with larger asymmetries, as reported by Farrell *et al.* (2021), it is still unknow if this occurs because cycling asymmetrically is advantageous for performance, or because the high volumes of training provide greater adaptation in a dominant limb resulting in the development of bilateral asymmetries.

2.4.7 Are interventions effective at ameliorating asymmetry?

During single training sessions, it has been observed that with the provision of feedback on the application of pedal forces, cyclists and non-cyclists can improve their pedal force effectiveness (80), defined as the ratio of force perpendicular to the crank (effective force) and total force applied (resultant force). Two studies have investigated whether the provision of feedback enables cyclists to reduce the magnitude of asymmetry during sub-maximal cycling (57,58). Kell and Greer (2017) asked participants to cycle for 10 min intervals at 60% of their $\dot{V}O_2$ peak and 80 rpm (58). They provided visual feedback on the percentage of total power each limb was contributing and instructed participants to 'try to pedal symmetrically'. They reported that with this feedback, participants with initial asymmetries within the typical range of 5 to 20% saw relative decreases in asymmetry indices by 46.2%. Interestingly, they also observed that participants with low initial asymmetries (<2.0%) demonstrated small increases in their asymmetry indices of ≤2.0% with the provision of this feedback (58). Bini *et al.* (2016) provided a similar intervention during 1 min trials of cycling at 70% of MAP and 90 rpm (57). Cyclists who presented with initial asymmetries >20% conducted pedal retraining intervals at the same intensity whilst being shown visual feedback of their lower limb contribution and being verbally instructed to increase the force of their 'weaker limb' and decrease the force of their 'stronger limb'. Following this acute intervention, asymmetries in these participants decreased to -7% ± 9% (57).

Both studies reported that participants who presented with initially considerable asymmetries were able to significantly reduce the magnitude of their bilateral asymmetries with verbal (57) and visual feedback (57,58) demonstrating that cyclists are able to adjust their pedalling technique to ameliorate the magnitude of asymmetry. It is unknown whether these effects are lasting, or whether attenuating these lower limb differences is desirable, as there is no conclusive evidence to suggest that asymmetries are performance limiting in cycling.

The findings of these studies do suggest the need to blind participants to the measurement of bilateral asymmetries to obtain data that truly reflects the participants' technique. However, of the twenty three studies included in this review, only two studies describe blinding their participants to the measure of asymmetry (53,54).

2.5 CONCLUSION AND FUTURE DIRECTIONS

This review aimed to investigate whether asymmetries during cycling are associated with incidence of injury or with cycling performance. There is a lack of evidence to substantiate these claims. To the best of our knowledge there are no longitudinal studies that assess whether participants who cycle asymmetrically have a higher incidence of overuse injury to establish a cause and effect. Further research is also required to understand the association between asymmetry and cycling performance as the few studies that have assessed this relationship have conflicting findings.

This review also aimed to examine the conditions under which asymmetries are most prevalent. The current literature does not identify a clear effect of exercise intensity on cycling asymmetry due to large participant variation in asymmetry indices and the presence of significant asymmetries across the spectrum of cycling intensities.

Based upon the current evidence, there appears to be an association between asymmetry and cycling cadence. Asymmetries appear to be exacerbated when increasing cadence at low to moderate cycling intensities. Increasing cadence has also resulted in decreases in asymmetry indices in negative power output, which is resistive against the propulsive power of the limb in the power phase (55). However, the effects of cadence appear to be highly variable and could be influenced by performance level and pedalling technique. When assessing the effect of bicycle configuration, there was no clear association between saddle height and asymmetry. Further research is required to understand whether cycling position, such as seated or standing cycling, effects the magnitude of asymmetry. The effect of performance level on cycling asymmetry is unclear, as current studies have conflicting findings. Studies have demonstrated that with visual or verbal feedback, participants are capable of temporarily adjusting their technique, and the manner at which they apply force around the pedal cycle, to pedal more symmetrically (57,58). However, it is still unclear whether attenuating these lower limb differences is desirable, as there is no evidence to suggest that asymmetry is performance limiting.

Amongst the existing literature, there is a lack of evidence or conflicting findings when attempting to answer the research questions raised in this review. It is challenging to critically review articles in this field to understand why results might be conflicting as there is considerable variation in the methodological design of studies that assess asymmetry during cycling. To elaborate on this, variation in the included studies exists amongst participants, equipment used to assess asymmetry, protocol design and the interpretation of data. There is a need to identify an optimal method for the assessment of bilateral asymmetries during cycling in non-injured populations (27) in the interest of understanding this topic. Once best practice is identified, future studies are required to understand the effects of asymmetry on injury occurrence and performance, as well as the conditions under which asymmetries are most prevalent.

CHAPTER 3

A methodological review: the measurement, analysis, and interpretation of interlimb asymmetries during cycling.

3.1 INTRODUCTION

Power meters fitted to a bicycle enable the measurement of bilateral forces for the assessment of asymmetry during cycling (19,32). It is accepted that asymmetries are common during cycling, with interlimb differences in uninjured cyclists typically ranging between 5 to 20% (3). It has been hypothesised that cycling asymmetrically may increase the risk of developing overuse injuries, and could compromise performance due to premature fatigue (3)**.** However, in **Chapter 2**, we determined that there is a lack of evidence to support these claims, or to establish any cause or effect of cycling asymmetrically with regards to injury or performance.

In **Chapter 2** we also concluded that many research studies demonstrate conflicting findings, which could in part be attributed to the varied methods used to measuring, analysing and interpreting asymmetry data. Currently, there is no current consensus on the best practise for assessing asymmetries during cycling (27) and there is considerable variation in the methods of assessing and interpreting bilateral asymmetries in cycling research. When assessing a cyclist for asymmetry, consideration must be taken for each of the following methodological components in isolation, and their interaction: 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 differences and 6) the magnitude of interlimb difference required to be considered asymmetrical.

There is a need to identify an optimal method for research and applied practise in this field (27). Therefore, the initial aim of this review was to assess cycling asymmetry literature to determine variance in the methodological approaches to measuring, analysing and interpreting asymmetries during cycling. Secondly, this review aimed to critically assess the varied methods to determine a best practice for measuring and interpreting asymmetries during cycling.

3.2 METHODS

A review of the literature was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (37). A diagram of the study selection process is shown in **Figure 3.1**. A literature search was performed in PubMed, Google Scholar, Scopus and Medline databases up to October 2022. 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').

3.2.1 Inclusion Criteria

As shown in **Figure 3.1**, studies were included 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.

3.2.2 Data Extraction

From the included studies, the following descriptive data were extracted to investigate methods used to quantify asymmetry during cycling (**Table 3.1**): 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.

3.3 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 eight articles. A diagram of the study selection process is shown in **Figure 3.1**

Of these forty-two 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.

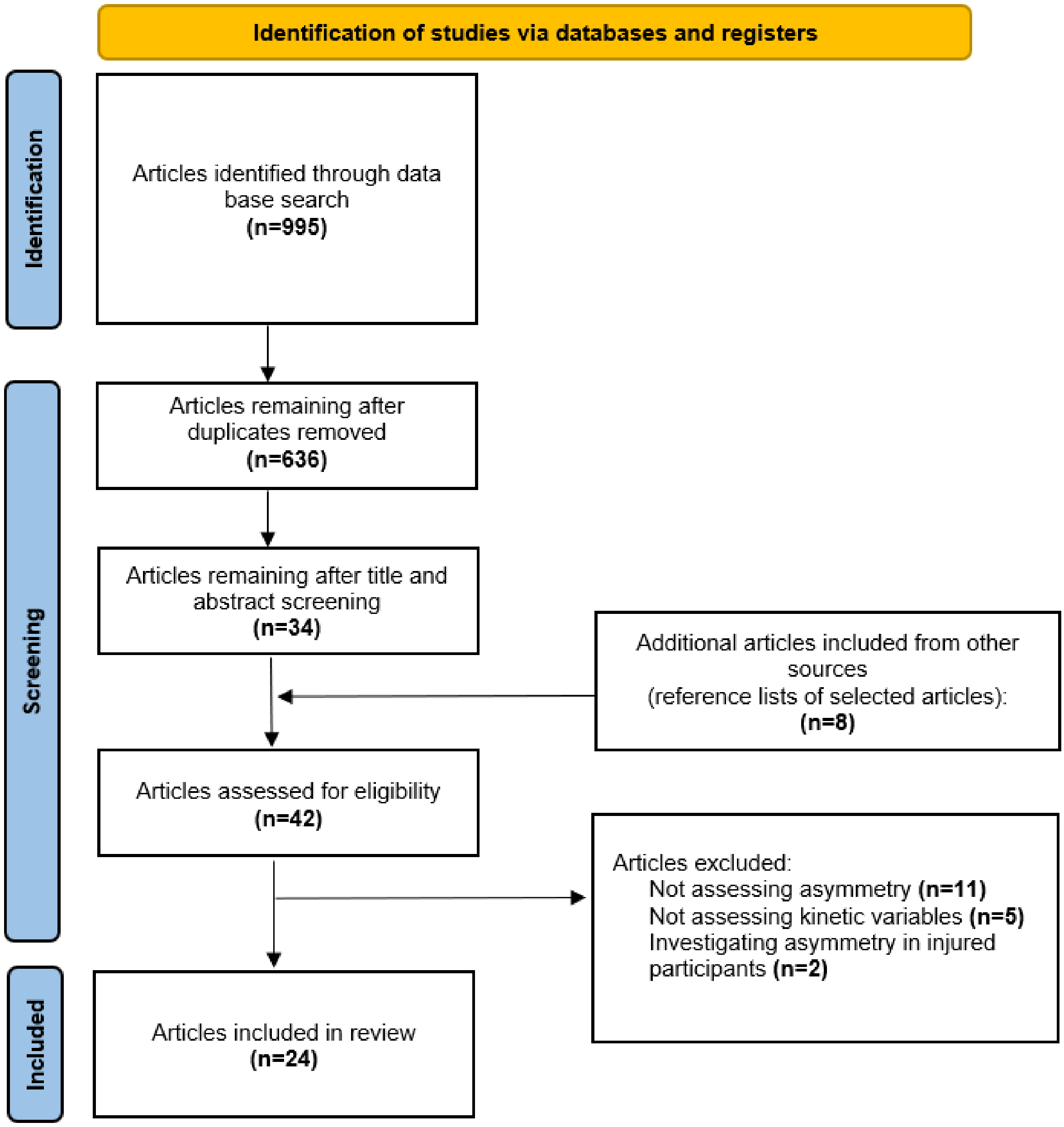


Figure 3.1 A flow diagram of the study selection process for methodological review.

A schematic of the varied methods used to measure, analyse, and interpret asymmetries during cycling is shown in **Figure 3.2** and suggests there are 12,600 possible methodological combinations amongst the existing literature. In **Table 3.1** we detail the methods used to assess bilateral asymmetries during cycling within each of the included studies.

To measure kinetic metrics of cycling eleven studies used power meters located at the crank (39,41,43–45,48–53). Of these eleven studies, five studies used the Lode Excalibur cycle ergometer with integrated strain gauges in the crank (39,48–50,52). Four studies used SRM (Schoberer Rad Messtecnik, Jülich, Welldorf, Germany) (41,43,44,53), one study used Power2Max cranks (45) and one used a custom device (51). Thirteen studies used power meters located at the pedal (27,38,40,42,43,46,47,54,55,57,59,69,81) and one study used a Wattbike ergometer (58).

When analysing asymmetries during cycling, five studies compared left and right limbs (42,46,47,59,81). Alternatively, nineteen studies identified the participants' dominant limb using varied methods. Six studies determined dominance using the Waterloo Inventory (27,38,43,50,54,57). Nine studies identified dominance as the kicking limb (40,41,48,49,51–53,55,69) and one study used a test of strength (51). Five studies determined dominance as the limb producing the highest torque, force or power during cycling (39,44,45,55,58).

To assess the magnitude of asymmetries during cycling, sixteen studies conducted statistical analyses to determine whether the magnitude of asymmetry was significant (27,38–42,44,46,48,50,52–55,58,69). Seventeen studies determined the magnitude of asymmetry by calculating asymmetry indices (27,38–40,43–45,49–51,53–55,57–59,69).

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 (39,41,43,44,48–50,52,53,59,69). Nine studies assessed asymmetries in power output

(40,45,47,49,54,55,58,69,81), three studies assessed asymmetries in force (27,38,57), three studies assessed asymmetries in work (42,51,59) and two studies assessed asymmetries in impulse (46,48). One study assessed asymmetries in the index of effectiveness (27) and two study compared limbs for their pedalling smoothness (69,81).

When assessing asymmetry at timepoints throughout cycling protocols, ten studies analysed kinetic data for durations of 30 s to 300 s (40,44,46,48,49,58,59,69,81), eleven studies measured 5 to 30 complete crank revolutions (27,38,39,41–43,47,52,53,55,57,81), and one study measured asymmetries continuously (45).

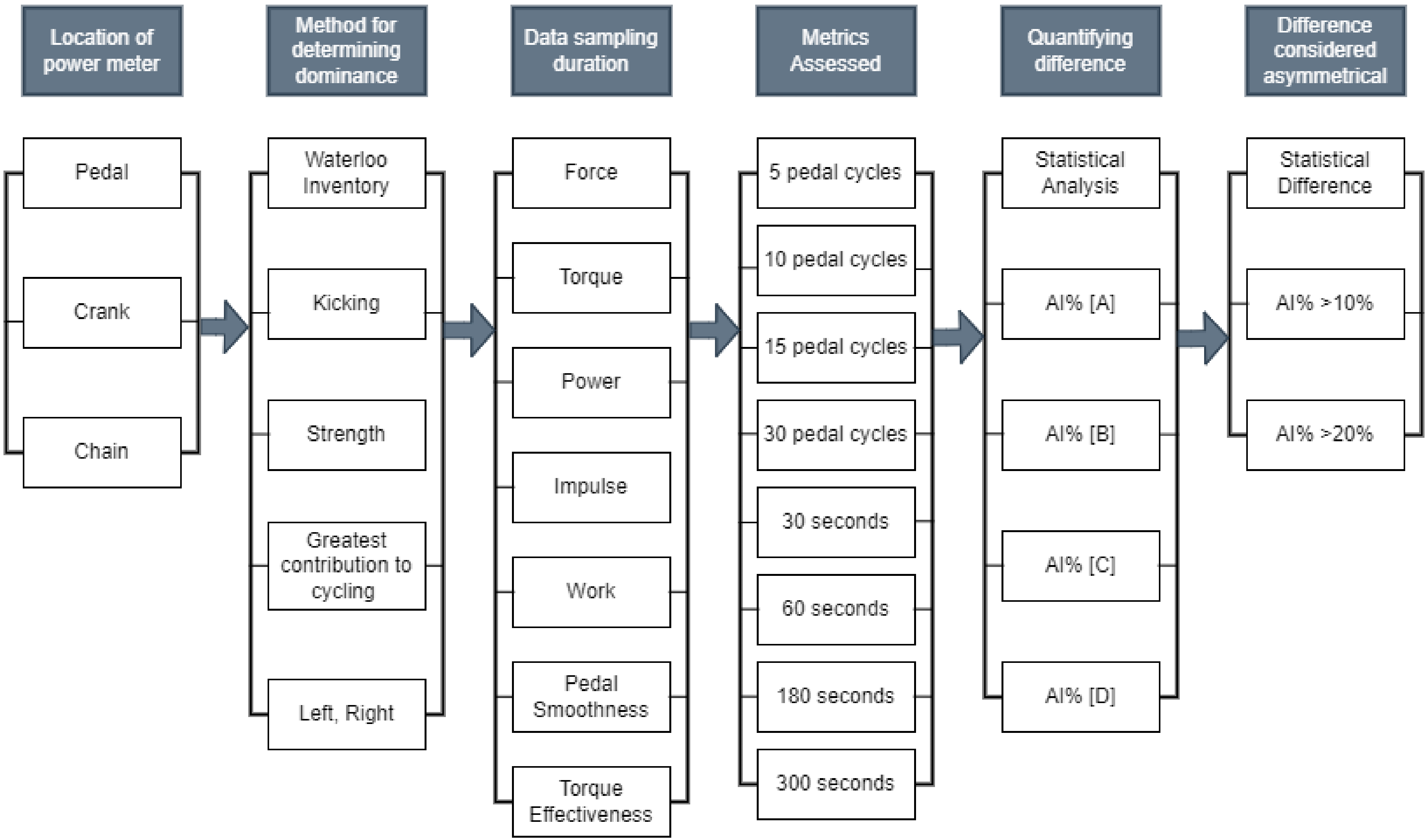


Figure 3.2 A schematic overview of the varied methods used to measure, analyse, and interpret asymmetries during cycling.

Table 3.1 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 (44)	Crank [SRM]	Greatest torque	30 s per stage	Peak torque	((D - ND) / D) x 100 **[A]** Paired Wilcoxon	Asymmetry index >10%
Bini and Hume 2014 (43)	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 and Hume 2015 (27)	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 (57)	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 (42)	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 (38)	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 (53)	Crank [SRM]	Kicking	10 cycles every 5 min	Peak torque (propulsive)	((D - ND) / D) x 100 **[A]**	Asymmetry index >10%
Carpes *et al.* 2008 (41)	Crank [SRM]	Kicking	10 pedal cycles per min	Peak propulsive torque	ANOVA	Statistically significant difference
Chen 2016 (59)	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*. 2017 (52)	Crank [LODE Excalibur]	Kicking	10 pedal cycles	Peak torque, torque curve	ANOVA, FANOVA	Statistically significant difference
Daly and Cavanagh 1976 (51)	Crank [Custom]	Kicking, strength		Work	(D / ND) x 100 **[B]**	
Diefenthaeler *et al*. 2016 (50)	Crank [LODE Excalibur]	Waterloo Inventory		Peak torque	((P - NP) / P) x 100 **[A]** ANOVA	Statistically significant difference
Farrell *et al.* 2021 (49)	Crank [LODE Excalibur]	Kicking	60 s	Peak torque, average torque, power	((D – ND) / (D + ND) / 2) x 100 **[C]** Absolute: D - ND	
Garcia-Lopez 2015 (48)	Crank [LODE Excalibur]	Kicking	300 s	Mean torque, peak torque, minimum torque, positive impulse, negative impulse	ANOVA	Statistically significant difference
Gonzalez-Sanchez *et al.* 2019 (54)	Pedal [Polar Keo]	Waterloo Inventory	180 – 300 s	Power	((D - ND) / D) x 100 **[A]** T test	Statistically significant difference
Hunt *et al.* 2004 (47)	Pedal [Custom]	Comparison between left and right limbs	15 pedal cycles	Power	(R - L) -1 ANOVA	Statistically significant difference
Javaloyes *et al.* 2020 (45)	Crank [Power2Max]	Greatest power	Continuous	Power	(D - ND) [percentage difference, calculation not specified]	Statistically significant difference
Kell and Greer 2017 (58)	Wattbike	Greatest torque	300 s	Power	((D - ND) / D) x 100 **[A]** ANOVA	Asymmetry index >20%
Rannama and Port 2017 (81)	Pedal [Garmin Vector]	Comparison between left and right limbs	30 s	Power, pedal smoothness	((D - ND) / (D + ND) / 2) x 100 **[C]**	

Rannama and Port 2015 (69)	Pedal [Garmin Vector]	Kicking	30 seconds	Power, pedal smoothness	((D - ND) / (D + ND) / 2) x 100 **[C]** T test	Statistically significant difference
Sanderson 1990 (46)	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 (55)	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 (40)	Pedal [Custom]	Kicking	30 seconds at intervals	Peak power	((D - ND) / D) x 100 **[A]** Kruskal-Wallis	Statistically significant difference
Trecroci *et al.* 2018 (39)	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

Abbreviations; 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 3.3**.

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 asymmetries during cycling. **Figure 3.2** shows the variety of methods used to measure, analyse, and interpret asymmetries during cycling amongst the existing literature. This schematic illustrates that there are 12,600 possible methodological combinations amongst research in the field. This review will critically assess the varied methods to determine a best practice for measuring and interpreting asymmetries during cycling.

3.4.1 The location of the power meter on the bicycle

A review by Bini *et al*. (2014) described the evolution of technologies used to determine force and power in cycling (32). 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 (19). Amongst cycling asymmetry research, the most commonly used technologies included pedal based and crank based power meters. Power meters located at the pedal included custom devices (27,38,40,42,43,46,47,55,57,59), GVPs (69,81) and the Polar Keo Power device (54). Power meters located at the crank included the LODE Excalibur (39,48–50,52), SRM (41,43,44,53), Power2Max (45) and custom devices (51)(51). One study utilised a Wattbike ergometer to assess asymmetry (58), which calculates power output via a load cell located next to the chain (82). A diagram of the location of these power meters is presented in **Figure 3.3**.

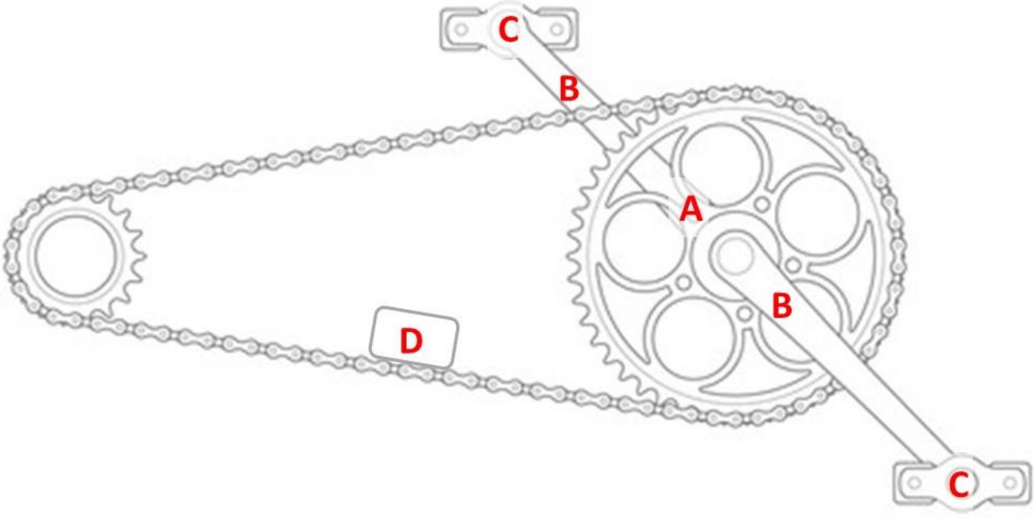


Figure 3.3 Anatomy of the drive train and location of power meters used to measure cycling kinetics.
A: spider of the crank arm (SRM device). B: crank arms (all crank based power meters). C: pedal (all pedal based power meters). D: chain (Wattbike loadcell).

The measurement of torque or power is affected by the location of the power meter on the bicycle (19). Frictional losses through components of the bicycle's drive train (pedals, cranks, chainrings, chain, cassette, derailer), dissipate some of the energy input (19,83). These frictional losses are thought to be proportionate to the total power output and have been suggested to be ~2.4% (19).

Some power meters are unable to accurately measure the contribution of each limb separately, as they are located on a component of the bicycle that is influenced by the net torque of both of the lower limbs (32,43,45,84). Power meters located at the crank or chain will attribute torque generated in each 180° of the crank cycle to the limb that is in the power phase or downstroke. It is possible for cyclists who use cleats or toe clips to produce propulsive forces during the upstroke, which would result in an overestimation of torque produced by the limb in the power phase. Alternatively, negative (resistive) forces have been observed during the recovery phase of the pedal cycle (51,55). Using these power meters, negative torque applied by the contralateral limb diminishes torque of the ipsilateral limb (43), which may result in an underestimation of torque, especially in those with less efficient techniques.

Bini and Hume (2014) conducted a study to compare bilateral asymmetries in cycling measures using power meters located at the crank and the pedal of a bicycle (43). During a maximal incremental cycling test performed on a cycle ergometer instrumented with both types of power meter, larger asymmetries in peak torque were detected using the pedal power meter compared to the crank (43). 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 power meters (43). Considerable asymmetries at low intensities were not detected by the crank based power meter which questions the validity of this equipment for the assessment of asymmetries during cycling (43).

Pedals measure forces directly at their application by the cyclist, before any frictional losses through the bicycles drivetrain (19). Additionally, pedals measure forces at a location on the bicycle with minimal (the least) left and right limb interaction. Therefore, pedals are the preferred power meter for the assessment of bilateral asymmetries during cycling (32,43,84).

Some pedal power meters can be purchased as unilateral devices, which reduces the cost to the consumer. The unilateral pedal power meters double the power measured at one limb to provide an estimate of 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 determined that the unilateral power meter provided a valid estimate of net power, but that in the presence of asymmetry, the validity of the unilateral power meter decreased (85). This provides further justification for the use of bilateral pedal power meters for the assessment of asymmetries during cycling.

3.4.2 The criteria for determining a dominant or preferred limb

In a clinical setting, injured and non-injured limbs might be compared to quantify asymmetry for the monitoring of rehabilitation. The aim in this scenario is to reduce the deficit of the injured limb, using the performance of the non-injured limb as a reference for comparison. However, in healthy populations, determining a ‘reference’ limb is more challenging. A reference limb could be selected by determining limb preference or limb dominance. These terms are often used interchangeably, however the limb that is subjectively preferred is not necessarily objectively dominant (86).

Within cycling asymmetry literature, some studies assessed limb preference to determine a reference limb. Of the studies selected for review, seven determined limb preference using the Waterloo Inventory (27,38,43,50,54,57). The Waterloo Inventory is a questionnaire that assesses participants preferences for two types of task: tasks for the foot manipulating an object (such as kicking a ball or picking up a marble) and tasks where the foot provides support during an activity (such as standing on one foot to balance) (87). These questions do not relate specifically to cycling actions, but they may give an indication of the preferred limb for daily activities. Alternatively, nine studies determined limb preference by selecting the limb used for kicking tasks (40,41,48,49,51–53,55,69).

Other cycling asymmetry studies determine a reference limb by assessing limb dominance. Five studies determined dominance as the limb producing the highest torque, force or power during cycling (39,44,45,55,58). One study used a test of cycling specific strength to determine dominance (51). Measuring force at the pedal spindle, with the crank of the bicycle horizontal at 90°, participants were asked to apply maximum force to the pedal as quickly as possible for 10 consecutive trials for each leg repeated on two separate visits. However, only thirteen of the twenty participants assessed demonstrated dominance with the same leg on both days, therefore this test was considered an unreliable measure of dominance (51).

There is a need for a consistent approach to defining dominance/preference within the literature, as it is possible that the same cyclist could be classified as left and right limb dominant depending on the method chosen. For example, a cyclist might kick a ball with their right limb, but during cycling produce greater torque with their left limb. Asymmetry should be reported as a vector quantity, expressing magnitude and direction (88). When only considering magnitude, asymmetry may appear consistent (e.g. 20% difference between limbs). However, further analysis of direction could reveal a change from 20% in favour of the left limb, to 20% in favour of the right limb. When defining dominance as the limb contributing most greatly to cycling (39,44,55,58), the calculated asymmetry indices will always be a positive value in favour of the dominant limb (89). In this instance, it would not be apparent if there was a switch in the limb contributing most greatly, which has been observed during cycling (50,51,55). Using this method during longitudinal analyses may mask considerable changes in asymmetry (89).

Positive or negative asymmetry indices provide direction of asymmetry, enabling the analysis of whether asymmetry is related to dominance. Of the twenty four studies in this review, nine reported that cycling asymmetry is associated with limb dominance, defined by the Waterloo Inventory (27,43,50) or the kicking limb (40,41,48,53,55,69). Conversely, six studies report that cycling asymmetry was not associated with limb preference or dominance when defined by the Waterloo Inventory (38,54,57), the kicking limb (49,51,52) or a test of strength (51). Therefore, it does not appear that asymmetries during cycling are related to limb preference or dominance.

Alternatively, three studies included within this review have conducted simple comparisons of left and right limbs which may be the best approach to longitudinal analysis of cyclists' asymmetries as this enables clear identification of which limb is contributing most and whether the direction of asymmetry changes. Within a group, there could be the presence of asymmetries in favour of both left and right limbs amongst the participants. Therefore, for group analysis using left and right comparisons, it is necessary to convert all calculated asymmetries into positive values, expressing magnitude only. Alongside this data on the magnitude of asymmetry, statistical methods such as Kappa Coefficients could be used to quantify the consistency in the direction of asymmetry to account for reversals in the limb contributing most greatly to metrics of cycling performance.

3.4.3 The metric assessed for asymmetry and duration of data sampling

Asymmetries are task and metric specific (90,91). Asymmetries have been calculated for a range of metrics in cycling research, including torque (39,41,42,44,48–50,52,53,59), power (40,45,47,49,54,55,58,69,81), force (27,38,57), work (42,51,59), impulse (46,48), index of effectiveness (also known as torque effectiveness) (27) and pedal smoothness (69,81). 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 3.2**.

Table 3.2 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.
Pedalling 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.

Most commonly amongst the studies included in this review, peak torque is the metric assessed for bilateral asymmetries during cycling. However, this metric may not truly reflect the contribution of each lower limb when it is considered that only 40 to 60% of force applied to the pedal results in crank torque (27), and peak values may be limited by the ability of the cyclist to drive forces perpendicular to the crank (27).

Furthermore, assessing sections of the pedal cycle (e.g. peak torque) may not truly reflect the contributions of each lower limb. Da Silva Soares *et al.* (2021) analysed asymmetries in the full torque curve, and subsequently in peak torque during sub-maximal cycling trials (92). 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 (92). Analysing the torque curve provides a thorough analysis of the contributions of each limb, and provides a useful insight into pedalling technique (92). However, few commercially available power meters will provide the user with the full torque profiles, therefore this analysis would be challenging for the majority of users.

Measuring bilateral power enables a comparison of the energy each limb in producing that will propel the bicycle. Calculating the work done by each limb could provide a useful measure of ‘asymmetrical load’ that describes total contribution of each limb for the duration of a ride. Additional measures, such as torque effectiveness and pedal smoothness, could compliment this data by providing an insight into pedalling technique, notably the proportion of total force that is effective, or propulsive.

The included studies in this review describe analysing kinetic data for either fixed sampling durations or for a number of complete crank revolutions. Studies which sampled data for a fixed time period used durations of durations of 30 s to 300 s (40,44,46,48,49,58,59,69,81). Studies which sampled data for a number of crank cycles used a range of 5 to 30 complete crank revolutions (27,38,39,41–43,47,52,53,55,57). Collecting small sample sets of data at timepoints throughout a period of cycling is common in this field of research but may not truly reflect the asymmetry of the participants. We will demonstrate this limitation using data from two studies which assessed the association between asymmetry and cycling performance (27,38). They assessed the effect of bilateral asymmetry on time trial performance over 4 km (27) and 20 km distances (38). The researchers describe analysing data for 5 complete crank cycles at 500 m segments of the 4 km time trial (27) and 5 km segments of the 20 km time trial (38). The completion of 5 crank revolutions equates to ~3 s when cycling at reported cadences between 90 to 105 rpm. This results in a total data sampling period of ~27 s during the 4 km time trial, and ~13 s for the 20 km time trial, which for the latter is less than 1% of the mean performance duration of 30 ± 3.7 minutes. A continuous analysis of asymmetry during training rides or competition, such as the methods adopted by Javaloyes *et al.* (2020), may provide a more valid representation of the differences between limbs during these trials (45).

3.4.4 The magnitude of interlimb difference required to be considered asymmetrical

Many researchers utilise statistical analyses to determine whether the magnitude of asymmetry during cycling in significant (38–42,47,48,50,52,54,55,69). Alternatively, many studies use arbitrary thresholds of >10% (27,44,53,59) or >20% (43,57,58) to classify interlimb differences as asymmetrical. 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 (27,90,93) and the calculation used to quantify asymmetry (94) therefore the use of arbitrary thresholds should be questioned (27).

In **section 3.4.5**, we used simulated data to demonstrate the effects of the calculation used to quantify the magnitude of asymmetry. This data is presented in **Table 3.3** 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 (93).

Alternatively, Exell *et al*. (2012) suggested that inter-limb differences should be greater than intra-limb variability to be considered asymmetrical (95). 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 (50,51,55). However, the majority of studies in the field of cycling asymmetry assessed participants on a single occasion, with only one study assessing participants under the same conditions on multiple visits (51).

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 (94). Future research should aim to define a range of acceptable asymmetries in uninured cyclists (27). Inter limb differences should be assessed relative to variability in the measures (91), therefore further research is needed to understand the day to day variability of asymmetries during cycling.

3.4.5 The calculation used to quantify asymmetry

Of the studies included in this review, eighteen presented the interlimb differences as a relative asymmetry index (27,38–40,43–45,49–51,53–55,57–59,69,81). However, amongst these eighteen studies, there are four different asymmetry index calculations used to quantify limb differences. Using simulated data, relative asymmetries have been calculated for each of the asymmetry index calculations to demonstrate the effect of the chosen calculation on the outcome. This data is presented in **Table 3.3**.

Table 3.3 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) (39,40,44,50,53,54,58)	((D-ND)/D) x 100	18.2%	-22.2%
[B] (n=1) (51)	(D/ND) x 100 [100=symmetry]	22.2%	18.2%
[C] (n=8) (27,38,43,49,57,59,69,81)	((D-ND)/(D+ND/2)) x 100 or ((D-ND)/0.5(D+ND)) x 100	20%	-20%
[D] (n=1) (55)	((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.

Firstly, the simulated data presented in **Table 3.3** demonstrates that the magnitude of asymmetry, when using the same net power of 200 W, varies considerably (10 to 22.2%)

depending on the calculation chosen. If arbitrary thresholds such as a >20% difference were used to classify asymmetry, for the same data this participant could be classified as symmetrical or asymmetrical depending on the calculation used quantify interlimb difference. This reinforces the need for a consistent method for quantifying asymmetries in this field, to enable studies to be reviewed systematically and for cyclists, coaches and practitioners to interpret data appropriately.

The data in **Table 3.3** have also been analysed with consideration that left and right limbs could be defined as 'dominant' depending on the method used to determine dominance. Using the simulated data, if dominance is defined as the limb producing most power, the left limb would be considered dominant (producing 110 W, 55% of the net power out 200 W). However, if we use kicking limb to define dominance, the right limb would be considered dominant. This is a limitation of calculations [A] and [B], as when using these calculations the magnitude of asymmetry differs depending on the limb which is defined as dominant (see **Table 3.3**). Analysing the simulated data, using calculation [A] the magnitude of asymmetry would be 18.2% or 22.2% depending on whether left or right limbs were considered dominant. This occurs because for these equations, the dominant limb is used as a reference. In healthy, non-injured cyclists there is no obvious reference limb. For these reasons, we would not recommend using calculation [A] or [B] for the assessment of bilateral asymmetries during cycling.

Calculations [C] and [D] do not use the dominant limb as a reference for comparison. Alternatively, calculation [D] compares the interlimb difference relative to the net of both limbs. Calculation [C] compares the interlimb difference relative to half of the net of both limbs. Using the simulated data (**Table 3.3**), at a net power output of 200 W, with perfect symmetry each limb would contribute 100 W. However, each limb is 10 W from perfect symmetry, with the left limb contributing 110 W and the right limb 90 W. Calculation [C] combines the difference from symmetry of both limbs (20 W) and compares this difference relative to the symmetrical power of one limb (100 W). Using calculation [C] results in the asymmetry being inflated two-fold compared to calculation [D]. Therefore, we recommend calculation [D] as the most appropriate for quantifying relative asymmetry during cycling.

There are limitations to presenting asymmetry relatively, which can also be demonstrated using the simulated data in **Table 3.3**. Using calculation [D], an absolute difference of 20 W between limbs at an intensity of 200 W equates to a 10% difference between limbs. If the intensity is increased to 400 W, and the cyclist still presents a relative difference of 10%, this outcome measure would suggest their asymmetry is unchanged. However, in absolute terms, the difference between limbs has increased twofold, to 40 W. As intensity increases, the same absolute difference will appear relatively smaller.

Calculation [D]*: ((D-ND)/(D+ND) X 100*

At 200 W: $\frac{(110\,W - 90\,W)}{(110\,W + 90\,W)} \times 100 = 10\% \qquad (20\,W\ absolute\ asymmetry)$

At 400 W: $\frac{(220\,W - 180\,W)}{(220\,W + 180\,W)} \times 100 = 10\% \qquad (40\,W\ absolute\ asymmetry)$

We recommend calculating absolute asymmetries during cycling. However, this would require further investigations to provide normative data and a meaningful difference to be able to classify results as symmetrical or asymmetrical.

3.4.6 Other considerations

Only two studies included within this review described in their methods that participants were blinded to the analysis of pedalling asymmetry (41,53). These studies explain the analysis of asymmetry was omitted from the participants' explanation of the study, to prevent this knowledge influencing their pedalling mechanics. One additional study stated that they blinded the participants to the power measurements during the protocol (54).

Two studies have investigated whether the provision of feedback enables cyclists to reduce the magnitude of asymmetry during sub-maximal cycling (57,58). Both studies report that participants who presented with initially considerable asymmetries were able to significantly reduce the magnitude of interlimb differences with verbal (57) and visual feedback (57,58) demonstrating that cyclists are able to 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.

3.5 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 are able to make the following recommendations for measuring, analysing and interpreting asymmetries in this field:

- Pedal power meters are the preferred power meter for the assessment of asymmetries during cycling as they can measure left and right forces separately and directly at their application by the cyclist before any losses through the bicycles drive train. Although, it should be noted that the validity of these power meter decreased during supramaximal sprint cycling.
- Assigning a dominant limb is challenging in healthy, uninjured cyclists. Therefore, simply comparing left and right limbs may be the best approach to 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 in 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 asymmetry 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.

CHAPTER 4

The reliability and validity of the Garmin Vector pedals for the assessment of interlimb asymmetries.

[presented as a poster at the British Association of Sport and Exercise Science (BASES) Conference 2017 – See **Appendix 2**].

BASES Conference 2017 – Programme and Abstracts, Journal of Sports Sciences, 35:sup1, 1-119, D1.P59. The validity and reliability of bilateral torque measured using Garmin Vector pedals. DOI: 10.1080/02640414.2017.1378421

ABSTRACT

Garmin Vector power pedals (GVPs) quantify forces applied to each pedal via integrated sensors that measure deformations at each pedal spindle. Power meters located at the pedals, such as the GVPs, enable bilateral measures to evaluate cyclists for asymmetries. GVPs are considered reliable and valid for the measurement of net power across a range of cycling intensities. To be able to determine whether a cyclist is producing power asymmetrically, left (LP) and right (RP) GVPs should be assessed separately for their accuracy and repeatability. Therefore, the aim of this study was to assess the validity and reliability of torque measured by both LP and RP. To eliminate the influence of biological variability, torque was measured from each pedal using static load testing. A unicycle, with the seat post fixed horizontally to a surface was used as a cycling rig. Both LP and RP GVPs were attached to the cranks of the unicycle and the crank was rotated and fixed at crank angles of 45° to 360°, at intervals of 45°. At each crank angle, pedals were separately loaded with 0, 8, 16, 24, 32 and 40 kg, using hook weights. For each load and crank angle, the applied torque was calculated to provide a criterion measure (CM) from which LP and RP pedal torque was compared using 95% limits of agreement (LoA). All pedal loads were applied to each pedal at all crank angles three times, to calculate reliability as the coefficient of variation (CV). Bland Altman analysis showed a mean bias of LP vs. CM of 0.14 Nm (95% CI: -0.69 and 0.98 Nm) for RP vs. CM of 0.18 Nm (95% CI: -0.99 and 1.34 Nm) and LP vs. RP of 0.03 Nm (95% CI: -1.15 and 1.08 Nm). To assess reliability, mean CVs were 0.25 ± 0.28% for LP and 0.28 ± 0.17% for RP. These results suggest that the GVPs are reliable and valid for the measurement of bilateral torque, and therefore are suitable for the assessment of bilateral asymmetries during cycling.

4.1 INTRODUCTION

There is a high prevalence of asymmetry across a range of physical qualities for sports performance (96). The presence of bilateral asymmetries have been investigated during cycling under varied conditions of intensity, cadence, bicycle configurations, cycling positions and participant performance levels (see **Chapter 2**).

In cycling, power output is commonly monitored to evaluate training and race performances (19). The SRM power meter, located at the crank, is considered to be the gold standard for assessing power output during cycling due to its high validity and reliability (97). In this study, both types of SRM power meter replaced the crank of a friction braked Monark ergometer (Monark model 814e, Varberg, Sweden). This ergometer was further adapted so the SRM crank set was propelled via a rear-wheel placed on a motorised treadmill. In doing so, theoretical power output at the ergometers flywheel could be calculated via the following calculation: Power (W) = Torque (Nm) x Angular Velocity (rad.s^{-1}) and manipulated by placing a variety of thirteen different frictional loads on the ergometers weight tray. Jones and Passfield (1998) observed 95% limits of agreement of ± 2 W for the SRM professional model which houses four strain gauges (SG) and ± 3.6 W for the laboratory model with twenty SGs, when testing a power range of 90 to 630 W using a dynamic calibration rig at a pedalling rate of 90 rpm (97). Both devices were also considered to be highly reliable, with variation of ± 2.1% and ± 1.0% for the four SG and twenty SG models, respectively (97).

Recent technological advancements have resulted in the development of alternative and more affordable power meters which measure power at the crank, rear hub, bottom bracket, chain and pedals of a bicycle (19). Subsequently, the use of power meters is much more prevalent amongst cyclists of all abilities.

In our review of the methods used to assess asymmetries during cycling (**Chapter 3**), we described that pedal and crank based power meters are the most commonly used equipment amongst research in this field. However, some power meters such as the SRM cranks, are unable to accurately measure the contribution of each limb separately for the assessment of bilateral asymmetries, as they are located on a component of the bicycle that is influenced by the net torque of both of the lower limbs (32,43,45,84).

In **Chapter 3**, we concluded that pedal power meters are the preferred equipment for the assessment of bilateral asymmetries during cycling (32,43,84), with two main justifications. Firstly, pedals measure forces directly at their application by the cyclist, before any frictional losses through the bicycles drivetrain (19). Secondly, pedals measure forces at a location on the bicycle with minimal (the least) left and right limb interaction.

Numerous studies have evaluated the validity of pedal power meters, including GVPs (28,29,98,99), PowerTap P1 (PT) (100,101), Favero Assioma (FA) (102,103) and Look Keos (LKPs) (104). Whilst GVPs, PT and FA are considered reliable and valid for the measurement of power output during cycling, it was described that data obtained using LKPs should be treated with caution due to statistical differences in power measured by these pedals in comparison to the SRM (104). Furthermore, the LKPs were considered to have poor reliability across repeated trials with a mean difference in power output of 18.6 W, compared to 0.6 W for the SRM (104).

The aforementioned studies assessed pedal dynamometers for measures of ‘net’ power output, a summation of the power produced by both limbs during dynamic cycling trials. In order to assess asymmetries during cycling with confidence, we must understand the reliability and validity of bilateral measures of power. A bilateral assessment examining the reliability and validity of torque measured by left and right pedals individually has yet to be conducted. This investigation would further support the use of pedal power meters for the assessment of bilateral asymmetry during cycling.

The preferred method of examining the reliability and validity of a power meter would be using repeated mechanical trials as this method compares measurements against a known criterion value without the influence of biological error that exists when conducting trials with participants (105). Mechanical trials can be conducted by using a dynamic calibration rig, which adds a known resistance to the bicycle at a controlled angular velocity (97), or alternatively for pedal based systems, via the application of a known force to the pedal during a static calibration (43).

Therefore, the aim of this study was to assess the reliability and validity of torque measured by left and right pedals during repeated static load trials to assess their suitability for the assessment of bilateral asymmetries during cycling.

4.2 METHODS

With the saddle removed, the seat post of a unicycle was fixed horizontally to a surface to act as a cycling rig for the static load evaluations. A diagram representing the rig used for the static load evaluations is presented in **Figure 4.1**. The fixed gear mechanism of a unicycle, with the crank fixed to the hub of the wheel, provides a rig which can be statically loaded at any crank angle by clamping the wheel to prevent rotation.

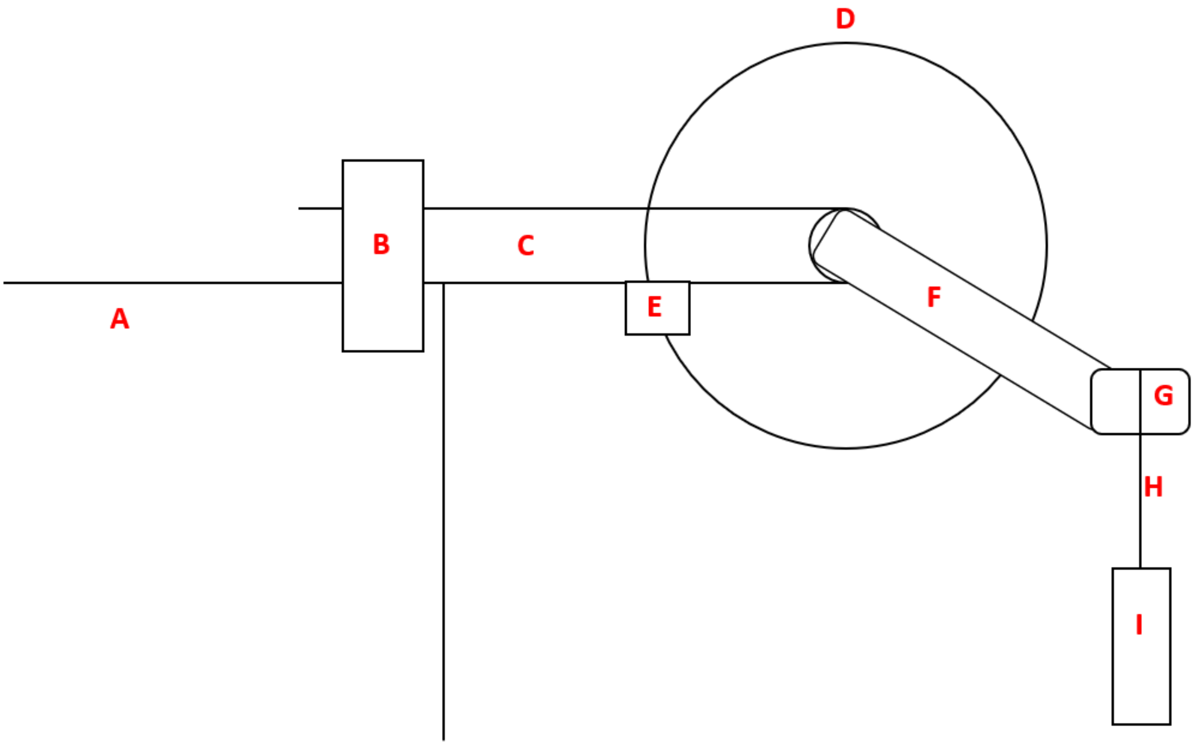


Figure 4.1 A diagram of the rig used for static load evaluations.

A: fixed surface, B: clamp attaching seat tube to surface, C: unicycle seat tube, D: unicycle wheel, E: wheel clamp, F: crank, G: GVPs, H: hook for loading weights, I: hook weights.

GVPs (Garmin Vector 1, Garmin International Inc., Olathe, USA) were attached to the cranks of the unicycle using a torque wrench, to a torque of 35 Nm, in line with manufacturer's recommendations (34 – 40 Nm). GVPs incorporate a plurality of sensors that measure the forces applied to the pedals based on the amount of deformation of the pedals spindle (106). Data from the GVPs was displayed using a cycling computer (Garmin Edge 510, Garmin International Inc., Olathe, USA) linked via Bluetooth. Crank length (127 cm) settings were adjusted on the cycling computer and further manufacturer installation procedures were followed. Pedals were calibrated to ensure a reading of 0.0 Nm was recorded when unloaded. The cycling computer remained in calibration mode during the static load testing, as this mode displayed the torque applied to the pedals when loaded.

A goniometer and a reference plumb line, hung from the unicycle's crank axle, and was used to determine crank angles of 45º, 90 º, 135 º, 180 º, 225 º, 270 º, 315 º and 360 º. Each crank angle was photographed, and the angle confirmed using free 2D Kinovea motion analysis software. Loads were applied vertically downwards via hook weights which were hung directly onto the GVPs (see **Figure 4.1**). Due to the direction at which the force was applied to each pedal, loads applied at angles which would be considered the upstroke of a typical crank cycle (180º to 360º), would be applied in a resistive manner, and therefore measured as a negative torque.

Loads of 0, 8, 16, 24, 32, and 40 kg were applied three times, for a duration of 10 s, at which time the value displayed on the cycling computer was recorded. For each load and crank angle, the torque applied to the pedal was calculated using **Calculation 4.1**. This provided a criterion measure for comparison with values measured by the GVPs.

Calculation 4.1

Torque (Nm) = rFsinϴ

where, r is the distance from the axis (0.127 m), F is force (load (kg) x 9.81 $m \cdot s^{-2}$), and ϴ is the angle with respect to the line of action of the force.

These loads were selected as they represent increments in torque of ~10 Nm if applied at angular velocities of 90 rpm, a common cadence for trained cyclists, the power range assessed would be approximately 0 to 470 W which is indicative of the intensities of aerobic cycling. The mass of each of the loads was confirmed using digital weighing scales to the nearest 0.1 kg (SECA Scale 813, Hamburg, Germany). Loads were applied to one pedal whilst the other remained unloaded, with the full protocol of angles and loads carried out for both left and right pedal, separately.

4.2.1 Statistical Analysis

Mean bias and 95% limits of agreement (LoA) were defined using the method of Bland and Altman (107), with comparisons made between torque measured by the left pedal and the criterion measure, between the right pedal and criterion measure, and between left and right pedals. Additionally, typical error of measurement (TE) was derived from log transformed data.

To assess the reliability of the GVPs, the mean coefficient of variation (CV) was calculated for load and crank angles at which criterion torque was above 0.0 Nm, at pedal loads of 8, 16, 24, 32, and 40 kg. The CV were calculated as the standard deviation to mean ratio and multiplied by 100. The mean CV for each pedal load was calculated, including trials from all crank angles for which that load was applied (45, 90, 135, 180, 225, 270, 315, 360°). Test-retest reliability was also assessed using intraclass correlation coefficients (ICC), using a two-way mixed effects model with absolute agreement definition (108). ICC were defined for each pedal load, assessing the three repeat applications of that load to the pedal at every crank angle.

4.3 RESULTS

4.3.1 Reliability

The mean CV for the left pedal was 0.25 ± 0.28%, and for the right pedal was 0.28 ± 0.17%. The ICC analysis demonstrated that at pedal loads of 8, 16, 24, 32 and 40 kg, both the left and right pedal had excellent test-retest reliability (1.000). At 0 kg, the left pedal demonstrated excellent reliability (0.935), whilst the right pedal was considered to show good reliability (0.899).

Table 4.1 Reliability analysis, including mean CV and ICC for each pedal across all pedal loads and crank angles.

Pedal	Pedal Load (kg)*	Mean CV (%)	Pedal Load ICC
Left pedal	0	-	0.935
	8	0.52	1.000
	16	0.35	1.000
	24	0.18	1.000
	32	0.09	1.000
	40	0.12	1.000
	ALL	0.25 ± 0.28	
Right pedal	0	-	0.899
	8	0.39	1.000
	16	0.38	1.000
	24	0.42	1.000
	32	0.09	1.000
	40	0.10	1.000
	ALL	0.28 ± 0.17	

4.3.2 Validity

Bland-Altman analysis show a mean bias of torque for the left pedal vs. criterion measure of 0.14 Nm (95% CI: -0.69 and 0.98 Nm) (**Figure 4.2**), for the right pedal vs. criterion measure of 0.18 Nm (95% CI: -0.99 and 1.34 Nm) (**Figure 4.3**) and the left pedal vs. right pedal of -0.03 Nm (95% CI: -1.15 and 1.08 Nm) (**Figure 4.4**).

The typical error of measurement was determined at 0.30 for the left pedal vs. criterion measure, 0.42 for the right pedal vs. criterion measure and 0.40 for the left pedal vs. right pedal comparisons.

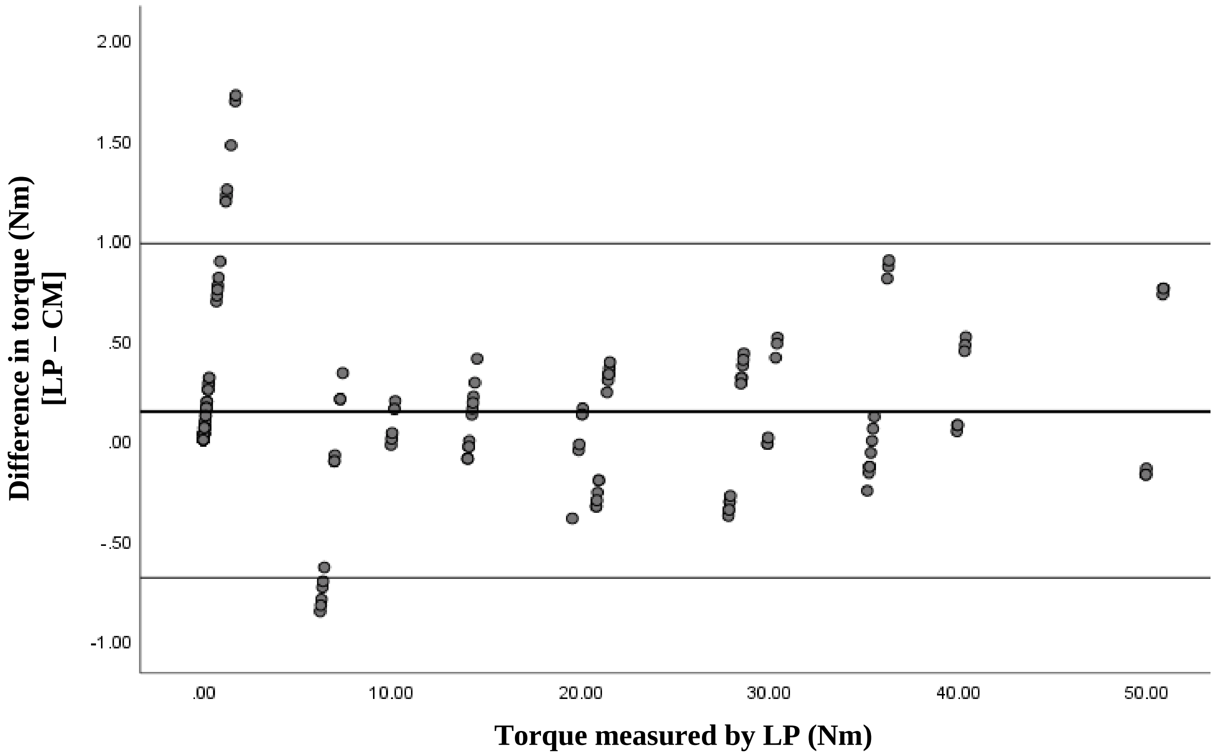


Figure 4.2 Bland Altman plot representing the 95% limits of agreement (LoA) between the left pedal (LP) and criterion measure (CM).

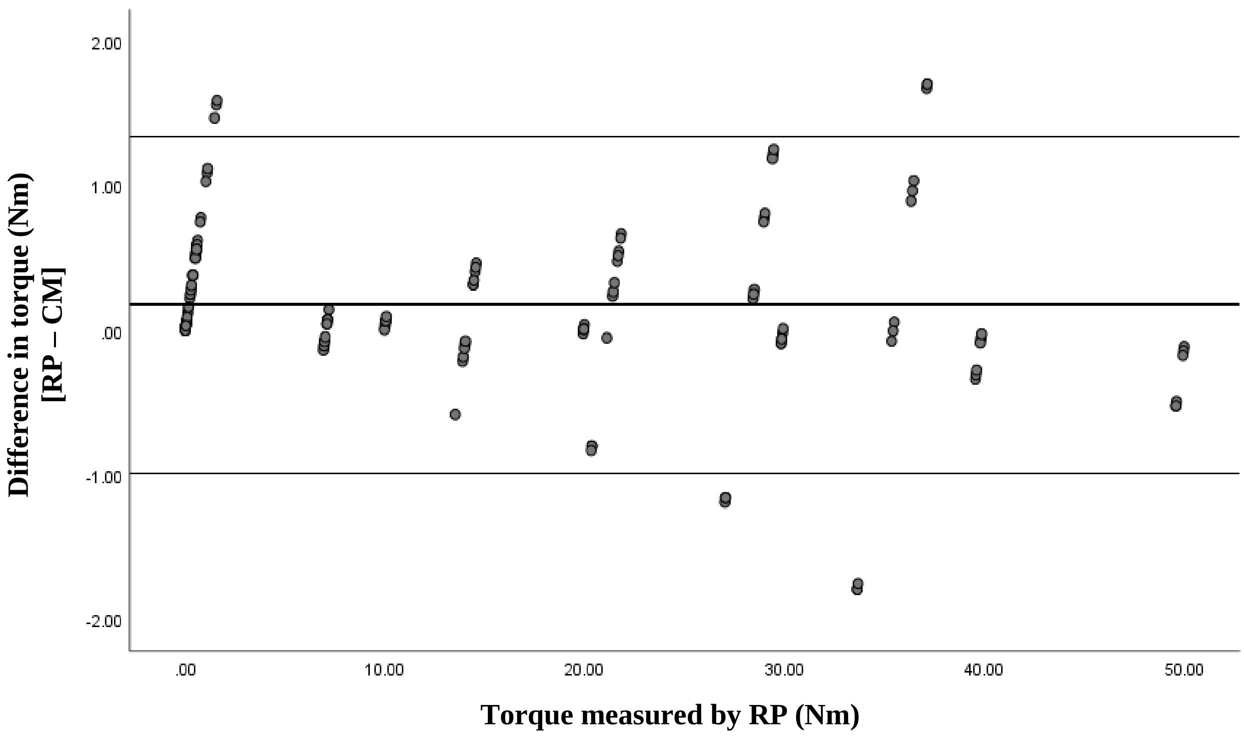


Figure 4.3 Bland Altman plot representing the 95% limits of agreement (LoA) between the right pedal (RP) and criterion measure (CM).

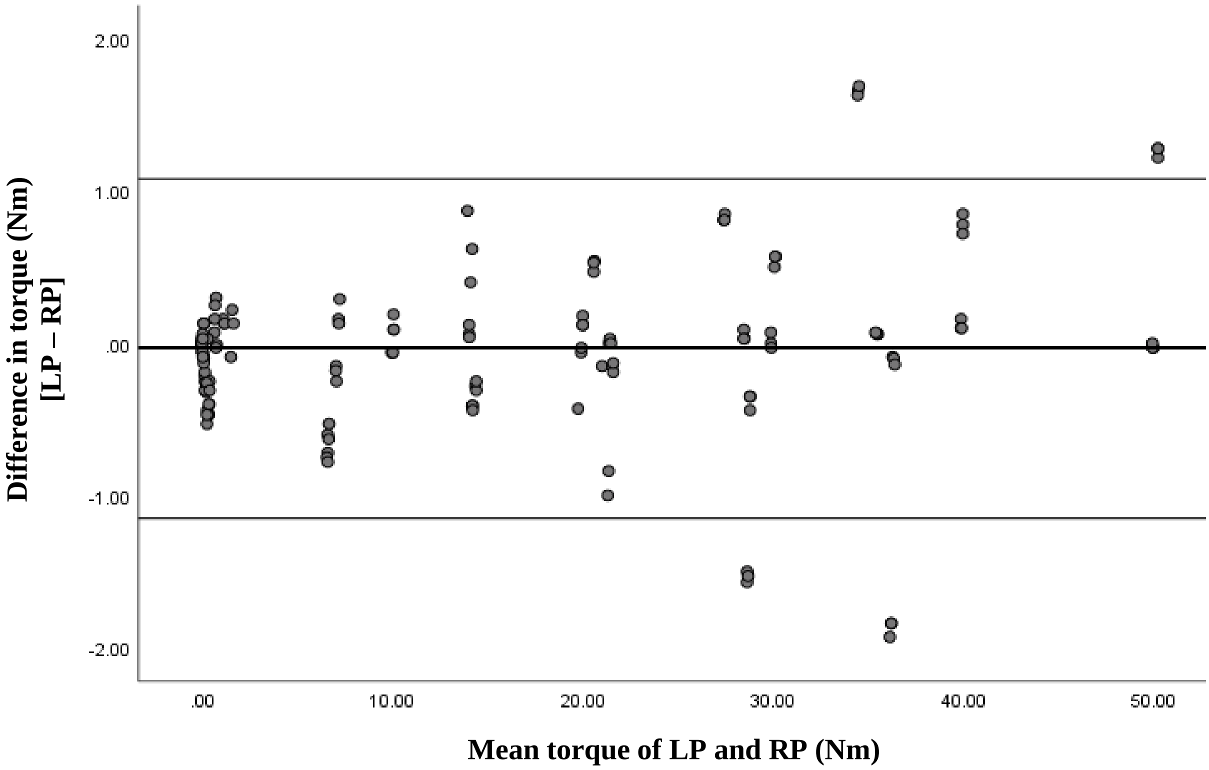


Figure 4.4 Bland Altman plot representing the 95% limits of agreement (LoA) between the left pedal (LP) and right pedal (RP).

4.4 DISCUSSION

The aim of this study was to evaluate the reliability and validity of the left and right GVPs separately, using repeated static load trials. This investigation was conducted to assess the suitability of this equipment for use in the assessment of bilateral asymmetries during cycling.

The reliability of the GVPs during the static load assessments in our study was reported as a CV of <0.3%, which is considerably lower than the 1.4% to 5.1% that have been measured in previous studies that have assessed the reliability of the net power measured using GVPs (29,98,99). The lower CV observed during our study could be attributed to utilising static load trials to assess reliability. Previous studies conducted participant trials, for which the results will include a combination of equipment error and biological error, particularly when exercise intensity is not controlled (i.e. during sprint trials) (109). Novak and Dascombe (2016) described that static load assessments were not possible for the GVPs, as the power meter does not transmit data if a cadence reading is not concurrently available (28). By design, the GVPs cadence sensor is only activated after completing two pedal revolutions, before an angular velocity can be determined. However, using the GVPs calibration mode, we were able to apply loads to the pedal to obtain measures of torque during static assessments.

When assessing validity during our study, Bland Altman analysis showed a mean bias of between 0.14 and 0.18 Nm when comparing the pedals to the criterion measure. A mean bias of 0.18 Nm equates to 1.7 W at cadences of 90 rpm, suggesting the pedals demonstrate good validity. The Bland Altman plots **(Figures 4.2 and 4.3)** show larger mean bias for both pedals in comparison to the criterion measure when the load trials should measure 0 Nm's of torque. When integrating the data, this marginally greater mean bias (which remains below 2

Nm's) occurs when applying the higher pedal loads (16-40 kg) at the 0° crank angle. Small misalignments of the crank angle these loads will result in the generation of torque, measured by the pedals and explains why at 40 kg loads, the pedal measured up to 1.72 Nm of torque at the 0° crank angle.

The GVPs have previously been reported to have good agreement with the SRM for measures of 'net' power output, a summation of the power produced by both limbs (28,29,98). Analysis of validity by comparison to another device could be considered a methodological limitation. In the comparison of pedal (GVPs) and crank (SRM) devices, the pedal is the direct point of contact, before any dissipations through the mechanical components of the bicycle. So, it is likely a pedal device will overestimate power output in comparison to a crank-based power meter.

Our study utilises novel methods by using static load trials to assess the torque measured by left and right GVPs, separately. This technique provides further evidence that this equipment is suitable for the assessment of bilateral asymmetries during cycling. Furthermore, earlier research indicated the net power output during maximal sprint trials might be underestimated by the GVPs in comparison to the SRM power meter (28,29,98). The SRM device samples at higher frequencies than the GVPs, which during phases of rapid acceleration in a sprint, could result in the GVPs underestimating sprint power in comparison to SRM (29). By design, the GVPs cadence sensor is only activated after completing two pedal revolutions, before an angular velocity can be determined. Next to differences in sampling frequency, this delayed power measure will have a great effect on the power output measured if sprint cycling trials are performed from a standing start (28). Novak and Dascombe (28) demonstrated that the typical error in mean power between GVPs and SRM decreased from 4.9 to 2.6% when comparing sprint power of those performed from a standing start to those from a rolling start. Additionally, Bouillod *et al.* (83) assessed the validity of the GVPs pedals during sprint cycling at various gear ratios, and only observed a significant difference between GVPs and SRM during sprints performed at a low gear ratio, where resistance is lower and cadence is faster. During sprints with higher gear ratios, there was no significant difference between GVPs and SRM (83).

Additionally, when comparing cadence measured by the GVPs and SRM, Novak and Dascombe (2016) reported no significant difference (28). Nimmerichter *et al.* (2017) did report a significant difference in cadence between these devices (29), however this difference was considered marginal at <1 rpm.

4.5 CONCLUSION

The results of this study reinforce that the GVPs are a reliable and valid device for the measurement of bilateral torque during cycling. In addition, this study demonstrates that independent left and right pedals measurements of torque are reliable and valid, justifying the use of this equipment for the assessment of bilateral asymmetries during cycling.

CHAPTER 5

The between day variability of interlimb asymmetries during cycling.

[sub sample of data presented at the European College of Sports Science (ECSS) Conference in 2018 – **See Appendix 3**].

ABSTRACT

Bilateral asymmetries are considered to be common during cycling, typically ranging between 5 to 20%. However, currently there is no consensus on the magnitude of asymmetry required to be classified as asymmetrical. It has been suggested that asymmetries should be defined relative to the variability in the measures. Surprisingly, little research has been conducted to assess asymmetries during cycling under the same conditions on multiple days. Towards this, the aim of this study was to assess bilateral power output on multiple days to observe the between day variability in asymmetries.

Upon completion of an incremental cycling testing during an initial visit, nine participants returned to the laboratory on three occasions to complete 4 x 4 min cycling trials corresponding to 40, 60, 75 and 90% of their MAP, at 90 rpm. Mean absolute power output asymmetries across these intensities, measured using GVPs, were 10.25 ± 10.62 W during visit one, 13.75 ± 8.56 W during visit two and 13.03 ± 7.42 W during visit three. Participants mean between day CVs for asymmetry ranged between 12.87% to 186.22%. Kappa coefficients showed that the consistency in the direction of asymmetry between days ranged from poor to perfect (-0.17 to 1.00). The results of this study showed that the magnitude and direction of asymmetry were highly variable between days. For future assessments of bilateral asymmetries during research or applied practice, we recommend assessing participants on multiple days.

5.1 INTRODUCTION

Bilateral asymmetries are considered to be common in cycling, but currently there is no consensus on the magnitude of interlimb difference required to be classified as asymmetrical. In **Chapter 3**, we discussed that many researchers define asymmetry as a statistically significant difference when comparing limbs. Whilst this method of data analysis is suitable for group data sets, as asymmetries are highly variant between participants, a more individualised approach to assessing asymmetry may be necessary. Interlimb differences of 10 or 20% have been used as arbitrary thresholds to classify results as symmetrical or asymmetrical (38–42,47,48,50,52,54,55,69) (see **Table 3.1** in **Chapter 3**). This method does enable individual analysis, however, this method should be discouraged (93) as the magnitude of asymmetry can vary vastly depending on the metric assessed (90,93) and the calculation used to quantify asymmetry (94) (see **Chapter 3**). Therefore, a one size fits all approach to defining asymmetry may not be suitable.

In the field of strength and conditioning, Bishop *et al*. (2021) suggested that interlimb differences should be assessed relative to variability in the measures (91). Variation represented by typical error comes from several sources, including equipment error and biological error (110). In **Chapter 4**, we assessed the equipment error of the GVPs that can be used to assess asymmetry in power output during cycling. When comparing the GVPs to a criterion measure, a mean bias of 0.18 Nm equating to 1.7 W at cadences of 90 rpm suggested the GVPs demonstrate good validity. The reliability of the GVPs was also good, reported as a CV of <0.3%.

Whilst equipment error is understood, little is known about the biological error of asymmetries during cycling. Of the twenty-four studies included in our review (**Chapter 3**), only Daly and Cavanagh (1976) assessed participants under the same conditions over multiple visits and used that data to investigate between day variability in asymmetry measures (51). In their 1976 study, participants completed nine trials of varying cadences and intensities on an ergometer with four foil strain gauges bonded to each crank. All trials were repeated on two separate days. They reported that measured asymmetry in work done was ‘extremely variable’ from day to day and that several participants demonstrated a reversal between days in the limb which did more work (51). They also reported that for several participants, there was a switch in the limb completing the most work between trials on the same day. This within day reversal in the direction of asymmetry has also been reported by researchers assessing cycling asymmetries during a single visit (50,55).

Few studies in the field of cycling asymmetry have assessed participants on multiple days, or with repeated trials of the same condition. Therefore, the initial aim of this study was to assess variance in cycling asymmetries over multiple visits. With this information, a secondary aim was to identify whether individual variance in asymmetry could be used as a threshold for defining interlimb asymmetries.

5.2 METHODS

5.2.1 Participants

Nine experienced male cyclists provided informed consent to participate in this study, which was approved by the University of Essex ethics committee (see **Appendix 1**).

Table 5.1 Descriptive participant characteristics.

	Mean	Standard Deviation
Age (years)	34.81	14.04
Height (cm)	177.06	7.59
Mass (kg)	76.26	12.09
Peak oxygen uptake (l/min)	4.12	0.35
Peak relative oxygen uptake (ml/kg/min)	54.49	9.97
Maximal aerobic power (W)	372.67	37.01

According to the guidelines for participant classification (79) using their relative $\dot{V}O_2$ peak, one participant was classified as untrained (P5), five participants were classified as recreationally trained (P2, P3, P6, P8, P9) two participants were classified as trained (P1, P7) and one participant was classified as professional (P4). For absolute peak power output, five participants were classified as trained (P2, P3, P5, P8, P9) and four were classified as well trained (P1, P4, P6, P7).

5.2.2 Protocol

Participants attended the laboratory on four occasions, each separated by 7 days. During the initial visit, following a 5 min warm up at 75 W, participants completed an incremental cycling test to exhaustion. The initial workload of 100 W was increased by 25 W per minute, and exhaustion was defined when participants could no longer maintain a cadence of 90 rpm. Respiratory parameters were sampled breath-by-breath, using open circuit spirometry (Oxycon Pro, Jaeger, Höchberg, Germany). Maximal aerobic power (MAP) was calculated using the following equation (111):

Calculation 5.1

$$\text{MAP} = \text{Power of final completed stage (W)} + \frac{\text{time in final stage (s)}}{\text{stage duration (s)}} \times \text{power increment (W)}$$

During visits two, three and four, participants completed 4 x 4 min cycling trials corresponding to 40, 60, 75 and 90% of MAP, at 90 rpm, with an 8 min recovery interval between each trial (**Figure 6.1**). Intensities were not randomised due to the potential effects of fatigue on asymmetry. The highest intensities which would be expected to elicit the most fatigue were conducted at the end of the protocol and 8 min recovery durations were utilised to minimise the effects of accumulative fatigue as the protocol progressed.

Both the incremental cycling test, and all subsequent trials during visits two to four were performed on an electromagnetically braked ergometer (LODE Excalibur Sport, Groningen, Netherlands), which standardised the intensity of the trials. The ergometer was fitted in accordance with the participants own bicycle set up, and this position was replicated for every visit. Experimental trials were conducted on the same day and time for three consecutive weeks. Participants were asked to abstain from exercise for two days prior and refrain from consuming alcohol or caffeinated beverages for twelve hours prior to each visit to the laboratory. Participants were asked to keep a weekly training log, and a diary of their dietary intake on the day of the first trial. They were then asked to replicate training each week and dietary intake on the day of each trial.

The cycle ergometer was installed with strain gauge instrumented pedals *(Garmin Vector 1, Garmin International Inc., Olathe, USA)* for the assessment of bilateral power output, and data was relayed to a cycling computer *(Garmin Edge 510, Garmin International Inc., Olathe, USA)* linked via Bluetooth. Participants were not informed of the nature of the study (the assessment of bilateral asymmetry), and were blinded to all power data, only viewing cadence throughout each trial to target maintaining 90 rpm.

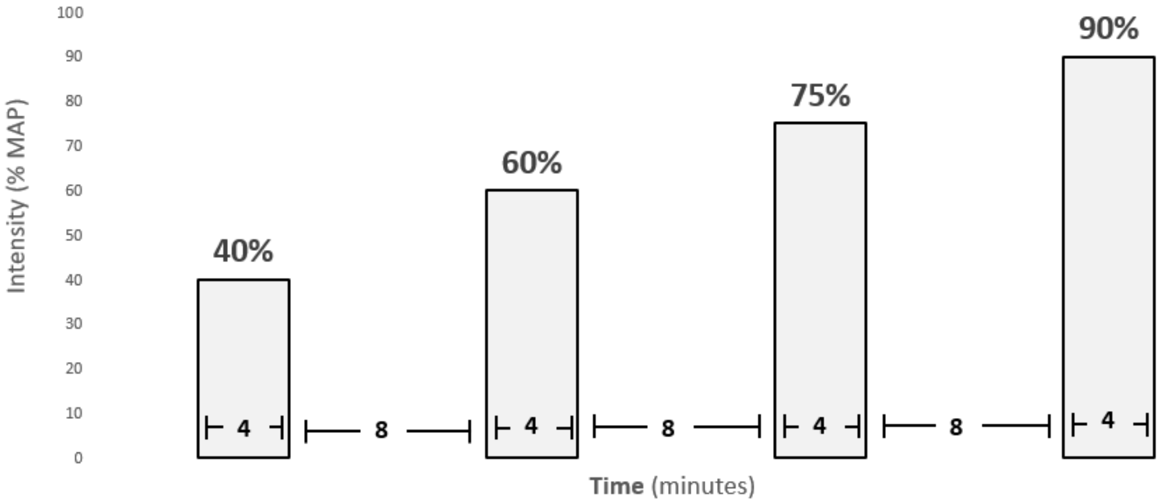


Figure 5.1 Schematic of the protocol conducted during visits 2,3 and 4.

5.2.3 Data Analysis

For each 4 min trial, the initial and final 30 s were excluded, and the remaining 3 min of data were analysed. The mean asymmetry in power for this 3 min period was expressed in watts (W) as the absolute difference between limbs, with positive values demonstrating a greater contribution of the right limb and negative values demonstrating a great contribution of the left limb.

Between Visit Variances

The change in the magnitude of asymmetry over the multiple visits was assessed using Cohen's d effect sizes (ES), presented with 95% confidence intervals. The calculated effect sizes were interpreted in accordance with Hopkins *et al*. (112) (<0.2 = trivial, 0.2 - 0.6 = small, 0.6 – 1.2 = moderate, 1.2 - 2.0 = large, 2.0 - 4.0 = very large, >4.0 = extremely large). Repeated visits were also assessed for their level of agreement in the direction of asymmetry using the Kappa coefficient in line with the recommendations of Bishop *et al*. (113). This data described how consistently an asymmetry favoured the same limb (direction of asymmetry).

The calculated Kappa values were interpreted in accordance with Viera and Garrett (114) (≤0 = less than chance agreement, 0.01 – 0.20 = slight agreement, 0.21 – 0.40 = fair agreement, 0.41 – 0.60 = moderate agreement, 0.61 – 0.80 = substantial agreement, and 0.81 – 0.99 = almost perfect agreement).

For each participant, coefficient of variation (CV) between visits were calculated per intensity using the mean and standard deviation of the difference in power output between limbs. For each participant, the CVs for each intensity were averaged to present a mean CV. Each participant was classified for the variance in the magnitude of asymmetry and the direction of asymmetry between visits. If the participants mean CV was <20%, the magnitude of asymmetry was classified as consistent (MC). If the mean CV was ≥20%, the magnitude of asymmetry was classified as inconsistent (MI).

If across all trials over the three visits, the participants asymmetries were always in favour of the same limb, the direction of asymmetry was classified as consistent (DC). If the participant demonstrated asymmetries in favour of both left and right limbs, the direction of asymmetry was considered inconsistent (DI).

For the between visit variance, participants were assigned to one of four possible classifications:

1) Magnitude consistent, direction consistent (MCDC)
2) Magnitude consistent, direction inconsistent (MCDI)
3) Magnitude inconsistent, direction consistent (MIDC)
4) Magnitude inconsistent, direction inconsistent (MIDI)

Within trial variance

For each experimental trial, CVs were calculated for the power output of each limb. For each participant data were presented as the mean CV for left and right limbs. Additionally, mean

CVs were calculated for the limb completing the most and the limb completing the least work during the 3 min period of data collection.

5.3 RESULTS

Six of the nine participants (P1, P3, P4, P5, P6, P7) had a complete data set for the four experimental trials during all three visits to the laboratory.

One participant (P2) had missing pedal power data for the experimental trial at 90% MAP for visit three. Two participants (P8 and P9) had a complete data set for all four experimental trials during only two visits to the laboratory. All missing experimental trials are due to erroneous power data from the GVPs.

Figure 5.2 shows individual absolute asymmetries for all trials performance across the three repeat visits.

Mean absolute asymmetries in power for each visit are presented in **Table 5.2**. Group mean absolute asymmetries in power were 10.25 ± 10.62 W for visit 1, 13.75 ± 8.56 W for visit 2 and 13.03 ± 7.42 W for visit 3. For absolute differences in power, Cohen's d effect sizes ranged from trivial to moderate (0.06 to -0.71) between visits (**Table 5.2**).

Mean between day CVs for the asymmetry in power ranged from 12.87% to 186.22% for the participants who had compete data for all experimental trials on all three visits (see **Table 5.3**).

Kappa coefficients, describing the consistency in the direction of asymmetry between visits, ranged from poor to perfect (-0.17 to 1.00) (see **Table 5.4**).

Mean within trial CVs in power output were 5.25% for the left limb and 5.65% for the right limb, or 5.11% for the limb generating the most power and 5.80% for the limb generating the least power (see **Table 5.5**).

Figure 5.2 Mean absolute asymmetry in power output (W)

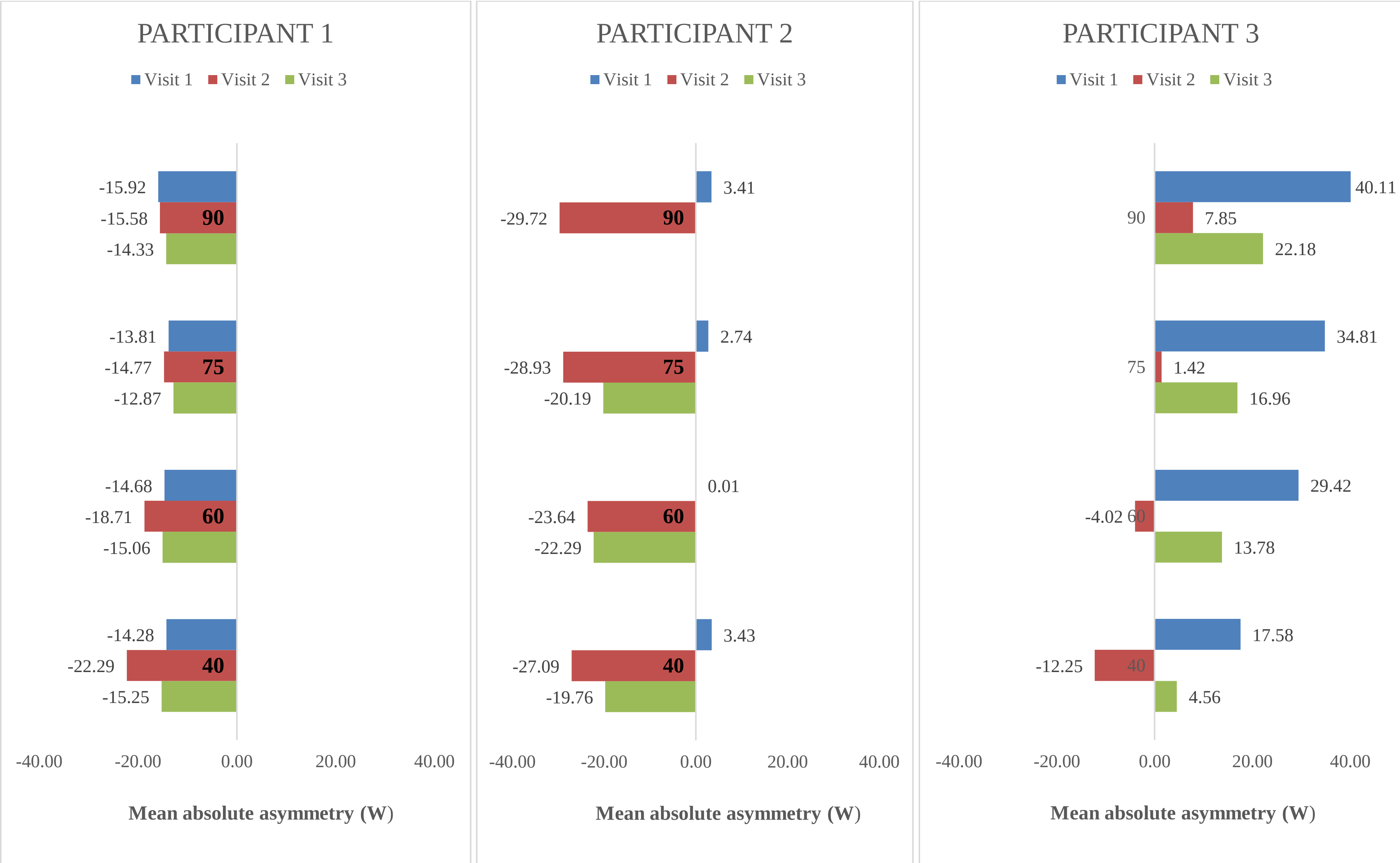


Figure 5.2 Mean absolute asymmetry in power output (W) [extended]

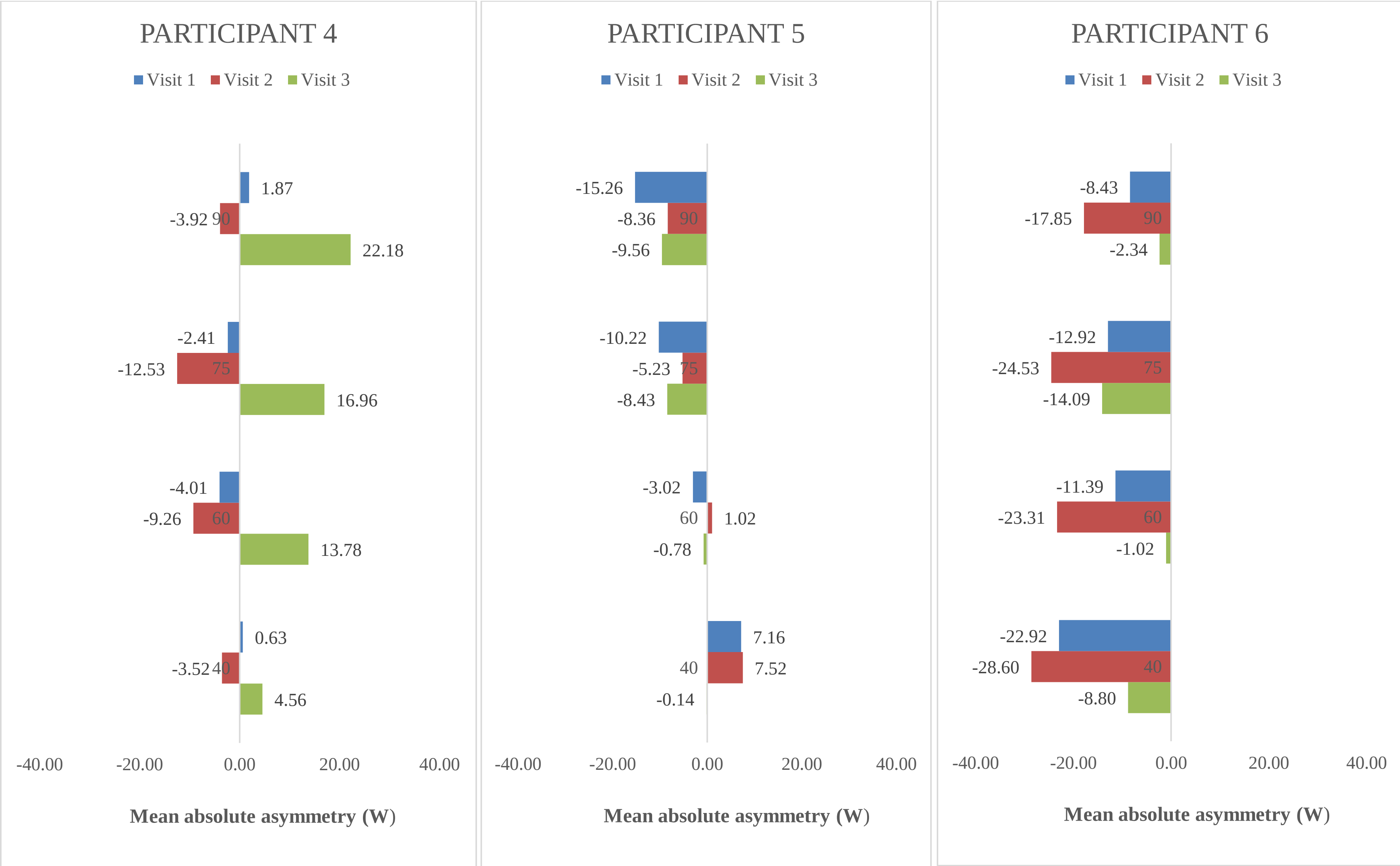


Figure 5.2 Mean absolute asymmetry in power output (W) [extended]

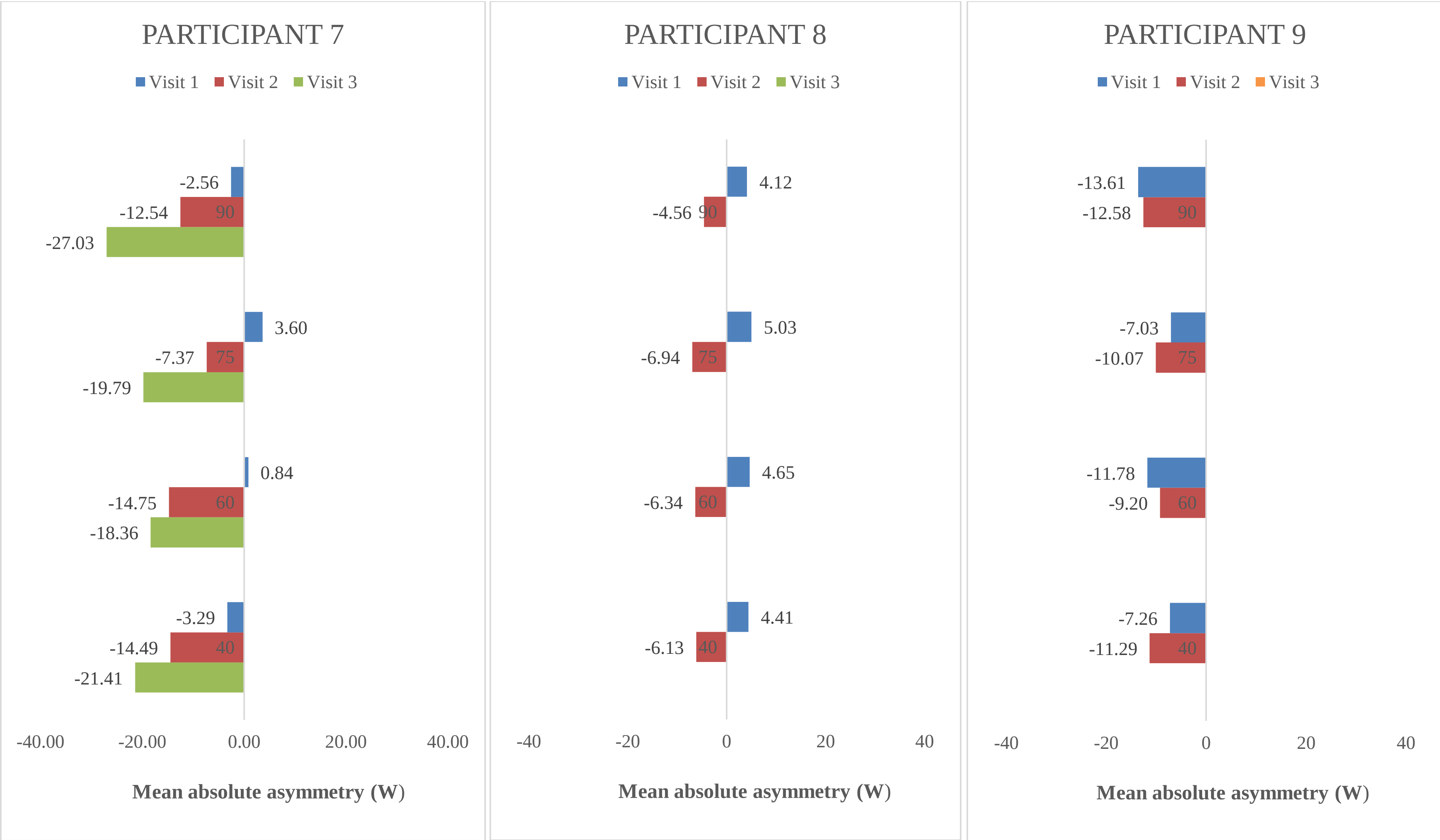


Table 5.2 Mean absolute asymmetry in power output (W) and effect sizes.

Intensity (%MAP)	**Absolute asymmetry in power (W)**			**Cohen's d effect sizes (magnitude)**		
	Visit 1	**Visit 2**	**Visit 3**	**V1 v V2**	**V1 v V3**	**V2 v V3**
All Intensities	10.25 ± 10.65	13.75 ± 8.56	13.03 ± 7.42	-0.36 (S)	-0.30 (S)	0.09 (T)
40	9.90 ± 8.56	16.54 ± 9.69	12.25 ± 7.96	-0.71 (M)	-0.29 (S)	0.49 (S)
60	9.05 ± 10.51	13.53 ± 9.05	12.16 ± 8.25	-0.46 (S)	-0.34 (S)	0.16 (T)
75	11.50 ± 11.36	13.54 ± 10.12	14.39 ± 4.88	-0.20 (S)	-0.34 (S)	-0.11 (T)
90	14.02 ± 14.11*	9.44 ± 5.24*	13.36 ± 9.76*	0.45 (S) *	0.06 (T) *	-0.52 (S) *

Mean ± SD values include the seven participants with full data for all three visits.

*Results for the 90% intensity include six participants (P2 excluded), due to missing data for one visit at this intensity.

Table 5.3 Between day CVs for absolute asymmetry in power output (W) and participant classification.

Participant No.	Intensity (%MAP)	Absolute asymmetry in power output (W)				Between Visit CV (%)	Mean Between Visit CV (%)	Classification
		Visit 1	Visit 2	Visit 3	Mean ± SD			
1	40	14.28	22.29	15.25	17.27 ± 4.37	-25.32	-12.87	MC DC
	60	14.68	18.71	15.06	16.15 ± 2.23	-13.79		
	75	13.81	14.77	12.87	13.81 ± 0.95	-6.87		
	90	15.92	15.58	14.33	15.27 ± 0.84	-5.49		
2	40	-3.43	27.09	19.76	16.76 ± 12.11	-110.08	-120.18	MI DI
	60	-0.01	23.64	22.29	15.31 ± 13.27	-86.77		
	75	-2.74	28.93	20.19	17.29 ± 13.33	-105.82		
	90	-3.41	29.72	-	16.57 ± 18.61	-178.06*		
3	40	-17.58	12.25	-4.56	11.46 ± 6.54	453.38	186.22	MI DI
	60	-29.42	4.02	-13.78	15.74 ± 12.81	128.09		
	75	-34.81	-1.42	-16.96	17.73 ± 16.71	94.25		
	90	-40.11	-7.85	-22.18	23.38 ± 16.16	69.14		
4	40	-0.63	3.52	15.83	6.66 ± 8.07	-137.18	-104.08	MI DI
	60	4.01	9.26	13.85	9.04 ± 4.92	-54.44		
	75	2.41	12.53	8.43	7.79 ± 5.09	-65.38		
	90	-1.87	3.92	4.72	3.50 ± 1.47	-159.34		
5	40	-7.16	-7.52	0.14	4.94 ± 4.16	89.16	-48.77	MI DI

	60	3.02	-1.02	0.78	1.61 ± 1.23	-219.15		
	75	10.22	5.23	8.43	7.96 ± 2.53	-31.80		
	90	15.26	8.36	9.56	11.06 ± 3.68	-33.29		
6	40	22.92	28.60	8.80	20.11 ± 10.19	-50.70	-65.88	MI DC
	60	11.39	23.31	1.02	11.91 ± 11.16	-93.68		
	75	12.92	24.53	14.09	17.18 ± 6.39	-37.20		
	90	8.43	17.85	2.34	9.54 ± 7.81	-81.93		
7	40	3.29	14.49	21.41	13.06 ± 9.14	-70.00	-100.35	MI DI
	60	0.84	14.75	18.36	11.32 ± 9.25	-94.84		
	75	3.60	7.37	19.79	10.25 ± 8.47	-148.97		
	90	2.56	12.54	27.03	14.04 ± 12.30	-87.61		
8	40	4.41	-	6.13	5.27 ± 1.22	-863.90*	-1364.30	MI DI
	60	4.65	-	6.34	5.49 ± 1.20	-915.23*		
	75	5.03	-	6.94	5.98 ± 1.35	-887.18*		
	90	4.12	-	4.56	4.34 ± 0.31	-2790.88*		
9	40	-	7.26	11.29	9.27 ± 2.82	-30.77*	-19.71	MC DC
	60	-	11.78	9.20	10.49 ± 1.82	-17.38*		
	75	-	7.03	10.07	8.55 ± 2.15	-25.13*		
	90	-	13.61	12.58	13.10 ± 0.73	-5.57*		

*data from only two visits were available for this condition

Table 5.4 Kappa Coefficients describing the consistency in the direction of asymmetry between visits.

Intensity (% MAP)	V1 v V2		V1 v V3		V2 v V3	
All Intensities	0.20	(slight)	0.36	(fair)	0.41	(moderate)
40	0.22	(fair)	0.22	(fair)	-0.17	(poor)
60	-0.24	(poor)	0.59	(moderate)	-0.17	(poor)
75	0.36	(fair)	0.36	(fair)	1.00	(perfect)
90	0.36	(fair)	0.57	(moderate)	1.00	(perfect)

Table 5.5 Within trial CV in power output.

Participant No.	Left Limb	Right Limb	Limb contributing most	Limb contributing least
1	4.39	5.24	4.39	5.24
2	6.38	8.01	6.67	7.72
3	3.41	3.29	3.22	3.49
4	5.61	6.25	5.64	6.22
5	6.53	6.28	6.28	6.53
6	3.67	4.09	3.67	4.09
7	4.25	4.58	4.30	4.53
8	6.12	5.57	5.37	6.32
9	7.02	7.76	6.58	8.20
MEAN	5.25	5.65	5.11	5.80

5.4 DISCUSSION

The aims of this study were to assess variance in cycling asymmetry over multiple visits, firstly to provide information on the biological error of measuring asymmetry and secondly, to determine whether individual variance could be used as a threshold for defining interlimb asymmetries.

Group data analysis shows there were mostly small to trivial differences in absolute asymmetry between visits and that the consistency in the direction of asymmetry ranged from slight to moderate. Individual participant analysis suggests that between visits, for many the magnitude of absolute asymmetry was highly variable and some participants demonstrated a reversal in the limb contributing most to total power output during the trials.

Between Visit Variances

Group data shows that the magnitude of asymmetry was consistent, with mostly trivial to small differences observed between visits. However, when assessing individual data, CVs presented in **Table 5.3** show that the asymmetries in power vary considerably between visits for many participants in this study.

Two of the nine participants (P1, P9) were classified as ‘magnitude consistent’ (MC) between visits, with CVs in the measured asymmetry of -12.87% and -19.71%, respectively (see **Table 5.3**). Due to erroneous data, CVs are calculated for only two visits for P9, which may affect their measured between visit variances. There is no obvious explanation for P1 demonstrating a consistent magnitude of asymmetry, as they were not the highest performing cyclist with regards to their $\dot{V}O_2$ peak or MAP. Data in relation to the participants training volume were not collected during this study, but it could be plausible that those with a higher volume of training are less variant in their asymmetries due to cycling technique being reinforced during repetitive pedal cycles over many hours of cycling.

The remaining seven participants were classified as ‘magnitude inconsistent’ (MI) with between visit CVs in absolute asymmetry far greater than 20% (CV range -48.77% to -1364.30%).

The high variability between visits is in agreement with the findings of Daly and Cavanagh (1976), the only other researchers known to have assessed asymmetries in kinetic variables of cycling under the same conditions on multiple visits (51). In their study, twenty male cyclists conducted nine cycling trials at varied intensities of 1.6, 2.2 and 3.6 kiloponds and 40, 70 and 100 rpm. These trials were repeated during two visits to the laboratory and the between day reliability was reported at 0.47, demonstrating considerable variance in asymmetries in work between visits (51). This study was conducted in 1976, where the authors measured torque to calculate work using foil strain gauges bonded to the crank of a cycle ergometer. Our study benefited from advancements in technology but observed similar findings. These findings necessitate measurements of asymmetry being taken on multiple days, as results are so variant that a single visit does not fully depict a cyclist’s asymmetry.

Within Trial Variance

For each experimental trial, CVs were calculated for the power output of each limb. This provides a measure of within trial variance for each limb (**Table 5.5**). Mean within trial CVs were 5.25% for the left limb and 5.65% for the right limb. In an alternative method of comparison, CVs were 5.12% for the limb producing the most power during each trial, and 5.82% for the limb completing the least power.

Previous studies have assessed the between day intralimb variability during time trials (27) and incremental cycling tests (115), drawing comparisons between dominant and non-dominant limbs classified using the Waterloo Inventory. The between day intralimb variability in effective force, measured during 4 km time trials, ranged between 20 to 22% for the non-dominant limb compared to 8 to 10% for the dominant limb (27). When assessing the between day reliability of pedal forces during incremental cycling tests, greater variability was observed for the non-dominant limb compared to the dominant for measures of normal force (12% vs. 6%) and total force (11% vs. 5%) (115). These findings may suggest that the pedalling technique of the non-dominant limb is less consistent than that of the dominant limb and that technique and motor coordination are possible factors influencing cycling asymmetry. In the current study, the within trial variance in power output was similar for both limbs. However, the trial durations were short (3 min). Therefore, the greater observed variability in the aforementioned studies may be larger in the non-dominant limb due to accumulating fatigue during maximal time trials and incremental cycling tests to volitional exhaustion.

Due to many participants in this study exhibiting considerable variation in the magnitude of their measured asymmetry, it is not possible to use individual variability as a minimum threshold for defining asymmetry. If we did use variability to define asymmetry, the interlimb differences would have to be very large to be classified as asymmetrical. An alternative approach to defining asymmetry may be to investigate whether asymmetry has an effect on any performance measures. If asymmetry was considered performance limiting, quantifying the minimum magnitude of asymmetry that effects performance may provide a meaningful threshold to define interlimb asymmetry.

Direction of asymmetry

In this study we also assessed variability in the direction of asymmetry to determine how consistently asymmetry favours the same limb, in accordance with the recommendations of Bishop *et al*. (113). When compiling all intensity trials, kappa coefficients show that the consistency in the direction of asymmetry ranged from slight to moderate between visits [0.20 – 0.41]. Individual analysis classified three participants as 'direction consistent' (DI) between visits, which describes that at each intensity these participants asymmetries were in favour of the same limb across all three visits to the laboratory (see **Table 5.3**). Contrarily, six participants saw a reversal in the limb contributing most greatly between visits at one or more of the experimental intensities. Furthermore, five of these six participants further demonstrated asymmetries in favour of both left and right limbs during trials within the same visit. This suggests that for many participants the direction of asymmetry is also highly variable, findings which agree with those of previous studies (50,51,55).

However, when assessing the individual data presented in **Figure 5.2**, it is apparent that for many participants, when there was a reversal of the limb contributing most, interlimb differences were often very small and might be considered symmetrical. This can be demonstrated using the data of participant 2 (P2). When their left limb produces the most power, the magnitude of absolute asymmetry ranges between 19.76 W to 29.72 W. However, during visit 1, participant 2's asymmetry was always in favour of the right limb demonstrating a reversal in the direction of asymmetry. During visit 1, the magnitude participant 2's asymmetry ranged between 0.01 W to 3.41 W. To put this into perspective using a more familiar method of quantifying asymmetry, their relative asymmetry indices ranged between 7.76 to 18.37% when in favour of the left limb and between 0.00 to 2.18% when in favour of the right limb. This reinforces the need for an agreed threshold to define asymmetry and participants should present interlimb differences above a minimum threshold for asymmetry in favour of both limbs to be considered direction inconsistent. Of the participants in our study, only one (P3) demonstrated considerable absolute asymmetries in favour of both left and right limbs.

The frequent reversal of the limb contributing most during cycling reinforces some of the methodological recommendations made in **Chapter 3**. Firstly, if dominance is defined as the limb contributing most greatly to total power, when calculating asymmetry indices, the outcome will always be a positive value in favour of the 'dominant limb'. In this instance it would not be apparent if there was a switch in the limb contributing most greatly to cycling (89). Simple comparisons of left and right limbs may be the best approach to longitudinal analysis of cyclists' asymmetries. Secondly, if asymmetries were presented as a scalar quantity, only considering magnitude, the between day variance would be underestimated. For example, if absolute asymmetries during visit one were 10 W and on visit two were 15 W, the between day variance expressed as a CV would be 28.3%. However, if we looked further at the direction of these asymmetries to discover that during visit one asymmetry was 10 W (in favour of the right limb) and during visit two they were -15 W (in favour of the left limb), the CV would be 707%. Asymmetries appear less variant when magnitude alone is considered. Presenting asymmetries as a vector quantity provides more opportunity for variability as values can vary either side of zero (88).

Assessing participants during multiple visits surely provides more information on their asymmetries and may identify individuals where intervention may be appropriate. This could be the outcome from the analysis of P1's data. Their data suggests that they are consistently generating a higher power output with one limb (direction and magnitude consistent), may provide a window of opportunity to provide an intervention to enhance the capacity of the underperforming limb. However, further information would be required to identify the source of this asymmetry.

5.5 CONCLUSIONS AND FUTURE DIRECTIONS

Both the magnitude and direction of asymmetries were highly variable between days in this study. Due to considerable variation in measured asymmetry, it is not possible to utilise individual variability as a threshold to define asymmetry. In order to establish a minimum interlimb difference required to be considered asymmetrical, we need to understand the effect of asymmetry on performance. Future work should look to investigate whether asymmetry has an effect on any cycling performance measures to consider whether a minimum magnitude of asymmetry that effects performance could be a suitable threshold for defining asymmetry.

Currently, two studies have assessed the effect of asymmetry on cycling performance (27,38). Both studies compared participants performance in a single time trail, assessing whether those who performed better had lesser or greater asymmetry indices in force measures (27,38). However, it is established that asymmetries are highly variant within and between participants. Therefore, assessing performance during a single trial and conducting a between participant comparison may not be a suitable method to assess the effects of asymmetry on performance. Alternatively, it is recommended to conduct repeated trials with participants to conduct within participant analyses on the effect of asymmetry on performance measures.

CHAPTER 6

The effect of intensity on the magnitude of asymmetry during cycling.

ABSTRACT

Previously, large asymmetries have been observed at low, moderate, high and supramaximal cycling intensities. Investigations into the effects of exercise intensity on the magnitude of asymmetry during cycling have shown conflicting findings, explained by methodological differences and limitations. The aim of this study was to assess the effects of intensity on the magnitude of asymmetry using best practice methodologies recommended in **Chapter 3**. Nine experience male cyclists completed 4 x 4 min cycling trials at intensities corresponding to 40, 60 75 and 90% of MAP, at 90 rpm, with 8 min recovery periods between each trial. All trials were repeated on three visits to the laboratory and were performed on cycle ergometer (LODE Excalibur) installed with Garmin Vector pedal power meters (GVPs). Across the four intensities, absolute and relative asymmetries in power output were calculated between left and right limbs. Mean absolute asymmetries ranged from 10.54 ± 8.28 W to 12.43 ± 9.68 W between intensities. Mean relative asymmetries ranged from 3.71 ± 2.93% to 7.27 ± 5.17% between intensities. When expressed as absolute asymmetries, no significant differences were found in power output between intensities (Effect sizes: 0.02 to 0.21). However, when interlimb differences were expressed as relative asymmetry indices, the one-way repeated measures ANOVA showed significant differences between intensities. Post hoc analysis identified that asymmetries in the 40% MAP trial were significantly different to all other intensities (60, 75 and 90% of MAP, $p < 0.01$ for all). The results of this study suggest that reporting interlimb differences as asymmetry indices results in misleading findings when assessing the effects of intensity on asymmetry. There is no clear effect of intensity on the magnitude of asymmetry during cycling.

6.1 Introduction

Cycling performance is directly related to the cyclists' ability to sustain the highest possible power output for the duration of the event. Road cycling event demands are dependent on numerous factors including, the events duration, type (time trial, mass start) and topography (12–17). Due to the varied topographical profiles of cycling events, containing climbs, descents, flat sections and sprints, power output is often stochastic in nature (10).

The effects of intensity on asymmetry during cycling was identified as the most commonly assessed research question amongst the literature reviewed in **Chapter 2**. However, the findings on the effects of intensity on asymmetries during cycling were conflicting. In our review (**Chapter 2**), we identified fifteen studies that assessed asymmetries during cycling at multiple intensities. Of these studies, eight reported no effect of intensity on asymmetry (42,44,47–52) whilst seven studies did observe an effect (39–41,43,46,53). Interestingly, amongst of the seven studies that did observe an effect, both positive and negative associations between intensity and the magnitude of asymmetry have been reported.

Amongst the literature, significant asymmetries have been observed at low, moderate, maximal, and supramaximal intensities. Conversely, symmetry has also been observed across the intensity spectrum. Critically reviewing these studies in **Chapter 3**, we identified some methodological differences and limitations that could explain the varied results in this field. Firstly, the magnitude of asymmetry can be vastly different depending on the metric assessed (27,90,93) and the calculation used to quantify asymmetry (94). Trecroci *et al.* (2018) reported the presence of significant asymmetries during the final stage of an incremental cycling test, with significance assessed using an ANOVA (39). The mean asymmetry in crank torque at the final workload of the incremental cycling was reported to be 5.61 ±

6.62%, a difference that other studies would report to be below the commonly use arbitrary threshold of >10% difference to be considered ‘asymmetrical’.

Secondly, the study design may also be a limitation to some of the previous studies. Four studies reported an association between intensity and asymmetry during incremental cycling tests (39–41,43) and one study assessed how asymmetries changed in response to changes in intensity during a 40 km time trial (53). During both incremental cycling tests and time trial efforts, the highest intensities occur towards the end of these protocols, when the participant is most fatigued (43). Furthermore, Javaloyes *et al*. (2020) observed a negative association between cycling intensity and asymmetry in professional cyclists competing in the Giro d’Italia (45). However, the cummulative volume and fatigue throuhgout the stages of this race likely influenced the reported asymemtry indices.

Fatigue during prolonged cycling may results in energy depletion, diminishing muscle activation, muscle trauma and altered biomechanics which could all affect the magnitude of asymmetry (116). A reduction in asymmetries at higher cycling intensities have been hypothesised due to potential increased bilateral neural input by interhemispheric cortical communication to facilitate the excitability of both legs (3). However, during incremental maximal cycling tests, asymmetries in muscle activation did not change with increasing power outputs (3), which does not support this hypothesis.

Therefore, the aim of this study was to assess bilateral asymmetry in power output during trials of different relative intensities, in isolation, to investigate the influence of intensity of the magnitude of asymmetry.

6.2 METHODS

6.2.1 Participants

Nine experienced male cyclists provided informed consent to participate in this study, which was approved by the University of Essex ethics committee (see **Appendix 1**).

Table 6.1 Descriptive participant characteristics.

	Mean	Standard Deviation
Age (years)	34.81	14.04
Height (cm)	177.06	7.59
Mass (kg)	76.26	12.09
Peak oxygen uptake (l/min)	4.12	0.35
Peak relative oxygen uptake (ml/kg/min)	54.49	9.97
Maximal aerobic power (W)	372.67	37.01

According to the guidelines for participant classification (79) using their relative $\dot{V}O_2$ peak, one participant was classified as untrained (P5), five participants were classified as recreationally trained (P2, P3, P6, P8, P9) two participants were classified as trained (P1, P7) and one participant was classified as professional (P4). For absolute peak power output, five participants were classified as trained (P2, P3, P5, P8, P9) and four were classified as well trained (P1, P4, P6, P7).

6.2.2 Protocol

Participants attended the laboratory on four occasions, each separated by 7 days. During the initial visit, following a 5 min warm up at 75 W, participants completed an incremental cycling test to exhaustion. The initial workload of 100 W was increased by 25 W per minute, and exhaustion was defined when participants could no longer maintain a cadence of 90 rpm. Respiratory parameters were sampled breath-by-breath, using open circuit spirometry

(Oxycon Pro, Jaeger, Höchberg, Germany). Maximal aerobic power (MAP) was calculated using the following equation (111):

Calculation 6.1

$$\text{MAP} = \text{Power of final completed stage (W)} + \frac{\text{time in final stage (s)}}{\text{stage duration (s)}} \times \text{power increment (W)}$$

During visits two, three and four, participants completed 4 x 4 min cycling trials corresponding to 40, 60, 75 and 90% of MAP, at 90 rpm, with an 8 min recovery interval between each trial (**Figure 6.1**). Intensities were not randomised due to the potential effects of fatigue on asymmetry. The highest intensities which would be expected to elicit the most fatigue were conducted at the end of the protocol and 8 min recovery durations were utilised to minimise the effects of accumulative fatigue as the protocol progressed.

Both the incremental cycling test, and all subsequent trials during visits two to four were performed on an electromagnetically braked ergometer (LODE Excalibur Sport, Groningen, Netherlands), which standardised the intensity of the trials. The ergometer was fitted in accordance with the participants own bicycle set up, and this position was replicated for every visit. Experimental trials were conducted on the same day and time for three consecutive weeks. Participants were asked to abstain from exercise for two days prior and refrain from consuming alcohol or caffeinated beverages for twelve hours prior to each visit to the laboratory. Participants were asked to keep a weekly training log, and a diary of their dietary intake on the day of the first trial. They were then asked to replicate training each week and dietary intake on the day of each trial.

The cycle ergometer was installed with strain gauge instrumented pedals *(Garmin Vector 1, Garmin International Inc., Olathe, USA)* for the assessment of bilateral power output, and data was relayed to a cycling computer *(Garmin Edge 510, Garmin International Inc., Olathe, USA)* linked via Bluetooth. Participants were not informed of the nature of the study (the assessment of bilateral asymmetry), and were blinded to all power data, only viewing cadence throughout each trial to target maintaining 90 rpm.

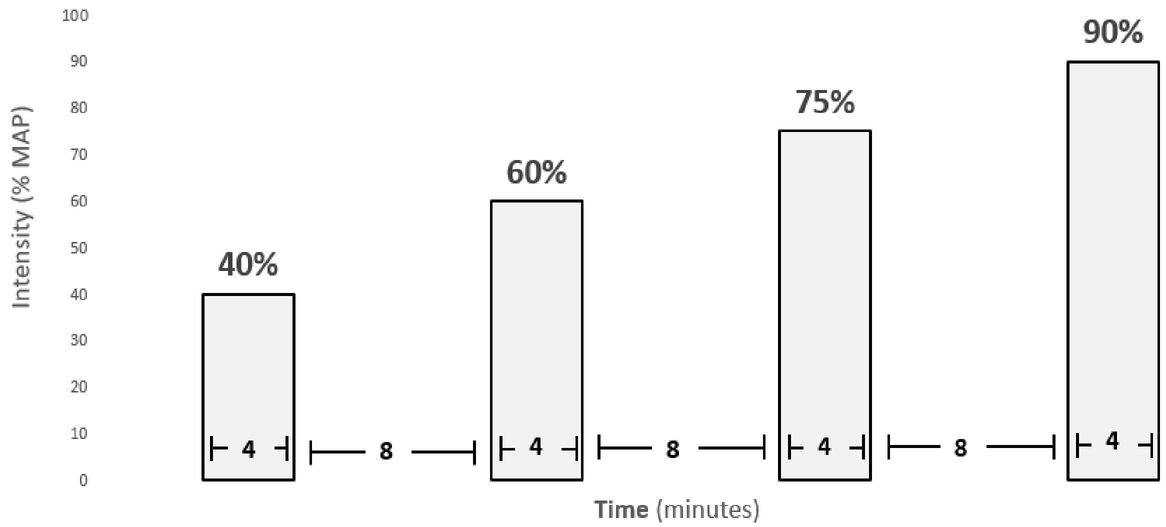


Figure 6.1 Schematic of the protocol conducted during visits 2,3 and 4.

6.2.3 Data Analysis

In this Chapter, the participants' repeat visits were not assessed on a test-retest basis. All intensity conditions were conducted during each visit to the laboratory. Therefore, each visit from each participant was treated as a single case for analysis. A total of 25 cases of data were analysed for the effect of intensity on the magnitude of asymmetry.

For each 4 min trial, the initial and final 30 s were excluded, and the remaining 3 min of data were analysed. Mean left limb and right limb power outputs were calculated, from which absolute and relative asymmetries were calculated. Absolute asymmetries were calculated by subtracting the mean power of the left limb from the mean power of the right limb (see **Calculation 6.2**). Relative asymmetries were calculated as an asymmetry index, using **Calculation 6.3**. The asymmetry indices were made absolute in order to pool group data to investigate the effects of asymmetry without positive and negative values reducing the measured effect.

Calculation 6.2

$$\text{Absolute asymmetry (W)} = \text{Right limb mean power (W)} - \text{Left limb mean power (W)}$$

Calculation 6.3

$$\text{AI\%} = \frac{\text{Right limb mean power (W)} - \text{Left limb mean power(W)}}{\text{Right limb mean power (W)} + \text{Left limb mean power(W)}} \times 100$$

The change in the magnitude of asymmetry between intensities was calculated using Cohen's d effect sizes, presented with 95% confidence intervals. The calculated effect sizes (ES) were interpreted in accordance with Hopkins *et al*. (112) (<0.2 = trivial, 0.2-0.6 = small, 0.6 – 1.2 = moderate, 1.2-2.0 = large, 2.0-4.0 = very large, >4.0 = extremely large).

Pearson's R correlations were used to explore the relationship between intensity and the absolute asymmetry in power and relative asymmetry in power. Spearman's Rho correlations were used to explore the relationship between intensity and relative asymmetry in power. Correlation coefficients were interpreted as negligible ≤ 0.30; low 0.31–0.50; moderate 0.51–0.70; high 0.71–0.90; > 0.90 very high.

A one-way repeated measures ANOVA (where appropriate followed by Bonferroni post hoc analysis) was performed to investigate the effect of intensity on the magnitude of absolute asymmetries in power, and the effects of intensity on the magnitude of relative asymmetry indices.

6.3 RESULTS

The mean ± SD absolute and relative asymmetries at each intensity are presented in **Table 6.2** and plotted in **Figure 6.2** and **Figure 6.3** for absolute and relative asymmetries, respectively. For the absolute measures, negligible ($r \leq 0.30$) non-significant associations were observed between intensity and asymmetry and trivial to small effect sizes were observed between intensity trials (**Table 6.3**). For the relative measures, low ($r = 0.274$) but significant ($p = 0.001$) associations between intensity and asymmetry were observed. Effect sizes are presented in **Table 6.3**. Moderate effects sizes were present between the 40% MAP trial and the 60%, 75% and 90% intensities. Trivial to small effect sizes were observed between all other intensities (60%, 75% and 90%).

The one-way repeated measures ANOVA showed no significant differences in the absolute asymmetries in power output between any of the intensities ($F (2.007) = 0.823$, $p = 0.45$). However, when assessing relative asymmetry indices, significant differences in the magnitude of asymmetry were observed ($F (1.512) = 14.20$, $p <0.01$) which post hoc analysis identified were between 40% MAP and 60% MAP, 40% and 75% MAP and 40% MAP and 90% MAP ($p <0.01$ for all).

Figure 6.2 A line graph showing mean and standard deviation (error bars) absolute asymmetries at the varied intensity trials.

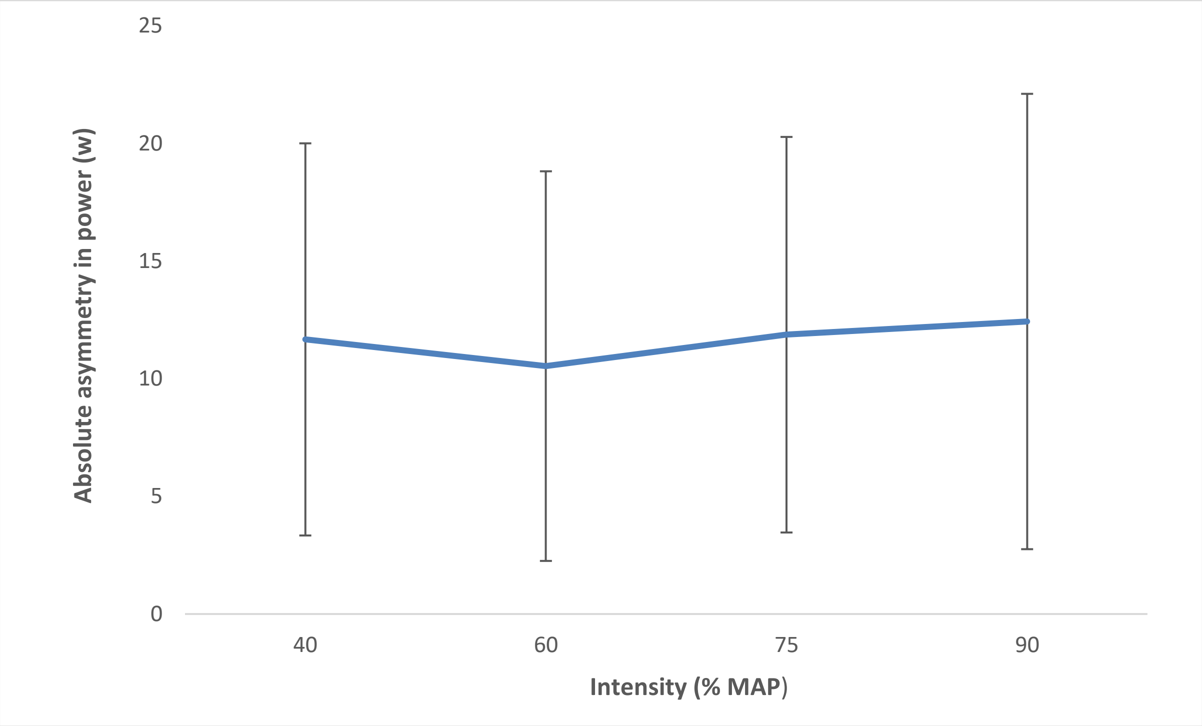
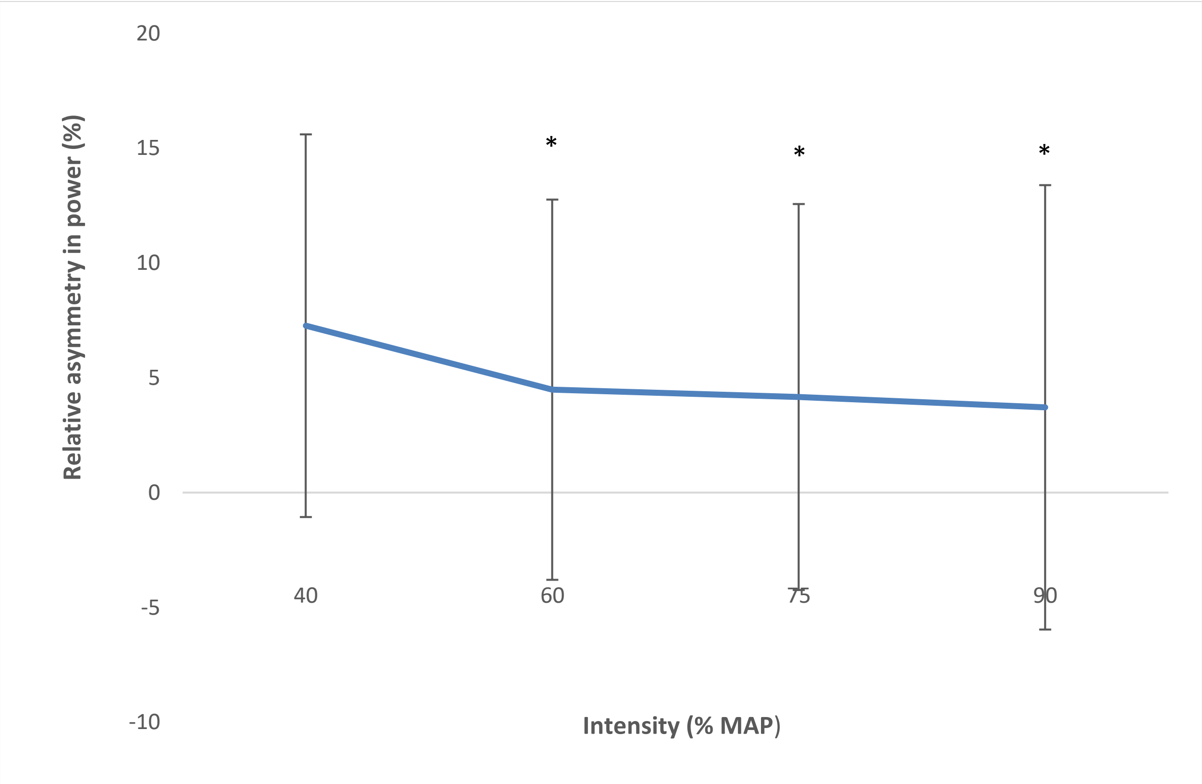


Figure 6.3 A line graph showing mean and standard deviation (error bars) relative asymmetries at the varied intensity trials.



*asymmetries at this intensity are significantly different to those at 40% MAP (p<0.01)

Table 6.2 A description of the intensity, physiological response, and asymmetry at each trial.

Intensity (% of MAP)	Intensity (%$\dot{V}O_2$ max)	Mean Power (W)	Absolute asymmetry (W)	Relative asymmetry (%)
40	58.97 ± 11.00	151.9 ± 12.74	11.67 ± 8.33	7.27 ± 5.17
60	78.37 ± 12.47	224.8 ± 21.79	10.54 ± 8.28	4.48 ± 3.56
75	90.57 ± 11.06	281.1 ± 26.91	11.87 ± 8.41	4.16 ± 3.05
90	-	339.0 ± 31.81	12.43 ± 9.68	3.71 ± 2.93

Mean ± SD

Table 6.3 Cohen's d between visit effect sizes for absolute and relative asymmetry at each cycling intensity.

	Absolute asymmetry (W)				**Relative asymmetry (%)**			
Intensity (%MAP)	**40**	**60**	**75**	**90**	**40**	**60**	**75**	**90**
40		0.14 (T)	0.02 (T)	0.09 (T)		0.60 (M)	0.69 (M)	0.79 (M)
60			0.16 (T)	0.21 (S)			0.10 (T)	0.20 (S)
75				0.06 (T)				0.04 (T)
90								

6.4 DISCUSSION

The aim of this study was to assess bilateral asymmetries in power output during trials of different relative intensities, to investigate the influence of intensity on the magnitude of asymmetry.

When reviewing group mean data for power output, absolute asymmetries appear to be similar across the intensity spectrum. However, if you express interlimb asymmetry as a relative asymmetry (using **Calculation 6.3**), it appears that as cycling intensity increases, asymmetry decreases. This inverse association has been reported previously amongst studies in this field using similar methods of analysing asymmetries (40,41,46,53). As described in **Chapter 3**, calculating asymmetry indices may result in misleading results when comparing trials of different intensities. For example, at 200 W an absolute interlimb difference of 20 W is calculated as a 10% asymmetry. At 400 W, for the same absolute interlimb difference of 20 W, the calculated asymmetry index will be 5% giving a false impression that interlimb differences have reduced as the intensity has increased. The data from this study reinforces the recommendations from **Chapter 3**, that asymmetries should be expressed in absolute terms during cycling.

Our results are in agreement with the eight studies that reported no effect of intensity on the magnitude of asymmetry during contant load trials (47,48,50–52), incremental cycling tests (42,44,49), and supramaximal cycling (50) (**Chapter 2**). A smaller weight of evidence from six studies reported varied effects of intensity on asymmetry with positive associatons (39,43) and negative associations observed (40,41,46,53). In **Chapters 2 and 3**, we described that many of these findigs may be affected to methodoligcal limitations and high between participant variabiltiy in asymmetry.

Whilst, in the current study, group data presents no clear and consistent trend between intensity and asymmetry, individual analyses provides a different insight for select participants (**Figure 5.2**). Individual responses to changes in cycling intensity are detailed below:

- **P3** – During all visits, as intensity increased, there is a greater contribution of the right limb to net power which results in either an increase in the magnitude of asymmetry, or a reversal in the direction of asymmetry.
- **P4** – During visit three, as intensity increased, the magnitude of asymemtry increased (40% MAP = 4.56 W, 60% MAP = 13.78 W, 75% MAP = 16.96 W, 90% MAP = 22.18 W).
- **P5** – During all visits, as intensity increased, there is a greater contribution of the left limb to net power which results in either an increase in the magnitude of asymmetry, or a reversal in the direction of asymmetry.
- **P6** – During two of the three visits, as intensity increased, the magnitude of asymmetry decreased.

Individual analyses does show some trends with intensity. For some participants, these trends are consistent between visits (P3, P5) but for others, the effects of intensity on asymmetry vary between visits.

6.5 CONCLUSIONS AND FUTURE DIRECTIONS

The results of this study suggest that there is no clear effect of intensity on the magnitdue of asymmetry during cycling. Further investigations are required to explore the cause of asymmetry during cycling to understand why reponses may be variant between days.

CHAPTER 7

The effects of interlimb asymmetry on gross efficiency during cycling.

ABSTRACT

Gross efficiency (GE) is a key determinant of cycling performance, defined as the percentage of effective mechanical work generated to the total energy expended to produce that work. Improving GE is a desirable effect of training interventions, and cyclists utilise aerodynamics and tactical strategies to increase their power output for a given oxygen cost, or in turn to sustain a given power output for a lower oxygen cost. Asymmetries in step time, step length and hip abductor strength have been shown to increase the metabolic cost of running (i.e., the efficiency). The effects of asymmetries on GE during cycling are not understood. The aim of this study was to investigate whether there is an association between asymmetries and GE during cycling.

In a within participant repeated measures study design, nine male cyclists completed 3 x 4 min cycling trials at 40, 60 and 75% of MAP, at 90 rpm, on three visits to the laboratory. Respiratory parameters and bilateral power output were measured continuously and the final minute of collected data in each cycling trial were averaged for analysis. A generalised mixed linear model (MLM) was developed to quantify the relationship between asymmetry and GE. The MLM showed a negative association between absolute asymmetry in power output and GE, which decreased by 0.04% for every 1 W interlimb difference in power output. The results of this study suggest that bilateral asymmetries may indeed limit cycling performance. Tests of reliability report that the smallest detectable change in GE is 0.6%, which based upon the results of our study, would result from an absolute asymmetry of 15 W. This absolute interlimb difference of 15 W could be meaningful threshold for defining asymmetry.

7.1 INTRODUCTION

Road cycling events, particularly at an elite level, take place over long distances, often across multiple days, resulting in considerable accumulation of energy expenditure. Assessing the training load, exercise intensities and performance characteristics of one elite cyclist during multiple three-week ‘Grand tours’ comprising 21 different stages, van Erp *et al.* (2018) reported impressive total energy expenditures of 74,000 to 80,000 kJ (117).

Professional cyclists exhibit high levels of aerobic fitness, as shown by their reported maximal aerobic power (MAP) and maximal oxygen uptake ($\dot{V}O_2$ max). For professional cyclists, absolute $\dot{V}O_2$ max typically ranges between 5.4 to 6.4 l/min, or when expressed relative to body mass $\dot{V}O_2$ max ranges between 70 to 85 ml/kg/min (118). Cyclists from recreational to elite level train to maximise this characteristic to subsequently enhance cycling performance. Whilst substantial improvements in $\dot{V}O_2$ max can be achieved via training, it is accepted that there is a physiological upper limit to the body’s ability to consume and utilise oxygen (119). Provided that a minimum level of $\dot{V}O2$ max is attained, reducing the oxygen cost of cycling might therefore be preferrable over further increases in the rate at which oxygen can be utilised. Producing high power outputs for the lowest possible oxygen cost is efficient, as this reduces the metabolic cost of cycling and saves energy (120).

Cycling efficiency can be assessed by the determination of gross efficiency (GE), which is expressed as the percentage of effective mechanical work generated to the total energy expended to produce that work (65). Increasing GE can be achieved by producing a higher power output for the same metabolic cost or by producing the same power output for a reduced metabolic cost.

Jeukendrup *et al.* (2000) explained that cycling efficiency has the potential for large effects on performance with the following example: An elite cyclist with a mass of 70 kg and a 1 hr sustainable power of 400W would improve their 40 km time trial time by 48 s with a 1% improvement in efficiency (10). Later, Moseley *et al.* (2003) explained that for the same metabolic energy expenditure, a cyclist with a GE of 23% could produce 28% more power than a cyclist with a GE of 18%. (121). Horowitz *et al.* (1994) observed that a 1.8% higher GE resulted in a 9% greater maximal sustained power during a 1 hour performance trial (122). A review article (123) aiming to clarify the link between GE and cycling performance reanalysing data from five investigations, including the aforementioned results of Horowitz *et al*. (1994), found that variation in efficiency explained 26% of the variation in power output during short cycling time trials and 36% of the variation during longer (40km to 1 hr) trials. These data suggest that GE is an important determinant of cycling performance (123).

Typically, GE has been reported to range between 18 to 23% (31). In a group of competitive cyclists, GE significantly increased during pre-season training and further throughout phases of the competitive season (124). These changes were related to training volume and intensity, with the proportion of time above the heart rate (HR) corresponding to the onset of blood lactate accumulation (OBLA) highly related to the increase in GE (124). Furthermore, a 7 year case study of a single multiple Tour de France winning cyclist observed an 8% increase in GE over this period (125). Although numerous other factors including reductions in body mass and periods of hypoxic exposure were expected to have contributed towards improved cycling efficiency. Potential mechanisms for improvements in efficiency with training include changes within the mitochondria, muscle fibre shortening velocities and changes to muscle fibre type (126). The mechanical efficiency of cyclists during a 1 hour performance trial was highly correlated with the percentage of Type 1 muscle fibres sampled by biopsy of the vastus lateralis muscle (122). In this study, a group of cyclists were grouped as normal (<56%: mean 48 ± 2%) or high percentage (>56%: mean 73 ± 3%) of Type 1 fibres. The $\dot{V}O_2$ max and pedalling cadence did not differ between the groups, however, the 1 hour mean power output was 9% greater for the high Type 1 group compared to the normal group (342 ± 9 W vs 315 ± 11 W) (122). Therefore, GE was significantly higher in the high percentage Type 1 group compared to the normal percentage Type 1 group (21.9 ± 0.3% vs. 20.4 ± 0.3%). Coyle *et al.* (1992) made similar observations in endurance trained cyclists whose GE varied from 18.5 to 23.5% at 300 W. They reported that more than half of the variability in GE was related to the percentage of Type 1 muscle fibres in the vastus lateralis muscle (127).

Road cycling is a unique sport, in that tactical components of cycling events can affect cycling efficiency considerably. Air resistance is by far the greatest retarding force affecting cycling. The aerodynamics of the rider, bicycle and its components are major contributors to cycling efficiency (128–131). In mass start events, cyclists benefit from the opportunity of drafting which has a considerable effect of the oxygen cost of cycling (132). When drafting a single cyclist at 32 km/h, a cyclist can spare ~18% of oxygen uptake. This effect increases at speeds of 37 and 40km/h, sparing 27% of oxygen uptake (133). Riding at 40 km/h behind a group of eight cyclists reduced oxygen uptake significantly more (39%) than drafting one, two or four cyclists in a line (133). To a lesser extent other variables have been reported to affect GE, such as the cyclists body position (seated or standing) and the rolling resistance (e.g. tyre pressure) (134).

In endurance running, asymmetries in step time, step length and hip abductor strength have all been reported to increase the metabolic cost (i.e., the efficiency) of running (135–137). However, the effect of asymmetry on efficiency during cycling is not fully understood. If asymmetries have a similar effect of endurance cycling as they do to running, this could provide evidence towards the hypothesis that asymmetries implicate cycling performance (as discussed in **Chapter 2)**.

Therefore, the aim of this study was to investigate whether there is an association between bilateral asymmetry and efficiency during cycling.

7.2 METHODS

7.2.1 Participants

Nine experienced male cyclists provided informed consent to participate in this study, which was approved by the University of Essex ethics committee (see **Appendix 1**).

Table 7.1 Descriptive participant characteristics.

	Mean	Standard Deviation
Age (years)	34.81	14.04
Height (cm)	177.06	7.59
Mass (kg)	76.26	12.09
Peak oxygen uptake (l/min)	4.12	0.35
Peak relative oxygen uptake (ml/kg/min)	54.49	9.97
Maximal aerobic power (W)	372.67	37.01

7.2.2 Protocol

Participants attended the laboratory on four occasions, each separated by 7 days. During the initial visit, following a 5 min warm up at 75 W, participants completed an incremental cycling test to exhaustion. The initial workload of 100 W was increased by 25 W per minute, and exhaustion was defined when participants could no longer maintain a cadence of 90 rpm. Maximal aerobic power (MAP) was calculated using the following calculation (111):

Calculation 7.1

$$\text{MAP} = \text{Power of final completed stage (W)} + \frac{\text{time in final stage (s)}}{\text{stage duration (s)}} \times \text{power increment (W)}$$

During visits two, three and four, participants completed 4 x 4 min cycling trials corresponding to 40, 60, 75 and 90% of MAP, at 90 rpm, with an 8 min recovery interval between each trial (**Figure 6.1**). Intensities were not randomised due to the potential effects of fatigue on asymmetry. The highest intensities which would be expected to elicit the most fatigue were conducted at the end of the protocol and 8 min recovery durations were utilised to minimise the effects of accumulative fatigue as the protocol progressed.

Both the incremental cycling test, and all subsequent trials during visits two to four were performed on an electromagnetically braked ergometer (LODE Excalibur Sport, Groningen, Netherlands), which standardised the intensity of the trials. The ergometer was fitted in accordance with the participants own bicycle set up, and this position was replicated for every visit. Experimental trials were conducted on the same day and time for three consecutive weeks. Participants were asked to abstain from exercise for two days prior and refrain from consuming alcohol or caffeinated beverages for twelve hours prior to each visit to the laboratory. Participants were asked to keep a weekly training log, and a diary of their dietary intake on the day of the first trial. They were then asked to replicate training each week and dietary intake on the day of each trial.

The cycle ergometer was installed with strain gauge instrumented pedals *(Garmin Vector 1, Garmin International Inc., Olathe, USA)* for the assessment of bilateral power output, and data was relayed to a cycling computer *(Garmin Edge 510, Garmin International Inc., Olathe, USA)* linked via Bluetooth. Participants were not informed of the nature of the study (the assessment of bilateral asymmetry), and were blinded to all power data, only viewing cadence throughout each trial to target maintaining 90 rpm.

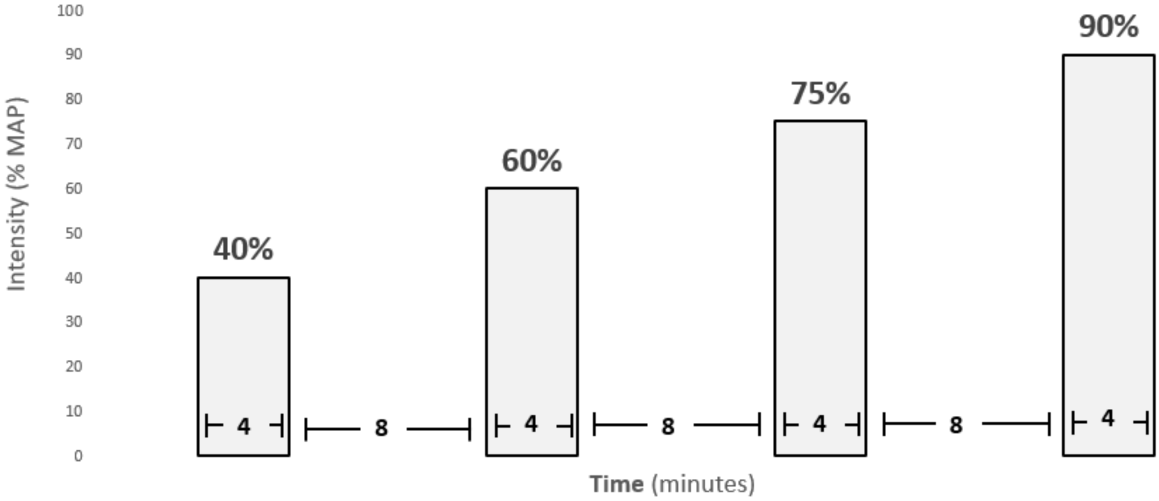


Figure 7.1. Schematic of the protocol conducted during visits 2,3 and 4.

7.2.3 Data Analysis

Statistical analyses were performed using IBM SPSS Statistics (v25). Data from 90% MAP trials were excluded from the analysis as respiratory data were not sampled during this intensity. A small amount of random data was missing (<10%) due to equipment error. Multiple imputation was used in order to utilise all available data and to preserve sample size, with procedures including five imputations which were pooled for analysis.

Using measures of $\dot{V}CO_2$ and $\dot{V}O_2$ obtained from the online gas analyser, energy expenditure (EE) was calculated according to the formula of Brouwer (138) (**Calculation 7.2**). GE was calculated as the ratio of work rate to the rate of energy expenditure expressed as a percentage (**Calculation 7.3**).

Calculation 7.2

$$\text{Energy expenditure (J.s)} = \left(\left(3.869 \times \dot{V}O2\right) + \left(1.195 \times \dot{V}CO2\right)\right) \times (4.186 \div 60) \times 1000$$

Calculation 7.3

$$GE\% = \frac{\text{work rate (W)}}{\text{energy expenditure (J.s)}} \times 100$$

Pearson’s product moment correlation was used to describe the relationship between absolute asymmetry in power and GE. we acknowledge that using multiple data points from the same individual does not meet the assumptions underlying the use of Pearson's product moment correlation, but we included this analysis to initially explore the data and identify any potential associations.

The GVPs used to measure bilateral power during our study also present additional pedalling variables that provide an insight into pedalling technique. One of the metrics, torque effectiveness (TEff), describes the percentage of the total torque produced that is positive, with smaller values representing greater negative or resistive torque applied to the pedal. Torque effectiveness has also been described as pedal force effective and index of effectiveness, which are defined as the ratio of force perpendicular to the crank (effective force) and total force applied (resultant force) (80)

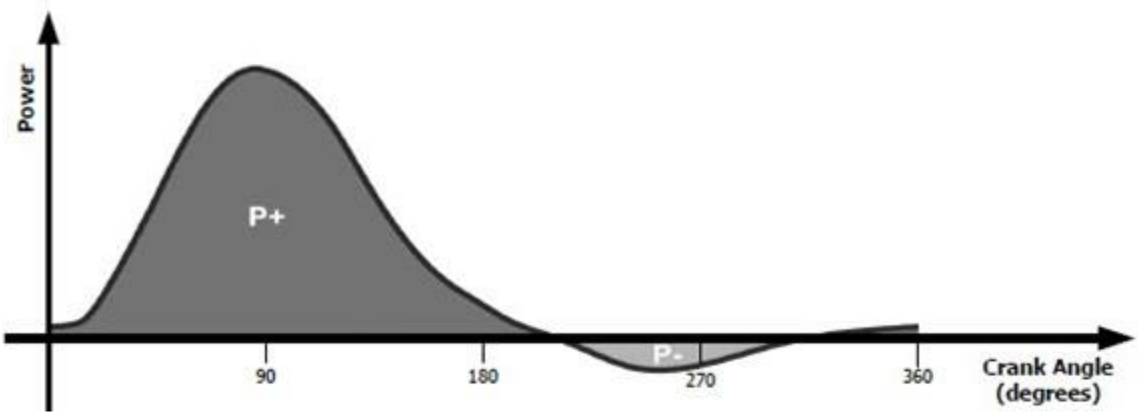


Figure 7.2 A typical power curve for one crank arm, where P+ represents the positive power applied to the crank and is the sum of the instantaneous power measurements. Similarly, P- is the sum of the negative instantaneous power measurements.
(**Source:** https://.support.garmin.com)

A generalised mixed linear model (MLM) was developed to quantify the relationship between asymmetry and GE. MLMs are a useful tool for analysing data with multiple repeated observations because they allow for the modelling of the within-subject correlation of the observations. MLMs account for the fact that observations from the same participant are likely to be more alike each other than observations from different participants.
MLMs provide a more accurate and precise estimate of the parameters of interest than traditional methods (such as repeated-measures ANOVA) that assume independence between observations. Data based on multiple repeated observations contain multiple sources of variation which can be accounted for as fixed or random effects in the MLM.

The structure of the MLM developed for this study is as follows. The dependant variable assigned to the model was GE. A source of variation in our data is the within-subjects variability. This is accounted for by including a time variable (to reflect the repeated nature of observations) and modelling the correlation between observations from the same participant using a covariance structure. The categorical variables of visit number (1,2,3) and intensity

(40, 60, 75, 90%) were included as fixed effects in our model. Absolute asymmetry was also included as a fixed effect in the MLM. The parameter of interest was the association between asymmetry and GE, and this was quantified as the main effect of asymmetry (a continuous variable) on GE. Another important source of variation is between-subject variability. This was accounted for in the MLM by including the categorical variable, participant ID, as a random effect in the model. A diagonal covariance structure was chosen using the Akaike Information Criterion (AIC) as a measure of model fit.

7.3 RESULTS

The mean absolute asymmetry in power output was 11.21 ± 8.13 W. The mean GE was 21.14 ± 1.95 %. Absolute asymmetry in power output and GE for each intensity are presented in **Table 7.2**.

Pearson's correlation showed a negligible association between absolute asymmetry in power output and GE (r = 0.287) (**Figure 7.3**). The MLM analysis showed a significant negative association between absolute asymmetry in power output and GE (**Table 7.3**). The linear mixed model showed that GE decreased by 0.04% for every 1 W interlimb difference in power output.

Table 7.2 Mean ± SD of GE and absolute asymmetry in power output during trials of varied relative intensities.

	All intensities	40% MAP	60% MAP	75% MAP
Absolute asymmetry (W)	11.21 ± 8.13	11.25 ± 8.42	10.23 ± 7.95	12.15 ± 8.22
Gross efficiency (%)	21.14 ± 1.95	20.25 ± 2.16	21.40 ± 1.79	21.77 ± 1.60
Oxygen Uptake (l.min)	2.98 ± 0.62	2.32 ± 0.20	3.09 ± 0.32	3.52 ± 0.50
Respiratory Exchange Ratio	0.97 ± 0.08	0.90 ± 0.05	0.98 ± 0.07	1.03 ± 0.05

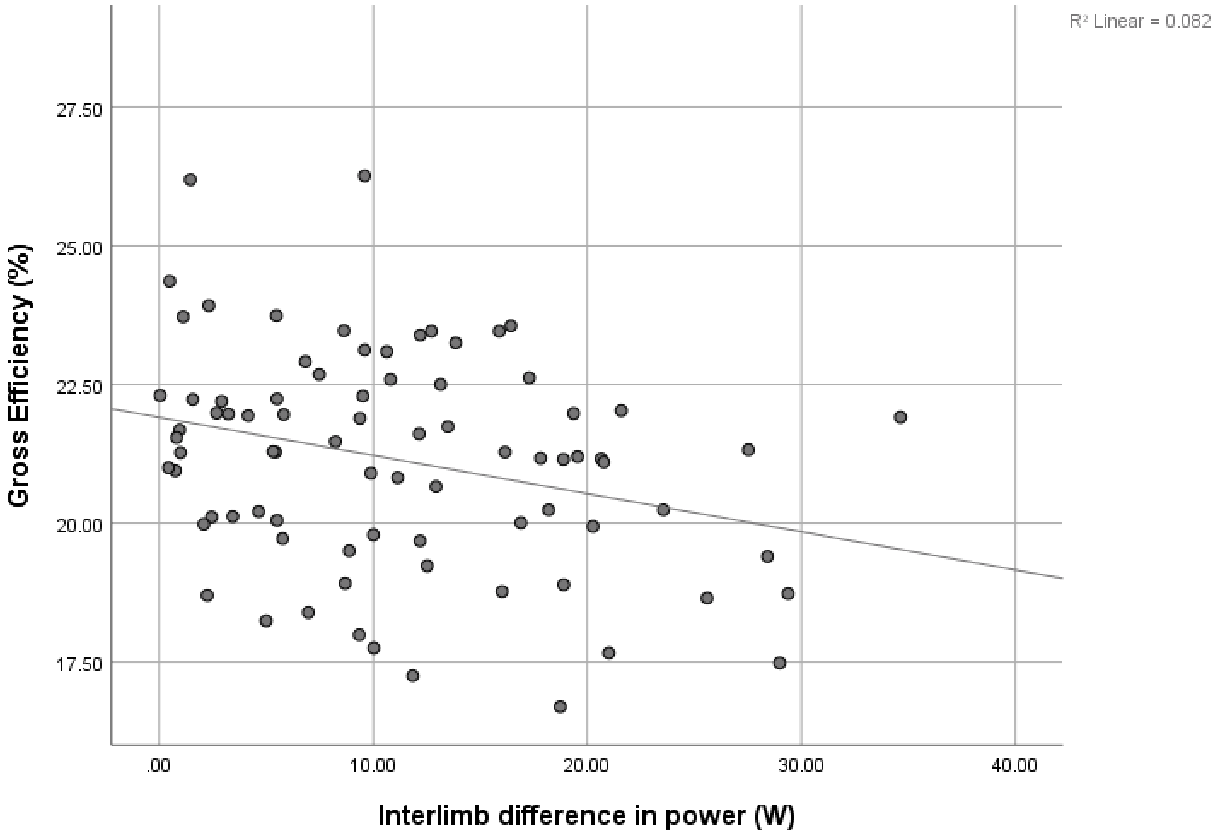


Figure 7.3 Illustration of gross efficiency plotted against the absolute interlimb difference in power.

Table 7.3 Linear mixed models examining the factors related to gross efficiency (GE) during cycling.

	Estimate	95% CI	P
Intercept	18.95	17.36 – 20.54	< 0.001
Intensity	0.043	0.03 – 0.06	< 0.001
Visit	0.069	-0.19 – 0.33	0.562
Absolute asymmetry (W)	-0.044	-0.08 – -0.01	0.011

Our results show that the lower limb that produced a higher power output during cycling also had a higher TEff in sixty-seven of the seventy-three cases of complete data (not including the imputed data). We also observed a moderate positive correlation between interlimb asymmetries in power and interlimb asymmetries in TEff, as shown in **Figure 7.4**.

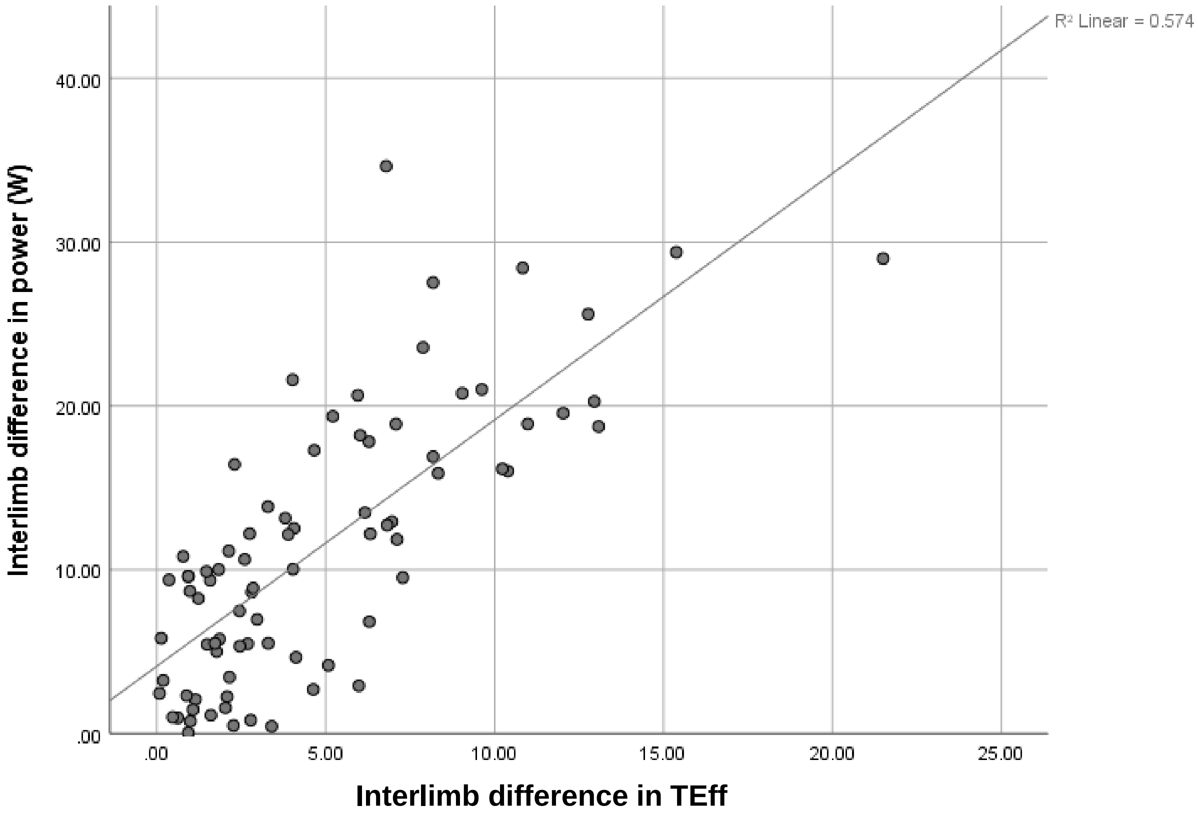


Figure 7.4 Illustration of asymmetry in power plotted against asymmetry in torque effectiveness (TEff).

7.4 DISCUSSION

In this study, we investigated the association between interlimb asymmetry and GE during cycling. Our results suggest there is a negative association between GE and absolute interlimb asymmetry in power output. The MLM described that GE decreased by 0.04% for every 1 W interlimb difference in power output. Ours is the first study to investigate the effects asymmetry on GE during cycling and our findings demonstrate that asymmetries are performance limiting.

7.4.1 Asymmetry and performance or key performance indicators

Two previous studies have assessed the effects of cycling asymmetry on performance (27,38), with conflicting results. Bini *et al.* (2016) found no clear association between peak pedal force asymmetries and 20 km time trial performance (38). On the contrary, larger asymmetries in effective forces (propulsive force) were associated with faster 4 km time trial performances (27), which is opposed to suggestions that asymmetries may be performance limiting. However, amongst the ten participants in this study, 4 km performance times and asymmetry indices varied considerably. In **Chapters 2 and 3**, we discussed some limitations to these studies. Firstly, the methods of these studies describe analysing data for 5 complete crank cycles at segments of the time trials, The data sampling period is estimated to equate to ~27 s of the 4 km time trial and ~ 13 s of the 20 km time trial. For the latter, that sample duration is <0.1% of the mean performance time of 30 ± 3.7 min, which may not truly reflect the participants' asymmetries during the full event. Additionally, participants also had autonomy over their gear ratio and cadence during the time trials, therefore results may be influenced by participants pacing behaviour. Furthermore, as there are numerous factors that influence cycling performance, including physiological characteristics and training status, acknowledging this and the considerable within and between participant variation in asymmetry measures (**Chapter 5**), a between participant analysis for the investigation of the effects of asymmetry on performance may not be suitable. Alternatively, a within participant study design, such as that used in the current study, would limit the influence of other performance determinants on the results.

Although they did not measure asymmetry during cycling, Rannama *et al.* (2015) observed that asymmetries in peak isokinetic torque of the knee extensors were negatively correlated with 5 s maximal power output during sprint cycling (66).

Whilst studies evaluating the effect of asymmetry on performance in cycling are scarce, multiple research groups have conducted these investigations in running. In sprint running, asymmetries in strength and kinematic parameters were shown to have no effect on performance (139,140). However, effects of asymmetry on the metabolic cost of running have been observed at low to moderate intensities (71,135–137). Increased step time and step length, enforced using a metronome, increased the metabolic power of running (135,137). Melo *et al.* (2020) observed that mechanical efficiency (ME) was correlated with global symmetry index (GSI) (71), a combined measure of symmetry in three planes of movement collected using accelerometers. They predicted that changes in GSI accounted for 43% of the variation in ME during a 10 km running trial (71). Furthermore, Blagrove *et al.* (2020) saw a negligible relationship between strength asymmetry and running economy (136). But when assessing female participants only, reported that asymmetries in hip abduction strength >9% negatively affected running economy (136).

Contrary to our research, many of the earlier studies of performance and asymmetry in running and cycling have utilised a between participants study design. We know from our review of the literature in **Chapter 2**, that asymmetries during cycling are highly variable between participants. We also identified that asymmetries are highly variable within participants (**Chapter 5**). This high variability is asymmetry presents challenges when assessing relationships using correlations, as the graph coordinates are spread and therefore the slope of a trendline is challenging to identify. Acknowledging this recent finding, we consider a within participant study design to be more appropriate for the assessment of asymmetries and their effects on performance and the MLM method enables us to account for participant variation in our analyses.

In our study, the mean GE for cycling intensities corresponding to 40, 60 and 75% of MAP were 20.25 %, 21.40 % and 21.77 %, respectively. These results were not dissimilar to those reported in the study of Hopker *et al*. (141). The trained male competitive cyclists in their study had a mean GE of 21.7 ± 1.6% during 8 min stages of cycling at 60% MAP (141). Increases in GE have been observed with training (124,126) and across a competitive season (124). Therefore, variance in training status could explain some of the variation in GE between participants in our study. According to the guidelines for participant classification (79) using absolute peak power output, five participants were classified as trained (P2, P3, P5, P8, P9) and four were considered well trained (P1, P4, P6, P7).

The GE data in this study may be influenced in part by the study design. Our participants were instructed to cycle at a fixed cadence of 90 rpm. Experienced cyclists are more efficient at higher pedalling cadences and cyclists generally may be more efficient at their freely chosen cadence (65). Furthermore, the trials in this experiment were collected in ascending order of cycling intensity to minimise the effects of fatigue and the initial 40% MAP trials was conducted without a prior warm up. Higher muscle temperatures facilitate metabolic processes and aid the exchange of oxygen from the blood to the working tissues (142).

Pedalling technique is cyclic, with limbs at opposite ends of the pedal cycle alternating through downstroke (0 to 180°) and upstroke (180 to 360°) phases. This alternating bilateral technique requires coordination and effective activation-deactivation dynamics to ensure the limb in the recovery phase (upstroke) is not producing excessing negative torque which would impede upon the work of the limb in the propulsive phase (downstroke) (74). Negative torque has been observed during cycling (51,55).

In our study, the participants were not informed of the intention to assess asymmetry and were blinded to any information relating to power output to ensure the data reflected the participants' innate technique. Our results show that the lower limb that produced a higher power output during cycling also had a higher TEff in sixty-seven of the seventy-three cases of complete data (not including the imputed data). We also observed a moderate positive correlation between interlimb asymmetries in power and interlimb asymmetries in TEff, as shown in **Figure 7.4**.

This could suggest that asymmetries in power output are partly explained by effectiveness of each limbs cycling technique. In most cases, the limb producing the least power is also producing greater negative or resistive forces during the pedal cycle. Therefore, the limb in the power phase (0 to 180° of the pedal cycle), is having to produce more force to overcome these resistive forces, which could result in larger asymmetry and an increased metabolic cost. Interestingly, Bini and Hume (2015) report that during a 4 km time trial, the intra limb variability for effective force in the non-dominant limb was considerably greater than the dominant limb. This may suggest that the pedalling technique of the non-dominant limb is less consistent than that of the dominant limb and that technique and motor coordination are possible factors influencing cycling asymmetry (27).

It has been observed that with the provision of feedback on the application of pedal forces, cyclists and non-cyclists can improve pedal force effectiveness within a single training session or during short duration studies (80). However, changes to pedalling technique significantly affect GE. When cyclists actively increase their propulsive torque during the recovery phase, between 180 and 360° of the pedal cycle, GE decreases as a result of the increased metabolic cost of activating the flexor muscles that facilitate this pulling action on the pedal (143–145).

Cyclists need to balance producing effective force with the resultant energy cost in order to produce and sustain high power outputs. To date, longitudinal research has not been conducted to examine the adaptations to training with a more effective pedalling technique that is initially less efficient to see whether with time, prolonged training with this technique results in a reduced metabolic cost and therefore greater efficiency.

7.4.2 Defining asymmetry

Tests of reliability report that the smallest detectable change in GE is 0.6% (30,31). Based upon the results of our study, an absolute asymmetry of 15 W would result in a 0.6% change in GE. This absolute interlimb difference of 15 W could be meaningful threshold for defining asymmetry. In **Chapter 3,** we discussed that there is currently no agreed magnitude of interlimb difference recommended to define asymmetry during cycling. Arbitrary interlimb differences of 10 or 20% are commonly used, however their use should be questioned because the magnitude of asymmetry can be vastly different depending on the metric assessed (27,90,93) and the calculation used to quantify asymmetry (94). Furthermore, in **Chapter 3** we acknowledged the limitations of expressing asymmetry as a relative value, such as a percentage difference, during sports such as cycling. Using an asymmetry index calculation, a 20 W interlimb difference in power output equates to a 20% asymmetry at 200 W, or a 40% asymmetry at 100 W. When expressed absolutely, interlimb differences at these two intensities have remained the same. The findings of our study provide a minimum absolute asymmetry required to have a measurable effect on GE, a key indicator of cycling performance.

Two studies have shown that acute technique focussed interventions are effective at reducing the magnitude of interlimb asymmetries during cycling (57,58). Participants in a study by Kell and Greer (2017) were provided with visual feedback on the percentage of total power each limb was contributing and instruction to ‘try to pedal symmetrically’(58). With this feedback, participants with initial asymmetries within the typical range of 5 to 20% significantly decreased their asymmetry indices to pedal more symmetrically with this intervention. Mean pre-intervention absolute asymmetries were 8 W and decreased to 2.5 W with the acute intervention which from the results in our study would have a small effect on GE, but less than the measurement error of this variable. Bini *et al.* (2016) provided a similar intervention and cyclists who presented with initial asymmetries >20% were able to decrease their asymmetry to -7% ± 9% (57). Both studies demonstrate that cyclists were able to adjust the manner at which they apply forces to the pedals to immediately ameliorate the magnitude of asymmetry which implies that asymmetry is related to cycling technique.

7.5 CONCLUSIONS

Our research suggests that absolute asymmetries in power output are negatively associated with GE during cycling. It appears that the limb contributing least to total power output cycles with a less effective pedalling technique, producing greater negative or resistive forces during the recovery phase. This less effective pedalling technique of the lesser contributing limb may be a cause of asymmetries in power output during cycling due to the requirement of the limb in the propulsive phase to produce greater power to overcome the additional resistance. This is turn could explain the increase metabolic cost of cycling with greater asymmetries in power output. Further work needs to be conducted to assess cycling technique and its link to asymmetries during cycling.

CHAPTER 8

GENERAL DISCUSSION

8.1 GENERAL DISCUSSION

It is expected that individuals with an existing injury would present with an interlimb asymmetry. Greater asymmetries in power output have been observed in those with an ACL injury (47) and those with OA (61), compared to healthy controls. However, asymmetries during cycling are also common amongst those without injury. In the current study, mean absolute interlimb differences in power output were 11.21 ± 8.13 W, with a range of 0.05 to 34.63 W. The underlying mechanisms responsible for interlimb differences in healthy cyclists are not well understood. Anthropometric asymmetries have been measured in adolescent and adult male road cyclists (146–148). Pimentel *et al.* (2019) reported that cyclists have greater asymmetries in lower body bone mineral density and lean mass compared to non-cyclists, assessed using dual x-ray absorptiometry (148). In a comparison of cycling performance levels, high performance road cyclists had fewer morphological asymmetries measured using 3D body scanning and segmental bioelectrical impedance analysis, compared to low performance cyclists (146). Additionally, Yanci *et al.* (2014) observed significant bilateral asymmetries for single leg jump height and power production during countermovement jump trials with a group of elite road cyclists (149). Furthermore, Rannama *et al.* (2016) found asymmetries in peak isokinetic torque of the knee extensors that were negatively correlated with 5 s maximal power output during sprint cycling (81).

In the last decade, the use of power meters has become much more prevalent amongst cyclists of all performance levels. This can be attributed to the advancements in technology which enabled the production of smaller, more affordable devices that can be fitted to any bicycle (19). Historically power meters were restricted to laboratories, were challenging to install and were only compatible with some bicycles. When linked to handlebar mounted cycling computers, modern power meters provide an array of live metrics which cyclists use to monitor training and event intensities. Notably, right/left balance is a common metric available to many cyclists in the field, which describes the percentage of the net power output produced by each limb. This facilitates the assessment of asymmetries during cycling. Although cycling is a bilateral sport, with no obvious lateral dominance, asymmetries of 5 to 20% are common in non-injured cyclists (3). Road cyclists perform a high proportion of their training and competition durations at low to moderate intensities (33–36). In 2011, Carpes *et al*. reviewed literature that investigated bilateral asymmetries during cycling and concluded that cyclists exhibit higher asymmetry indices during low to moderate intensity exercise, whilst bilateral contributions at maximal intensities were suggested to be more symmetrical (3). Therefore, during training and competition, cyclists may produce repeated asymmetrical loads (3). It has been hypothesised that cycling asymmetrically may increase the risk of developing overuse injuries, and could compromise performance due to premature fatigue (3). However, there is little evidence to support either of these claims. Whilst research studies have been designed to assess whether interventions in pedalling technique are effective at reducing the magnitude of bilateral asymmetries during cycling, it has yet to be confirmed that asymmetries indeed result in 1) a greater occurrence of overuse injury and/or 2) that asymmetries have negative implications for cycling performance.

Due to a surge in cycling asymmetry research articles with the technological advancements that made power meters more accessible, we began our thesis with an initial literature review (**Chapter 2**) to update that of Carpes *et al.* (2011) (3).

Our review included studies that used power meters to assess asymmetries in any kinetic metrics, measured during cycling. The primary aim of this review was to identify whether there is any evidence to answer the following research questions:

1) Are asymmetries associated with incidence of injury during cycling?

2) Is there an association between the magnitude of asymmetry and cycling performance?

Furthermore, this review examined the conditions under which asymmetries are most prevalent, including the effects of intensity, cadence, bicycle configuration, cycling position and participants performance level on the magnitude of asymmetry. In addition, we reviewed articles that assessed whether technique interventions are effective at ameliorating asymmetries during cycling.

In **Chapter 2**, we established that there are many conflicting findings in the field and therefore there was a lack of consistent and conclusive evidence to answer the research questions posed. When attempting to critically review the potential cause of the disparity in the results, the heterogenous study characteristics amongst the included literature made it impossible to systematically review the literature. Before conducting research studies to further investigate some of these primary research questions, we first identified the need to determine an optimal method for assessing bilateral asymmetries during cycling, a suggestion made by other researchers in the field.

In **Chapter 3** of this thesis, we evaluated the current methods used to measure, analyse, and interpret interlimb asymmetries during cycling. Critically reviewing the literature, we identified variance in the methods amongst 1) the location of the power meter on the bicycle, 2) the criteria for defining dominance, 3) the metric assessed for asymmetry, 4) the duration of data sampling, 5) the calculation used to quantify interlimb differences and 6) the magnitude of interlimb difference required to be considered asymmetrical. Accounting for the varied methodological choices amongst all of the components, we identified that there are 12,600 possible methodological combinations amongst the current literature. Our aim was to critically review these methods to determine a best practice for assessing asymmetries during cycling to inform future research and applied practice. Our recommendations for measuring, analysing and interpreting asymmetries during cycling are detailed below in **section 8.2**

Many of the limitations in the methodological design of previous studies were a result of the limited and suboptimal technologies that were available at the time these studies were conducted. Many studies measured bilateral contributions using a power meter that was located on a component of the bicycle that is influence by the net torque of both of the lower limbs (32,43,84). For example, power meters located on the crank spider or on a load cell alongside the chain attribute torque generated in each 180° of the crank cycle to the limb that is in the power phase or downstroke. It is possible for cyclists who use cleats or toe clips to produce propulsive forces during the upstroke, which would result in an overestimation of torque produced by the limb in the power phase. Alternatively, negative forces have been observed during the recovery phase of the pedal cycle (51,55). Using these power meters, negative torque applied by the contralateral limb diminishes torque of the ipsilateral limb (43), which may result in an underestimation of torque, especially in those with less efficient techniques. Alternatively, power meters located in the pedal measure forces directly at their application by the cyclist, before any frictional losses through the bicycles drivetrain (19) at a location on the bicycle with minimal (the least) left and right limb interaction. Many commercially available pedal power meters have been assessed as determined as reliable and valid for the measurement of power output during cycling. However, these studies have assessed the pedal power meters for their measures of net power output, a summation of the power produced by both limbs. We identified a gap in the literature, to assess the reliability and validity of torque measured by left and right pedals, separately. This would further justify the use of power meters located at the pedal when investigating asymmetries during cycling.

In **Chapter 4,** we assessed the GVPs for their reliability and validity. To eliminate the influence of biological variation in our assessment of the reliability of the GVPs (105), we chose to conduct static load trials on each pedal for a range of pedal loads and crank angles. The reliability of the GVPs during the static load assessments in our study was reported as a CV of <0.3% and mean bias was reported at 0.18 Nm which equates to 1.7 W at cadences of 90 rpm. These results demonstrate that left and right GVPs were reliable and valid in their measures of torque, justifying the use of this equipment for the assessment of bilateral asymmetries during cycling.

Measurement error is comprised of equipment and biological error. Whilst **Chapter 3** answered questions on the equipment error of the GVPs, variation in participants' asymmetries during cycling in less well understood to inform us on the biological error. Looking back at our literature reviews in **Chapter 2** and **3**, we identified that a single study conducted in 1976 had assessed participants for bilateral asymmetries on multiple days. They reported that measured asymmetry in work done was 'extremely variable' from day to day and that several participants demonstrated a reversal between days in the limb which did more work (51). Before moving on to conduct studies which investigate whether asymmetries are performance limiting, and the conditions under which asymmetries are most prevalent, we first needed to investigate the variance in asymmetry using modern power meter technologies. In agreement with the findings of Daly and Cavanagh (1975) (51), our study in **Chapter 5** found that both the magnitude and direction of asymmetry are highly variable between visits. The mean CVs for absolute asymmetries in power output ranged between 12.87 to 186.22%, and many participants demonstrated a reversal in the limb contributing most to net power output. This finding furthered our recommendations we made in the review of the methods of assessing asymmetries during cycling that we presented in **Chapter 3**, to include assessing participants asymmetries on multiple visits.

Upon determining a best practice approach to measuring asymmetries during cycling, we then revisited our earlier literature reviews to identify research questions that required revisiting. The most commonly investigated research question identified in **Chapter 2** was whether there is an association between cycling intensity and the magnitude of asymmetry. The main conclusion of the review conducted by Carpes *et al*. (2011) was that asymmetries were greater at low to moderate intensities, which represent the highest proportion of training and event durations. Therefore, during training and competition, cyclists may produce repeated asymmetrical loads (3). In **Chapter 6**, our aim was to investigate the effects of cycling intensity on the magnitude of asymmetry using the methodological recommendations of **Chapter 3**. Our results suggested that there was no clear effect of intensity on the magnitdue of asymmetry during cycling. However, when scrutinsing the data of individual participants, we observed that negative and positive associations between intensity and asymemtry were present amongst our participant group, and for most participants the effect of intensity on the magnitude of asymmetry varied day to day.

Lastly, in **Chapter 7** we assessed the effects of the magnitude of asymmetry on GE, a key determinant of endurance cycling performance. Earlier studies in runners showed the metabolic cost at endurance intensities increased due to asymmetries in step time (135,137) step length (137), hip abductor strength (136) and accelerometery data from three planes of movement (71). However, to the best of our knowledge, the effect of asymmetry on GE during cycling had not been investigated. The results of our analysis presented in **Chapter 7** showed a negative association between GE and absolute interlimb asymmetry in power output. Our MLM estimated that GE decreased by 0.04% for every 1 W interlimb difference in power output. Tests of reliability report that the smallest detectable change in GE is 0.6% (30,31). Based upon the results of our study, a 0.6% change is GE would result from an interlimb asymmetry in power output of 15 W. This absolute interlimb difference of 15 W could be meaningful threshold for defining asymmetry, which provides further recommendations for interpreting asymmetry data during cycling. Adding to the literature, these findings support the hypothesis that asymmetries are indeed performance limiting.

Whilst anthropometrical and strength asymmetries that have been observed in cyclists (146–149) may contribute towards interlimb asymmetries during cycling, these measures do not vary considerably day to day to explain the high between day variation of asymmetry that was observed in **Chapter 5**. However, the additional pedalling metrics presented by the GVPs suggest that the limb contributing least to total power output cycles with a less effective pedalling technique, producing greater negative (or resistive) forces during the recovery phase. This less effective pedalling technique of the lesser contributing limb may be a cause of asymmetries in power output during cycling due to the requirement of the limb in the propulsive phase to produce greater power to overcome the additional resistance. This is turn could explain the increase metabolic cost of cycling with greater asymmetries in power output.

The key contributions of this thesis to field include:

- Recommendations for best practice methods to measuring, analysing and interpreting asymmetries during cycling.
- Evidence to support that cycling intensity is not associated with the magnitude of asymmetry.
- Evidence to support that asymmetries during cycling are performance limiting, with reports of a negative association between asymmetry and GE.
- An initial insight into a potential cause of asymmetry during cycling, with associations identified between the magnitude of asymmetries in power output and asymmetries in torque effectiveness.

8.2 PRACTICAL APPLICATIONS

Absolute asymmetries in power output are negatively associated with GE, justifying the assessment of asymmetries during cycling. This thesis provided recommendations for measuring, analysing and interpreting asymmetries in cycling:

- Pedal dynamometers are the preferred power meter for this assessment as they can measure left and right forces separately, and directly at their application by the cyclist before any losses through the bicycles drive train. Although, it should be noted that the validity of this power meter decreases during supramaximal sprint cycling.
- Assigning a dominant limb is challenging in healthy, uninjured cyclists. Therefore, simply comparing left and right limbs may be the best approach to 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 Kapp Coefficient.
- We recommend analysing asymmetries in 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 difference over prolonged durations could result in considerable differences in the work conducted by each limb.
- We recommend calculating absolute asymmetries rather than relative percentage differences between limbs during cycling, as relative values can result in misleading findings when reviewing asymmetry at varied intensities.

- Asymmetries during cycling are highly variable, therefore we recommend assessing participants on multiple days.
- A meaningful threshold for defining asymmetry is an absolute interlimb difference of 15 W, as this is the estimated asymmetry that would decrease GE by a magnitude greater than the measurement error of this variable.
- Cyclists can adjust their pedalling with feedback or instruction; therefore, 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.
- Individual analysis and within participant study designs are recommended due to high variability between participants.

8.3 THESIS LIMITATIONS

During the studies of this thesis, participants were instructed to cycle at a predetermined cadence of 90 rpm due to the potential effects of cadence on the magnitude of asymmetry reported in our scoping review (**Chapter 2**). Data from our studies may have differed if we had allowed participants to cycle at their freely chosen cadence. A review of the factors affecting cadence choice during submaximal cycling and cadence influence of performance support this notion (150). During high intensity, close to the maximal aerobic power output, they reported that cyclists' chose an energetically economical cadence that was also favourable for performance (150). In contrast, they found that the choice of a relatively high cadence during cycling at low to moderate intensity was uneconomical and could compromise performance during prolonged cycling (150). These findings might have implications for the 90% MAP trials as participants may have self-selected a higher cadence to reduce the muscular forces required per pedal revolution to encourage recruitment of more energy efficient type I muscle fibres (65).

For these reasons, fixed cadences might also have affected the GE measured in **Chapter 7.**

Participants were instructed to abstain from exercise for two days prior to each visit to the laboratory. They completed a training diary in the week preceding the initial experimental trial and were asked to replicate their training load each week, for the 3 weeks of data collection. Furthermore, participants were instructed to record their dietary intake on the evening before and day of their initial visit, and to then replicate this for subsequent visits. If participants did not comply with these instructions, changes in training or dietary intake would influence data collected during **Chapter 5, 6 and 7**. Prior exercise and the associated fatigue may influence the between day variability of asymmetry measured in **Chapter 5**, the effects of intensity on asymmetry in **Chapter 6** and GE measured during **Chapter 7**. Furthermore, carbohydrate content of foods consumed prior to the experimental trials may also affect substrate utilisation and subsequent estimated of energy expenditure to determine gross efficiency during cycling in **Chapter 7**.

8.4 FUTURE DIRECTIONS

Training intervention studies

Presently, there is a lack of evidence to suggest asymmetries are performance limiting. Within **Chapter 2**, we reviewed the existing studies that investigated the effects of asymmetry on cycling performance. We concluded that the results of these studies were conflicting, and that the between participants study design chosen by these studies made it challenging to isolate the effects of asymmetry as there are numerous participant factors that affect performance, including physiological parameters and training status.

Randomised control trials within training studies, assessing the effectiveness of interventions designed to ameliorate asymmetry, would be beneficial to the field to elucidate the potential causes and effects of asymmetry on cycling performance.

Assess the effects of cycling asymmetry on a performance outcome measure.

Our study (**Chapter 7**) was the first to investigate the effects of the magnitude of asymmetry on GE during cycling. GE is a key determinant of endurance cycling performance. However, in order to determine the effects of asymmetry on performance, measuring a performance outcome would be preferable. In **Chapter 3**, we critiqued studies that performed a between participant analysis of the effects of asymmetry on time trial performance, due to numerous participant factors effecting performance. During **Chapter 5**, we identified that asymmetries are highly variable between days which facilitates a within participant study design to evaluate the effects of asymmetry on performance across multiple visits, alike the methods used in **Chapter 7**. A future study would include trials at fixed relative intensities, performed on multiple visits, to determine whether the magnitude of asymmetry effects time to exhaustion. This study design would also enable the assessment of the effects of fatigue on the asymmetry, a question that requires further investigation.

Research asymmetries during cycling in female populations.

A number of the studies included in our literature reviews (**Chapters 2 and 3**) assessed asymmetries in a group consisting of male and female participants. There are no studies that have assessed asymmetries during cycling exclusively in female participants. During this thesis, we have determined that asymmetries are highly variable within participants and that asymmetry effects GE. However, these investigations were conducted in male cyclists and may not apply to a female cohort. Future research should replicate the studies of **Chapters 5, 6 and 7** in female participants, and new study areas should include male and female participant groups. In future studies that assess the effects of fatigue on asymmetry during cycling, as suggested above, it is important to consider that females exhibit different fatigue characteristics than males, whereby females can sustain higher relative intensities for longer durations than males before task failure occurs (151,152). Therefore, it would be necessary to recruit male and female participant groups to investigate this research question independently in male and female populations.

The inclusion of kinematic data to studies to investigate the cause of asymmetry during cycling.

In **Chapter 2**, we identified many studies that concluded that changes in the magnitude of asymmetry are likely associated with changes in cycling technique. Garcia-Lopez *et al.* (2015) used motion capture to assess joint angles alongside asymmetries in crank torque (48). However, asymmetries were not observed amongst the participants in this study with reported AI% of <2%. When Smak *et al.* (1999) reported increases in negative power asymmetries when cadences increased from 60 to 120 rpm, they were able to support this observation with the use of kinematic data showing smaller hip extensor torque in the non-dominant limb during the upstroke (55). Measuring kinetic and kinematic data concurrently, would enable further investigation into the potential cause of any observed asymmetries during cycling. Smak *et al.* (1999) further recommended incorporating electromyography data to identify motor control differences in the timing and magnitude of muscle activations during cycling

(55). Of the studies included in our literature reviews (**Chapters 2 and 3**), only Chen *et al.* (2016) and Rannama and Port (2015) have included EMG alongside the kinetic data in their studies (59) (69). Chen *et al*. (2016) reported that although asymmetries in stepping torque were present during cycling, there were no significant differences in the EMG amplitude between left and right legs (59). Rannama and Port (2015) showed that in sprint cycling, asymmetries in pedal power were related to asymmetries of the vastus lateralis muscle firing patterns (69).

Future studies would benefit from utilising motion capture and EMG alongside the kinetic data provided by the power pedals.

Analysis of asymmetries in the field.

The assessment of asymmetries in the controlled environment of the laboratory is the first step to understanding this topic, whilst minimising external factors that might influence the results. However, little is understood about asymmetries in the field.

Amongst the cycling asymmetry studies included in our scoping literature review (**Chapter 2**), a single study assessed asymmetries in the field. Javaloyes *et al*. (2020) assessed asymmetries in professional cyclists during a twenty-one stage Grand tour cycling event (the Giro d'Italia) (45). However, the authors acknowledged two key limitations of their study. Firstly, a crank-based power meter was used to determine asymmetries during this event. In **Chapter 3**, we determined that power meters located at the crank are less accurate and sensitive in the assessment of left and right limb contributions to net power output.

Furthermore, the cumulative volume and intensity during stage races of this event were not accounted for in the analysis, so fatigue may have had an effect of the reported asymmetries (45).

The use of power meters is much more prevalent amongst cyclists of all abilities due to recent technological advancements that have resulted in the development of more affordable power meters for commercial use. Utilising large databases to extract initially simple information about the magnitude of asymmetry of varied cycling populations, from recreational to elite, male and female, and varied age groups, would provide an interesting insight into the prevalence of asymmetry during cycling, with greater ecological validity. This could be furthered to include the assessment of asymmetries during ascents of varied magnitudes and lengths, or during multiday events to investigate the effect of the asymmetrical load of previous days on the magnitude of asymmetry on subsequent days.

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APPENDICES

Appendix 1: University of Essex institutional ethical review board approval

University of Essex

Application for Ethical Approval of Research Involving Human Participants

This application form must be completed for any research involving human participants conducted in or by the University by masters and undergraduate students. 'Human participants' are defined as including living human beings, human beings who have recently died (cadavers, human remains and body parts), embryos and foetuses, human tissue and bodily fluids, and human data and records (such as, but not restricted to medical, genetic, financial, personnel, criminal or administrative records and test results including scholastic achievements). Research must not commence until written approval has been received (from departmental Director of Research/Ethics Officer, Faculty Ethics Sub-Committee (ESC) or the University's Ethics Committee). This should be borne in mind when setting a start date for the project. Ethical approval cannot be granted retrospectively and failure to obtain ethical approval prior to data collection will mean that these data cannot be used.

Applications must be made on this form, and submitted electronically, to your departmental Director of Director/Ethics Officer. A signed copy of the form should also be submitted. Applications will be assessed by the department Director of Research/Ethics Officer in the first instance, and may then passed to the ESC, and then to the University's Ethics Committee. A copy of your research proposal and any necessary supporting documentation (e.g. consent form, recruiting materials, etc) should also be attached to this form.

A full copy of the signed application will be retained by the department/school for 6 years following completion of the project. The signed application form cover sheet (two pages) will be sent to the Research Governance and Planning Manager in the REO as Secretary of the University's Ethics Committee.

1. Title of project:
   Asymmetries in cycling

2. Principal Investigator (i.e. name of student)

Name:	Department:
Kelly Murray	School of Sport, Rehabilitation and Exercise Sciences

3. Name of supervisor(s):

Name:	Department:
Florentina Hettinga	School of Sport, Rehabilitation and Exercise Sciences

4. **Proposed start date of research (note ethical approval cannot be granted retrospectively):** 03/10/17

5. **Probable duration:** 24 months

6. Will this project be externally funded? Yes ☐ / No ☒
   If Yes,

7. What is the source of the funding?

Research and Enterprise Office (smp) December 2015 Page: 1 of 7

8. If external approval for this research has been given, then only this cover sheet needs to be submitted

External ethics approval obtained (attach evidence of approval) Yes ☐/ No ☒

Declaration of Principal Investigator:

The information contained in this application, including any accompanying information, is, to the best of my knowledge, complete and correct. I/we have read the University's *Guidelines for Ethical Approval of Research Involving Human Participants* and accept responsibility for the conduct of the procedures set out in this application in accordance with the guidelines, the University's *Statement on Safeguarding Good Scientific Practice* and any other conditions laid down by the University's Ethics Committee. I/we have attempted to identify all risks related to the research that may arise in conducting this research and acknowledge my/our obligations and the rights of the participants.

Signature(s): ....

Name(s) in block capitals: Kelly Murray..........

Date: [redacted] 10.11.17..........

Supervisor's recommendation (Student Projects only):

I have read and approved the quality of both the research proposal and this application.

Supervisor's signature: ....

Outcome:

The departmental Director of Research (DoR) / Ethics Officer (EO) has reviewed this project and considers the methodological/technical aspects of the proposal to be appropriate to the tasks proposed. The DoR / EO considers that the investigator(s) has/have the necessary qualifications, experience and facilities to conduct the research set out in this application, and to deal with any emergencies and contingencies that may arise.

This application falls under Annex B and is approved on behalf of the ESC ☑

This application is referred to the ESC because it does not fall under Annex B ☐

This application is referred to the ESC because it requires independent scrutiny ☐

Signature(s): ....

Name(s) in block capitals: J.P. MILLS..........

Department: SRES..........

Date: 14/11/17..........

The application has been approved by the ESC ☐

The application has not been approved by the ESC ☐

The application is referred to the University Ethics Committee ☐

Signature(s): ....

Name(s) in block capitals: ....

Faculty: ....

Date: ....

Appendix 2: Conference abstract of the work conducted in **Chapter 4** for the British Association of Sport and Exercise Science (BASES) Conference 2017.

Evaluating U.S. tackling techniques, may guide future training protocols to reduce injury.

D1.P59. The validity and reliability of bilateral torque measured using Garmin Vector pedals.

KELLY MURRAY* & FLORENTINA HETTINGA

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The Garmin Vector pedals (GVP's) are considered to be a valid and reliable device for the measurement of power output during cycling across a range of intensities, when compared to an SRM (Novak & Dascombe, 2016, *Measurement in Physical Activity and Exercise Science*, *20*, 167–172) (Nimmerichter, Schnitzer, Prinz, Simon, & Wirth, 2017, *International Journal of Sports Medicine*, *38*, 439–446). The GVP's consist of strain gauges which measure torque at both the left (LP) and right (RP) pedals. Measuring bilateral torque allows coaches and scientists to evaluate cyclists for bilateral asymmetries, which could influence performance (Bini and Hume, 2014, *Journal of Sports Physiology and Performance, 9,* 876–881). However, to be able to determine whether a cyclist is producing torque asymmetrically, left and right GVP's should be assessed, independently, for their accuracy and repeatability. Therefore, the aim of this study was to assess the validity and reliability of torque measurements from both left and right GVP's. To eliminate the influence of human variability, this aim was investigated using static load testing. A unicycle, with the seat post fixed horizontally to a surface, was used as a cycling rig. GVP's were attached to the cranks, and each pedal was rotated and fixed at crank angles of 0^0 to 360^0, with steps of 45^0. At each crank angle, each pedal was loaded with 0, 8, 16, 24, 32, and 40 kg, using hook weights. Known crank loads and angles were used to calculate expected (TRUE) torque values, which were compared against those measured by both left and right GVP's using 95% limits of agreement (LoA). The LoA between left and right pedal torque measurements were also assessed. The 6 loads were applied to each pedal 3 times, at all crank angles, to calculate the reliability as the coefficient of variation (COV). Bland Altman analysis shows a mean bias of torque for LP vs. TRUE of 0.11 N.m (95% CI: −0.75 and 0.97 N.m), for RP vs. TRUE of −0.04 N.m (95% CI: −1.25 and 1.18 N.m) and LP vs. RP of 0.15 N.m (95% CI: −0.95 and 1.24 N.m). COV was <1.5% for LP, and <2% for RP. These results demonstrate a good agreement between TRUE torque and torque measured by both LP and RP, as well as a good agreement between LP and RP. These findings suggest that GVP's are valid and reliable in the assessment of bilateral torque, and therefore could be used to assess bilateral asymmetries during cycling.

D1.P60. Is there a correlation between GPS and Tracab outputs for physical performance markers within soccer?

JOSHUA RICE*

Liverpool John Moores Univerisity
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Background: Demands of modern day soccer have increased, increasing the challenge for players; to both recover and then reproduce typical match outputs in forthcoming fixtures. Subsequently player tracking is required to; better understand the demands of practice maximise performance and minimize injury risk and optimise training load patterns. An accurate way of measuring the above is required throughout the game week, with the integration of MEMS (StatSports Viper) and TracAb against each other key. *Objectives:* To understand whether there is a correlation between MEMS and TracAb outputs for physical performance markers within soccer. *Methods:* 9 Professional footballers (mean ± SD: age 27 ± 4, body mass 78.2 ± 8.7 kg, height ± 181.9 ± 7.3 cm) participated in this study. Data was collected simultaneously from both MEMS; StatSports Viper (10 Hz) TracAb (25 Hz) and downloaded for analysis after the completion of the game. Metrics analysed for correlation; High intensity distance, High speed running distance, sprint distance, total distance covered, high metabolic load distance, explosive distance, decelerations, accelerations and total number of sprints. Results: (1) All workload measures that were quantified had no significant difference allowing for integration of the two systems against each other; (2) the correlations between the TracAb system and the MEMS technology all showed strong positive correlation (>0.94). Conclusions: Findings allow for practitioners to interchangeably use physical performance outputs from both MEMS (wearable technology) with the semi automated camera tracking (TracAb) system to create a periodized training week for the players.

Appendix 3: Conference abstract of the work conducted in **Chapter 4** for the British Association of Sport and Exercise Science (BASES) Conference 2017.

23rd annual ECSS Congress Dublin/Ireland, July 4-7 2018

THE BETWEEN DAY VARIABILITY OF ASYMMETRIES IN CYCLING.

Murray, K.A., Hettinga, F.J.

University of Essex

INTRODUCTION:
A number of previous studies have determined that bilateral asymmetries in force and torque production are prevalent during cycling. Research has investigated the effect of intensity, cadence and seat position on the magnitude of asymmetry during cycling. However, at present little is understood about the day to day variation in cyclists asymmetries when performing standardised cycling trials across multiple visits. The aim of this study was to investigate the variability of asymmetry between cycling trials on multiple days.
METHODS:
Five well trained cyclists (mean maximal aerobic power of 362.8±28.3W) visited the laboratory on four occasions, each separated by seven days. The initial visit consisted of a maximal incremental cycle test to volitional exhaustion, to determine the cyclists' maximal aerobic power (MAP). The following three visits were all the same, whereby cyclists performed 4 x 4-minute trials at various relative intensities (40%,60%,75% and90% of MAP). Cycling trials were standardised at 90rpm and performed on a Lode Excalibur ergometer fitted with Garmin Vector pedals (GVP's). GVP's were used to measure the bilateral contribution to total power output during each of the cycling trials. Bilateral data from the GVP's were used to calculate the mean Asymmetry Index (AI%) for each trial, to assess the magnitude of each cyclists asymmetry. AI%=((DOM-NONDOM)/DOM)x100, with dominance (DOM) defined by the limb contributing most greatly to total power output. An asymmetry index of 0% would represent an equal contribution of the lower limbs to total power output.
Coefficient of Variation (CV) was calculated for each cyclist to determine their variation in the magnitude of asymmetry between the three visits. CV was also calculated between the three visits for each intensity, to determine whether the variation of AI% is influenced by intensity.
RESULTS:
The mean AI% for all participants and cycling intensities was 10.8±6.5% (AI% range 2.4-31.0%). CV calculations demonstrated that, on average, the cyclists AI% varied 40.0±27.1% (CV range 18.7-68.5%) between the three visits. The mean CV of AI% at 40%MAP was 44.4±23.5 (CV range 18.7-68.5%), at 60%MAP was 37.0±27.5% (CV range 9.1–73.3%), at 75%MAP was 39.4±31.4% (CV range 1.5-82.6%) and at 90%MAP was 26.2±33.6% (CV range 3.5–64.7%).
CONCLUSION:
The results of this study substantiate others which conclude that bilateral asymmetries during cycling are prevalent. However, our novel finding is that these asymmetries demonstrate considerable variability between visits. The high variability is evidenced by an average CV of 40.0%, present across the range of cycling intensities. These findings demonstrate that single day analysis is not sufficient to assess asymmetry during cycling. Further research should investigate the cause of these highly variable asymmetries, and their impact on performance.
Lastly, these results are currently based on five cyclists, so they should be interpreted with care. Data collection is ongoing.

Appendix 4 Mixed linear model outputs from **Chapter 7**

Estimates of Fixed Effects

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	18.947191	.784359	35.181	24.156	.000	17.355151	20.539232
Visit	.069115	.126795	28.934	.545	.590	-.190235	.328466
Intensity	.042864	.008742	41.182	4.903	.000	.025212	.060516
Absolute Asymmetry (W)	-.043765	.016468	42.989	-2.658	.011	-.076977	-.010553

a. Dependent Variable: GE%

Covariance Matrix for Estimates of Fixed Effects

Parameter	Intercept	Visit	Intensity	Absolute Asymmetry (W)
Intercept	.615219	-.033275	-.004957	-.002020
Visit	-.033275	.016077	8.700000E-5	-.000264
Intensity	-.004957	8.700000E-5	7.600000E-5	-8.000000E-6
Absolute Asymmetry (W)	-.002020	-.000264	-8.000000E-6	.000271

a. Dependent Variable: GE%.

Covariance Parameters

Estimates of Covariance Parameters

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Repeated Measures	Var: [Intensity=40.00]*[Visit=1.00]	2.571373	1.324787	1.941	.052	.936744	7.058447
	Var: [Intensity=40.00]*[Visit=2.00]	1.497635	.814696	1.838	.066	.515659	4.349603
	Var: [Intensity=40.00]*[Visit=3.00]	2.077480	1.108857	1.874	.061	.729806	5.913796
	Var: [Intensity=60.00]*[Visit=1.00]	.669829	.403432	1.660	.097	.205728	2.180894
	Var: [Intensity=60.00]*[Visit=2.00]	2.665140	1.329829	2.004	.045	1.002293	7.086721
	Var: [Intensity=60.00]*[Visit=3.00]	.856556	.534225	1.603	.109	.252273	2.908313
	Var: [Intensity=75.00]*[Visit=1.00]	.479223	.319115	1.502	.133	.129933	1.767478
	Var: [Intensity=75.00]*[Visit=2.00]	1.257793	.686703	1.832	.067	.431408	3.667161
	Var: [Intensity=75.00]*[Visit=3.00]	.660384	.420656	1.570	.116	.189492	2.301449
Intercept [subject = Participant]	Variance	1.796981	.978204	1.837	.066	.618278	5.222796

a. Dependent Variable: GE%.

Covariance Matrix for Estimates of Covariance Parameters[a]

Parameter		Repeated Measures									Intercept [subject = Participant]
		Var: [Intensity=40.00]*[Visit=1.00]	Var: [Intensity=40.00]*[Visit=2.00]	Var: [Intensity=40.00]*[Visit=3.00]	Var: [Intensity=60.00]*[Visit=1.00]	Var: [Intensity=60.00]*[Visit=2.00]	Var: [Intensity=60.00]*[Visit=3.00]	Var: [Intensity=75.00]*[Visit=1.00]	Var: [Intensity=75.00]*[Visit=2.00]	Var: [Intensity=75.00]*[Visit=3.00]	Variance
Repeated Measures	Var: [Intensity=40.00]* [Visit=1.00]	1.755059	.163203	-.151223	.092317	.019768	-.123625	.048735	-.111660	-.098374	.071120
	Var: [Intensity=40.00]* [Visit=2.00]	.163203	.663729	-.116451	.035628	.086891	-.098161	.044115	-.016079	-.095508	.031565
	Var: [Intensity=40.00]* [Visit=3.00]	-.151223	-.116451	1.229563	-.062927	-.063500	.150681	-.063781	.055585	.087989	-.119298
	Var: [Intensity=60.00]* [Visit=1.00]	.092317	.035628	-.062927	.162757	-.010679	-.047298	.010653	-.064637	-.021322	.068940
	Var: [Intensity=60.00]* [Visit=2.00]	.019768	.086891	-.063500	-.010679	1.768445	-.021307	-.008742	.076409	-.070671	.012819
	Var: [Intensity=60.00]* [Visit=3.00]	-.123625	-.098161	.150681	-.047298	-.021307	.285396	-.049143	.045950	.071857	-.075558
	Var: [Intensity=75.00]* [Visit=1.00]	.048735	.044115	-.063781	.010653	-.008742	-.049143	.101835	-.005967	-.018774	.012875
	Var: [Intensity=75.00]* [Visit=2.00]	-.111660	-.016079	.055585	-.064637	.076409	.045950	-.005967	.471561	.010423	-.060423
	Var: [Intensity=75.00]* [Visit=3.00]	-.098374	-.095508	.087989	-.021322	-.070671	.071857	-.018774	.010423	.176952	-.021993
Intercept [subject = Participant]	Variance	.071120	.031565	-.119298	.068940	.012819	-.075558	.012875	-.060423	-.021993	.956882

a. Dependent Variable: GE_% .

Random Effect Covariance Structure (G)[a]

	Intercept | Participant
Intercept | Participant	1.796981

Variance Components

a. Dependent Variable: GE%