THE PHYSIOLOGICAL DETERMINANTS OF PEAK POWER OUTPUT IN SPRINT CYCLING

A thesis submitted for the degree of Doctor of Philosophy awarded by Northumbria University

by

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Acknowledgements

"It always seems impossible until it is done" – Nelson Mandela

This PhD thesis was an opportunity that does not come around very often and was my lifeblood for over 6 years. Like all PhDs, it was all-consuming, a roller coaster of emotions and never straight forward which left me physically, mentally and emotionally exhausted for a lot of the time. Despite this, I would not have changed a thing from this experience. The people I met, the experiences I had, the relationships I formed and the stories I recount are things I will cherish and look back with only fond memories. It is hard to believe that those 6 years are simply condensed down to less than 200 pages.

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Abstract

Sprint cycling represents up to eight medal opportunities at the Olympic Games (six in track cycling and two in BMX). Previous studies and high-resolution data collected from instrumented cranks by practitioners at the English Institute of Sport working at British Cycling have established that peak power output (PPO), which can be defined as the highest mechanical power output produced over a revolution of the pedal cycle, is a significant determinant of sprint cycling performance. Despite this being well-established and considering the number of Olympic medal opportunities in the sprint cycling disciplines, the research investigating the physiological determinants are limited.

Of the limited data available, maximal strength has been strongly associated with sprinting ability. Other studies have tried to investigate other putative physiological estimates and their relationship with PPO in isolation, such as muscle architecture, muscle activation and lean leg volume. However, whilst these studies have been valuable in trying to get a better physiological understanding of PPO, none have attempted a multi-faceted approach that examines a number of physiological measurements simultaneously, seldom are they carried out longitudinally and, typically, they use untrained participants or endurance-trained athletes. Thus, the overarching aim of this thesis was to ascertain the physiological determinants of PPO in sprint cycling.

The series of investigations that set out to address this aim has led to new data that inform coaches, practitioners and cyclists to better understand how to apply, and potentially optimise, training and improve performance. Study 1 has established between-session reliability for all aspects of the power-cadence (P-C) and torque-cadence (T-C) relationships for two separate sprint cycling tests, as well as comparing

all the measurements between tests. The findings show that both tests exhibited good between-session reliability, but all P-C and T-C measurements were different between sprint cycling tests. Accordingly, both tests could be used with good between-session reliability but could not be interchanged. Study 2 demonstrated that between-session surface EMG was unreliable when used during sprint cycling assessments and unsuitable to be used to determine any changes between-participants or over time. The main findings from study 3 have confirmed that, of all the major lower body muscle groups, the maximal strength of the knee extensors best predict PPO and therefore, the main physiological determinates of PPO were likely to be rooted in the thigh and more specifically, the knee extensors. However, PPO is better predicted when compared to maximum strength measurements from an isometric maximum voluntary contraction of a cycling-specific isometric task. Study 4 built on the findings of the previous study and focused on a number of physiological measures in the thigh in a broad range of elite level cyclists. The findings suggests that the muscle volume of the quadriceps and the pennation angle of the vastus lateralis best predict PPO in elite cyclists. Lastly, the final study also built on the findings of study 3, which conducted a training intervention that used maximal isometric cycling training to manipulate the P-C and T-C relationship. This was done by increasing the maximal torque of the T-C relationship. Furthermore, sprint cycling training also increased pennation angle of the vastus lateralis and explosive strength at 200 ms.

Collectively, this thesis adds to the understanding of the physiological determinants of PPO in sprint cycling. Despite maximal strength, explosive strength, muscle volume and pennation angle all being linked and being predictive of PPO, the underlying mechanisms remain elusive. However, strong evidence is provided that

supports the use of a novel training intervention to improve performance in elite sprint cyclists.

Contents Page

List of Figures

List of Tables

List of Symbols and Abbreviations

The following abbreviations have been defined in the text in the first instance.

ACSA	Anatomical Cross-Sectional Area
ACh	Acetylcholine
ADP	Adenosine Diphosphate
ANOVA	Analysis of Variance
ARP	Anatomical Reference Position
ATP	Adenosine Triphosphate
ATPase	Adenosine Triphosphatase
BF	Bicep femoris, long head
BMX	Bicycle Motocross
Ca^{2+}	Calcium Ions
CKase	Creatine Kinase
CNS	Central Nervous System
C_{MAX}	Maximal Cadence
C_{OPT}	Optimal Cadence
CSA	Cross-Sectional Area
CV	Coefficient of Variation
DXA	Dual-energy X-ray absorptiometry
EMG	Electromyography
Fl_{VL}	Fascicle Length of Vastus Lateralis
F_{MAX}	Maximal Force
GL	Gastrocnemius Lateral Head
GM	Gluteus Maximus

ICC	Intra-class Correlation Coefficient
K^+	Potassium Ions
LBLM	Lower Body Lean Mass
Mrem	Millirem
MRI	Magnetic Resonance Imaging
MT	Muscle Thickness
MVC	Maximum Voluntary Contraction
Na^+	Sodium Ions
$P\theta_{VL}$	Pennation Angle of Vastus Lateralis
PCSA	Physiological Cross-Sectional Area
P-C	Power-Cadence
PCr	Phosphocreatine
$P_{i.}$	Inorganic Phosphate
PNS	Peripheral Nervous System
$Q_{tw.pot}$	Potentiated Twitch Force
RF	Rectus Femoris
rmsEMG	root-mean-square EMG amplitude
$rmsEMG_{60}$	peak rmsEMG amplitude at 60 RPM
$rmsEMG_{PPO}$	peak rmsEMG amplitude at PPO
RPM	Revolutions per minute
ST	Semitendinosus
SM	Semimembranosus
TBLM	Total Body Lean Mass
TDC	Top Dead Centre
T_{MAX}	Maximal Torque

T-C	Torque-Cadence
TT	Time Trial
UCI	Union Cycliste Internationale
VI	Vastus Intermedialis
VL	Vastus Lateralis
VM	Vastus Medialis
V_{MAX}	Maximal Shortening Velocity

PUBLICATIONS ARISING FROM THE THESIS

Full papers

Kordi, M., Goodall, S., Barratt, P., Rowley, N., Leeder, J. and Howatson, G. 2017. The Relation between peak power output in sprint cycling and maximum voluntary isometric torque production. *Journal of Electromyography and Kinesiology*, *35*, pp.95-99.

Kordi, M., Folland, J., Goodall, S., Barratt, P. & Howatson G. 2019. Reliability of traditional and task-specific reference tasks to assess peak muscle activation during two different sprint cycling tests. *Journal of Electromyography and Kinesiology*; DOI: 10.1016/j.jelekin.2019.03.008.

Adjunct papers that arose from using data collected directly from this Thesis

Kordi, M., Menzies, C., and Parker Simpson, L. 2018. Relationship between power–duration parameters and mechanical and anthropometric properties of the thigh in elite cyclists. *European Journal of Applied Physiology*, *118*(3), pp.637-645.

Kordi, M., Haralabidis, N., Huby, M., Barratt, P.R., Howatson, G. and Wheat, J.S. 2019. Reliability and validity of depth camera 3D scanning to determine thigh volume. *Journal of Sports Sciences*, *37*(1), pp 36-41.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Competitive cycling races range from 200 m to 5,000 km and, from a competitive performance perspective, there are eight Olympic medal opportunities in sprint cycling ([track and BMX] Team Sprint, Match Sprint and Keirin and BMX [for men and women]) compared to four available Olympic medal events in road cycling (Road race and time trial for men and women). There are even more medal opportunities at World Championships level for the sprint disciplines, amounting to ten: four track sprint events (Team Sprint, Match Sprint and Keirin for both genders and the 1000 m and 500 m time trial for both men and women), with BMX offering two (men and women). Meanwhile, road race cycling again offers four medal opportunities. Despite this, the majority of research is heavily focused on improving endurance physiology and performance. Given the number of Olympic and World Championship medal opportunities, it is somewhat surprising that more research has not focused on the underpinning mechanisms of sprint cycling and, as such, improving sprint cycling performance. There may be a few reasons as to why research in sprint cycling is so scarce. Firstly, according to the UCI (1st January 2019), the participation numbers are over 300% higher in elite level road cycling than track sprint cycling. Secondly, instruments that measure crank power and the quality of the relevant physiological measurements have only recently advanced in terms of resolution, accessibility and ease-of-use. Notwithstanding, a better understanding of the physiological determinants of sprint cycling ability will help better inform coaches, practitioners and sprint cyclists to optimise training prescription and, subsequently, sprint cycling performance.

Peak power has been identified as a key predictor of performance in a number of sports, such as rowing (Ingham *et al.*, 2002), sprint running (Bundle & Weyand,

2012), and jumping (Ferretti *et al.*, 1994). Instrumented cranks that are fitted on to bikes allow the measurement of mechanical torque, cadence and power output. Practitioners at the English Institute of Sport working at British Cycling, coupled with reports from the literature (Dorel *et al.*, 2005; Martin *et al.*, 2007), have identified that peak power output (PPO) is an important determinant of sprint track cycling performance. A common definition of PPO is the highest power output over a revolution in a maximal effort. It is usually achieved within the first 7 s of commencing the effort. Despite this being well-established with the practitioners and coaches at British Cycling, and being well-documented in the literature, the physiological determinants are poorly understood and not well-researched. The current body of research is limited to crude estimates, and their association with PPO is usually with untrained or endurance-trained cyclists. What is not known are If the physiological determinants can be identified, it could better inform coaches, practitioners and athletes to optimise training methods to improve performance. The primary aim of this thesis was to gain a greater understanding of the physiological determinants of PPO in sprint cycling.

2 Literature Review

CHAPTER 2

2.1 Introduction

This chapter aims to give an overarching review of track sprint cycling performance and a critical review of the physiological literature pertaining to sprint cycling performance before concluding with the thesis aims. More specifically, an introduction to track sprint cycling events and performance is provided, followed by a brief overview of the anaerobic energy systems that are involved in sprint cycling disciplines. The review then evaluates the relationship of mechanical PPO and its relationship to sprint cycling ability/performance, as well as the underpinning power-cadence (P-C) and torque-cadence (T-C) relationships. Moreover, it provides a critical review of potential physiological factors that could improve PPO and subsequently sprint cycling ability.

2.2 Track Sprint Cycling Events

Track sprint cycling events range between 200 – 1000 m, are short in duration (usually between 9.5 and 60 s) and maximal in nature. There are a number of variants within the track sprint cycling discipline which are available at Olympic and/or World Championship level (Table 2-1). The individual time-trial (TT) events are only available up to World Championship level and are 1000 m for men and 500 m for women. They are the most rudimentary of the races as they simply commence from a standing start and the fastest time taken to complete the distance deems the finishing order.

There are a further three variants of track sprint cycling at the Olympic (and World Championship) level in track:

1) **The Team Sprint.** The men's team sprint is a three-rider pursuit over three laps of a velodrome. All three riders start from a stationary start and at the end

of each lap, the leading rider 'peels off' up the bank and exits the race by riding up the banking leaving the remaining rider(s) to do the same, eventually leaving 'Rider 3' to complete the last lap on his own. The timing stops once 'Rider 3' / the final rider crosses the start line. The women's team sprint event is identical but currently has two, rather than three, riders. The team sprint is considered the 'blue ribbon' event, particularly as if a nation qualifies a team for the Olympics, they are automatically awarded two individual places for the individual events: match sprint and keirin.

2) **The individual match sprint.** This event starts with a 'flying' 200 m TT where riders are allowed to build speed over 2 or 3 laps before commencing the 200 m at high velocity (as opposed to standing starts in the aforementioned TTs). Of the riders who perform the 200 m TT, the fastest pre-set quota will qualify and are seeded in order of fastest time for the subsequent one-on-one races. This is done by pitting the fastest qualifier against the slowest qualifier and so forth. Knock-out rounds then proceed, which are usually 2 or 3 laps long, are not completely maximal for the duration of the round and involve tactics and skill as well as sprinting ability. However, basic analysis has shown that the ranking from the 200m TT is associated with the final results (Dorel *et al.*, 2005).

3) **The keirin.** This race consists of a total of six laps and starts with up to eight riders in a line behind a derny bike (the order is randomly pre-determined before the race) which starts at 30 km/h and builds to 50 - 60 km/h over three laps. Once the derny bike peels off the track, there are three remaining laps where the riders race until the end with the first past the finish line winning the

event. Like the match sprint, skill and tactics, as well as sprinting ability, determine the outcome of the race.

World record times of these events are shown in Table 2-1.

Table 2-1: The World Record times of the different timed track sprint events for both men and women on 1st January 2019: Total team sprint time with respective rider lap times; 'Flying' 200m TT time; standing 1000m TT and 500m TT. In addition, the relative contribution from the three different energy systems: alactic, anaerobic glycolysis and aerobic systems are presented for the respective events, which are taken from Jeukendrup et al.*, 2000; *denotes performed at altitude; # denotes non-Olympic event.*

Track Sprint Event	Time(s)		Contribution from the Energy System (%)		
	Men	Women	Alactic	Anaerobic Glycolytic	Aerobic
Team Sprint	41.871*	32.034			
Rider 1	16.984*	18.353	40	55	5
Rider 2	12.332*	13.681	30	60	10
Rider 3	12.555*	-	20	40	40
Flying 200 m TT	9.347*	10.384*	40	55	5
1000 m TT#	56.303*	-	10	40	50
500 m TT#	-	32.268*	10	45	35

2.3 Bioenergy during Mechanical Peak Power Output

Humans need to have a continual supply of energy to meet the basic metabolic needs to remain alive, as well as the demands for muscular contraction during activities such as cycling. At the cellular level, adenosine triphosphate (ATP) is described as the currency of energy. The hydrolysis of ATP, which is catalysed by adenosine triphosphatease (ATPase), cleaves the phosphate bond to release energy, as well as two new compounds: adenosine diphosphate (ADP) and inorganic phosphate (P_i). The reaction is summarised as follows:

$$ATP + H_2O \overset{ATPase}{\leftrightarrow} ADP + P_i \text{ (+ energy)}$$

Thus, energy liberated from ATP hydrolysis powers all forms of biological "work". The body maintains a continuous supply of ATP from three different pathways: alactic, anaerobic glycolytic and aerobic energy systems (McArdle *et al.*, 2010), all of which play a role in track sprint cycling performance (Table 2-1). As previously mentioned, PPO occurs within the first 7 s of commencing maximal cycling. This is said to occur in the 'fatigue-free' state (Gardner *et al.*, 2007), and from a bioenergetics perspective, this coincides with the time period where the 'anaerobic' energy systems (i.e. alactic and glycolytic energy systems) are the most predominant when PPO is achieved (Table 2-1; Jeukendrup *et al.*, 2000).

2.3.1 The Alactic Energy System

The alactic energy system is also known as the ATP-phosphocreatine (PCr) energy system. It is the predominant source of energy production in the early stages (< 10 s) of very high-intensity exercise. Large sources of energy can be yielded very quickly, but are limited in duration, with full depletion occurring within 20 - 30 s (Bernús *et al.*, 1993; Gastin, 2001). The rate of anaerobic provision of ATP is critical to the development of high-power output and this energy comes almost exclusively from intramuscular high energy-phosphate compounds: ATP and PCr (Gastin, 2001).

Muscle cells have intramuscular ATP stores that undergo hydrolysis but can only provide the first few seconds worth of explosive, high-intensity exercise before being completely depleted, although this is dependent upon the rate of energy demand. Once the intramuscular ATP stores have been used, ATP needs to be promptly resynthesised. This is brought about with the transient increase in ADP (from the hydrolysis of intramuscular ATP) which reacts with intracellular PCr (McArdle *et al.*, 2010). This reaction, which is catalysed by creatine kinase, cleaves the phosphate-

bond which forms creatine (Cr) and resynthesised ATP, which becomes available for hydrolysis in the following reaction:

$$PCr + ADP \underset{CKase}{\leftrightarrow} Cr + ATP$$

The decreasing force generation during brief, maximal exercise is the result of either a reduced rate of ATP resynthesis or a decreasing rate of ATP utilisation by the contractile apparatus (Hermansen, 1981; Taylor, 1990). Previous studies have demonstrated that 5-months of resistance training of triceps brachii resulted in a 28% increase of maximal elbow extension strength, and an 11% increase in circumference (a crude measure of hypertrophy) led to significant improvements of ATP and PCr stores (MacDougall *et al.*, 1977). The results concluded that heavy strength training, most likely through hypertrophy training, increases ATP and PCr stores. This could, at least in theory, give scope to the idea that hypertrophy from heavy resistance training could improve PPO and enhance sprint cycling performance by eliciting improvements in ATP and PCr stores rather than sprint training in isolation (Dawson *et al.*, 1998). The ATP-PCr energy system is predominant during maximal power- and force-velocity relationships at muscle level, and is thought of as being 'fatigue-free'. Once PCr stores are depleted, the body must use the anaerobic glycolytic energy system to provide ATP for muscle contraction (Table 2-1).

2.3.2 Glycolytic Energy System

Once PPO is achieved, usually between 3 – 5 s (Martin *et al.*, 1997; Baron *et al.*, 1999; Gardner *et al.*, 2007), there is a systematic reduction in power output with every pedal revolution (Weyand *et al.*, 2006). As soon as maximal exercise commences, the glycolytic energy system becomes more involved, reaching its

maximal rate in the first 5 s and providing energy for up to 2 – 3 minutes. This pathway is the predominant energy system after approximately 10 s and accounts for 40 – 60% of the energy contribution in the different track sprint timed events (Table 2-1; Jeukendrup *et al.*, 2000). In comparison to the alactic system, the resynthesis of ATP is approximately ten times slower, thus power output is reduced as the duration of maximal exercise increases (McArdle *et al.*, 2010). High-energy phosphates are resynthesised via rapid muscle glycogen breakdown usually in the absence of oxygen or where the demand for energy exceeds aerobic capacity or ability to deliver oxygen. One molecule of glucose produces two of ATP and the by-product of glycogen breakdown is the accumulation of either inorganic phosphate and/or other metabolites which reduces ATP synthesis and, subsequently, muscle contraction force (Westerblad *et al.*, 2002).

It is important to understand the basics of the bioenergetics of sprint cycling to add context to the likelihood of which physiological factors may be involved in determining sprinting ability. However, the aim of this thesis is to focus on the physiological factors, as opposed to bioenergetic manipulation, in order to influence performance in sprint cycling ability.

2.4 Performance in Track Sprint Cycling

Peak speeds in the majority of sprint cycling events can reach in excess of 70 Km/h; at these speeds over 85% of the resistance is from aerodynamic drag (Figure 2-1). Accordingly, there are a plethora of non-physiological factors that may affect performance times by influencing the impact of aerodynamic drag, such as environmental conditions (which can affect performance times in the order of 1.5% alone [Dwyer, 2014]), attire and equipment selection. This highlights the high degree

of influence external factors can have on performance. As such, using times in isolation (such as 200 m TT times) cannot be reliably and accurately compared longitudinally; an improvement in performance time does not necessarily equate to a physiological improvement and/or sprint cycling ability and *vice versa*.

However, short efforts from stationary starts can be more reliably compared within and between riders. For example, let us take the performance time of 'Rider 1' in the team sprint. Rolling resistance and body mass) rather than aerodynamic resistance is the largest contributor to resistance in accelerations from stationary or slow-moving starts (Figure 2-1). Practitioners at the English Institute of Sport working at British Cycling investigated the determinants of 'Rider 1' performance in the Team Sprint. Using timing analysis from over 400 data samples (Figure 2-2), they identified that the time taken to reach 62.5 m (the first quarter of the lap [which takes approximately 6.6 – 7.6 s]) and 125 m (first half of the lap [which takes approximately 10.4 – 11.6 s]) accounted for 73% and 91% of the variation of the final lap time. Furthermore, the time from 125 to 250 m (i.e. from half lap to completion of the lap) accounted for only 14% of the variation (Figure 2-2). The conclusion of this data was that the performance of 'Rider 1' is largely determined in the first 6 – 11 s, where the largest fraction of resistance comes from rolling resistance (or body mass, from a

physiological perspective) and likely to be determined from power-to-mass ratio, which can be easily measured and compared.

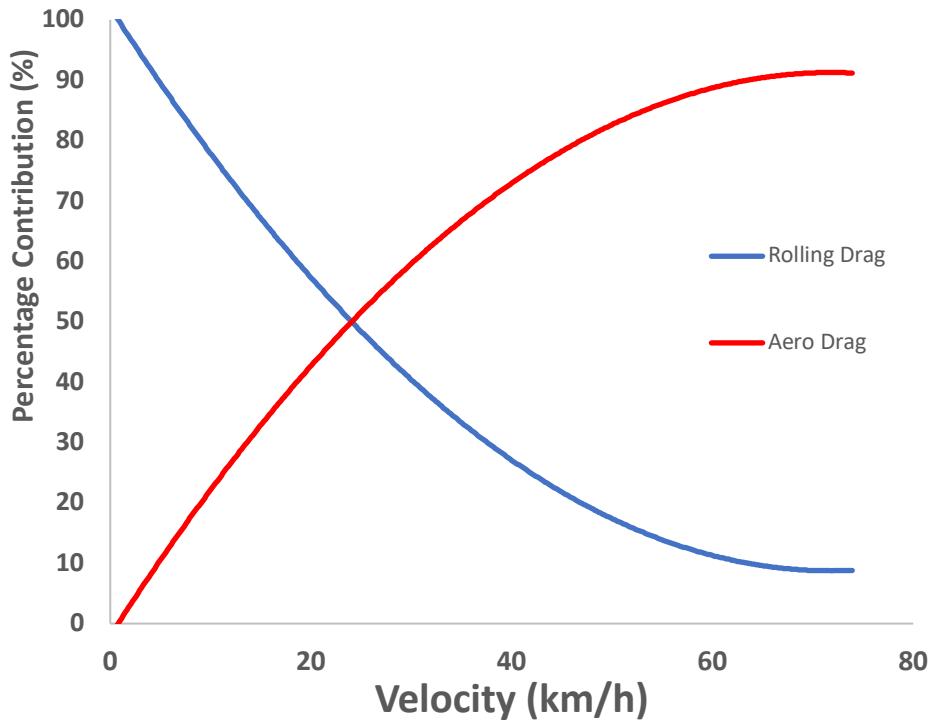

Figure 2-2:An example of the fractional distribution of resistance from aerodynamic drag (aero drag) and rolling resistance drag (rolling drag) of a rider that has a coefficient of drag of 0.3 , and coefficient of rolling resistance of 0.005; note: units for coefficient of drag and rolling resistance are dimensionless.

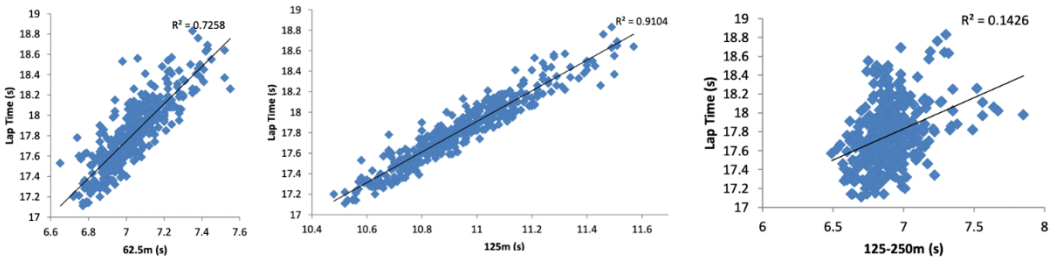

Figure 2-1: Timing analysis and coefficient of determination of final lap time of 'Rider 1' in the Team Sprint (0 – 250 m) in relation to 0 - 62.5 m (R^2 = 73%), 0 - 125 m (R^2 = 91%) and 125 - 250 m (R^2 = 14%) All data collected from training longitudinally from practitioners at the English Institute of Sport working for British Cycling ; n = 405).

2.5 Mechanical Power Output Predictors of Track Sprint Cycling Performance

The work of Weyand and colleagues required the participants to visit their laboratory on a number of occasions and complete a minimum of 13 maximal efforts at a pre-determined cadence of 100 RPM that lasted 5 – 300 s (Weyand *et al.*, 2006). The findings suggested that maximal sprint performance (i.e. non-sustainable force application) is determined by mechanical peak power output (PPO), which can be defined as the maximum mechanical power output measured over a revolution in a short period of time of < 10 s (Weyand *et al.*, 2006). The same study concluded that the fraction of fatigue subsequent to PPO is constant until maximal aerobic power is attained (Figure 2-3).

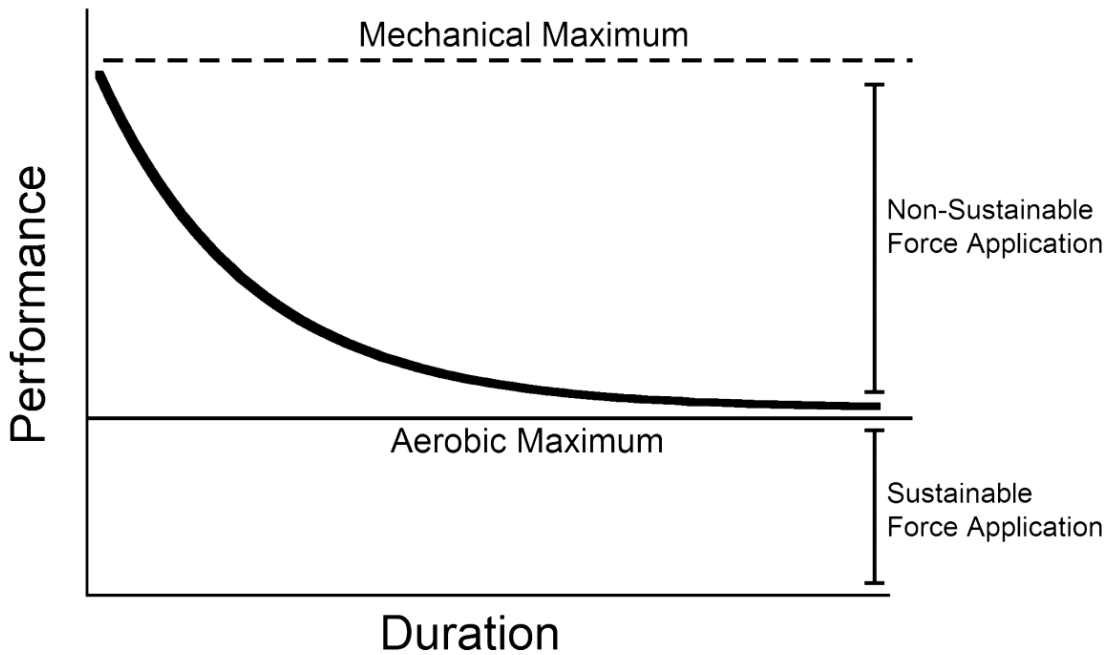

Figure 2-3: Performance-duration curve of 'all-out', maximal cycling. When peak power output (mechanical maximum) is achieved, there is a constant fraction of fatigue that is theorised to be constant between humans until maximal aerobic power is achieved. Taken form Weyand and Bundle (2012)

Instrumented cranks can be fitted on to track bicycles to measure the mechanical power output produced by riders (Figure 2-4). They can be used to compare and monitor physical changes between competitions, training efforts and fellow riders. In recent years, portable instrumented cranks that measure torque, cadence and, consequently, power have become more accessible and easier to use.

Mechanical power output is calculated by measuring and multiplying cumulative torque (rotational force around a moment/crank) around the cranks with angular velocity (which is expressed as cadence, in cycling) over each revolution. Torque (measured in Newtons meters [N·m]) is quantified by fitting strain gauges (that are usually located on either the crank arms or around the 'spider' [between the crank axle and chainring]) that measure the deformation (of the crank or spider) which is proportional to the torque generated over each pedal revolution.

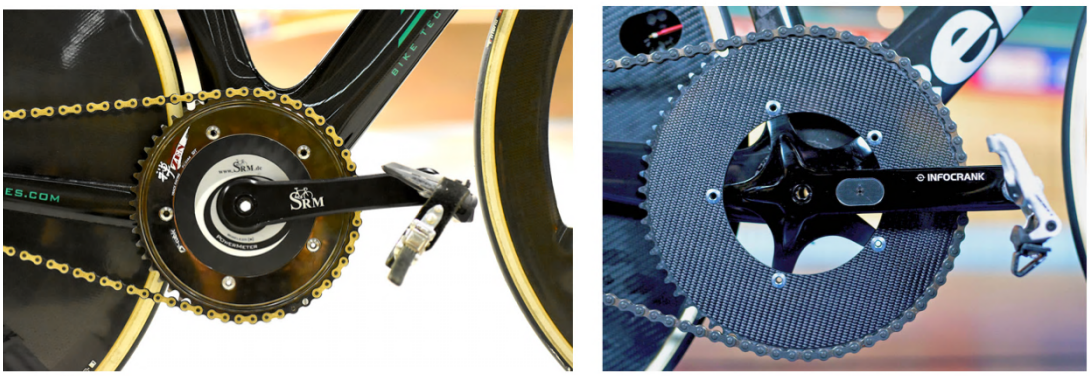

Figure 2-4: Picture of two different instrumented track cranks that measure mechanical power output by multiplying torque by cadence (angular velocity). Left picture (from www.momnium.com) is SRM where strain gauges are fitted in the 'spider' which is connected within the chainring bolts and cadence is measured from a magnetic reed switch. Right picture of track Verve Infocrank (from www.bikerumor.com), which measures torque on both crank arms and cadence, is measured using the peak torque trace.

Cadence (measured as revolutions per minute [RPM]) is the cycling metric for angular velocity and is calculated as the time taken for the cranks to complete a full revolution. This is usually done by using a magnet to trip a reed switch or by using an accelerometer or, more recently, detecting the time interval between each peak torque

of each revolution. The sampling of data from the strain gauges range from 1 to 1,000 Hz, producing values that represent one revolution averages. These data can be easily (and now, almost instantly) accessed either via personal computer or smartphone for analysis. Previously instrumented cranks have been fitted to the track bikes of elite level sprinters and can collect high-resolution data in competition and training (Dorel *et al.*, 2005; Gardner *et al.*, 2005, 2007).

Practitioners at the English Institute of Sport working with British Cycling also collected high-resolution mechanical power output data longitudinally from international, elite-level track sprint cyclists in competition and training. The data collected from 'Rider 1' in the team sprint, using basic bivariate correlation analysis was in agreement with Weyand *et al*. (2006) and PPO to systemic mass was identified as the biggest determinant of performance in track sprint cycling. In particular, large, negative and significant relationships with PPO relative to body mass (Figure 2-5) as a predictor of standing lap for 'Man 1' of the Team Sprint (an example of power-duration and cadence-duration trace is shown in Figure 2-6), Men's 1000 m (an example of power-duration and cadence-duration is shown in Figure 2-7) and Women's 500 m TT.

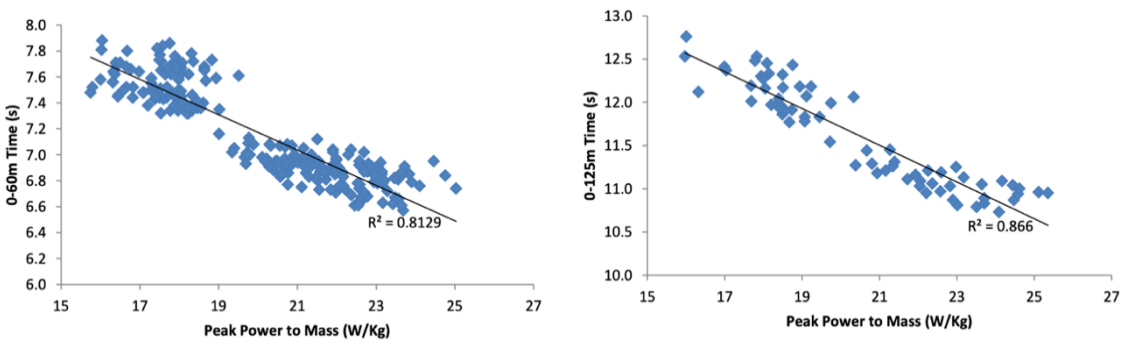

Figure 2-5: Coefficient of determination of mechanical peak power output-to-mass with time of 0 - 60 m (81%) and 0 - 125 m (87%) of a British male and female 'Rider 1'. Data collected longnitudinally in traning by practitioners at the English Institute of Sport working at British Cycling

In addition, Dorel *et al*. (2005) demonstrated that the ratio of PPO-to-frontal area ratio is strongly associated ($r = 0.75$; $p = 0.01$) to 200 m TT performance (Dorel *et al.*, 2005). Put simply, if all other factors remain constant, such as body mass, aerodynamic drag, gear ratio, bike geometry, crank length, attire, environmental conditions and equipment, then an increase in PPO should equate to an improvement in sprint cycling performance up to 1000 m TT. Accordingly, along with the findings of Bundle and Weyand, power output in sprint cycling performance up to 1000 m TT in terms of power output can be predicted in track sprint cycling (Bundle & Weyand, 2012).

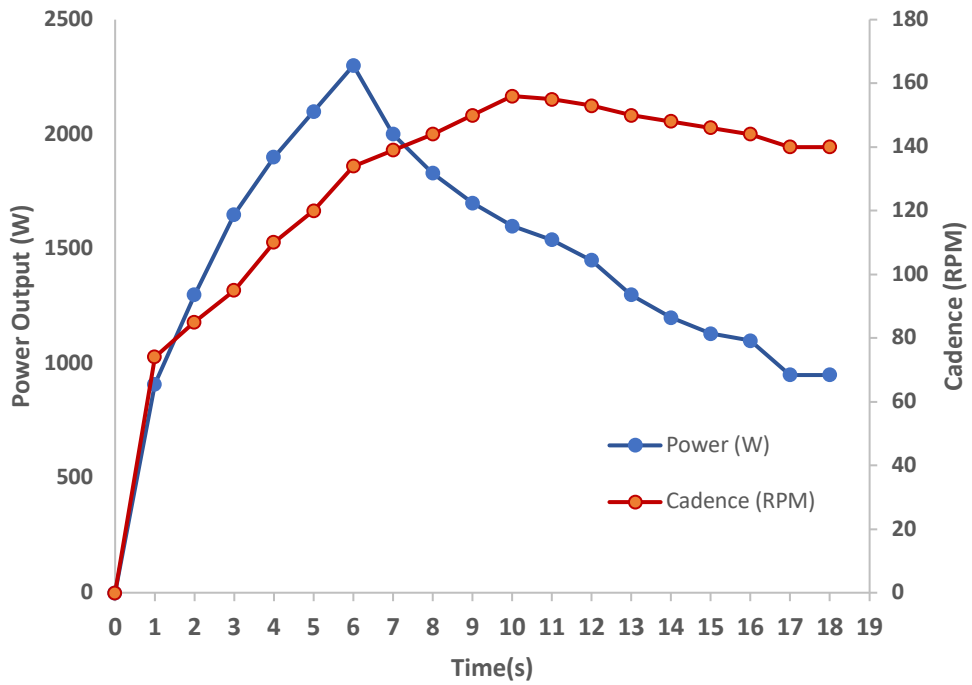

Figure 2-6: Power-duration (blue) and cadence-duration (red) example of an elite 'Rider 3' Team Sprinter performing a standing lap. Peak power output is the highest power output measured. Data presented as 1 Hz

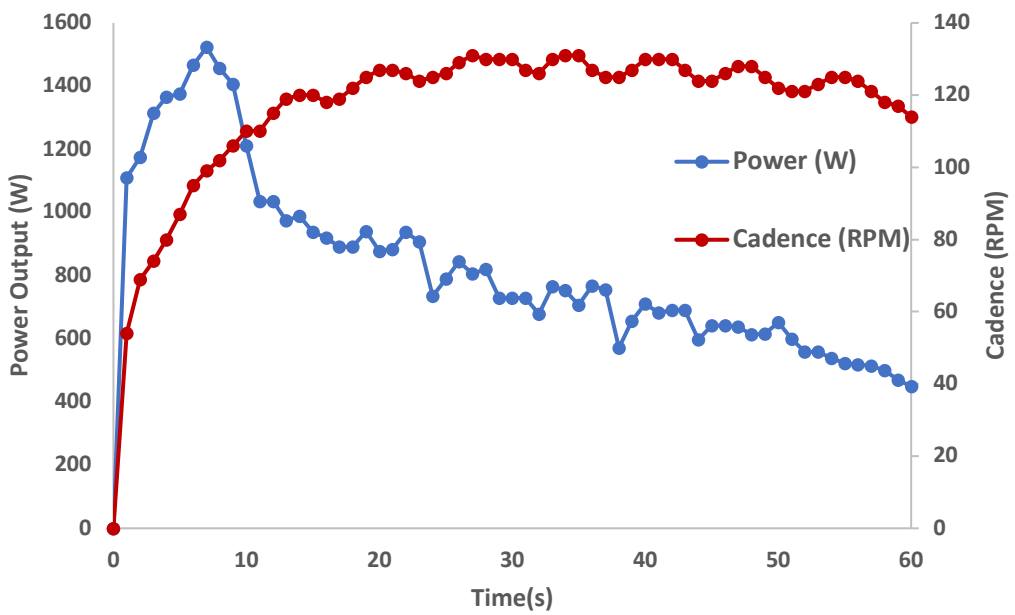

Figure 2-7:The power-duration (blue) and cadence-duration (red) relationship of an elite track sprinter (Rider X) performing a 1000m TT at a UCI Track World Cup event. Peak Power Output is as the maximum power output recorded in the effort. Data presented as 1 Hz.

2.6 Power-Cadence and Torque-Cadence Relationships

Since it was first proposed by A.V. Hill in 1938, it is widely accepted that the maximal concentric mechanical properties of a muscle and/or muscle groups are described by the power-velocity and force-velocity relationship (Hill, 1938). In single muscle (groups), the power-velocity relationship has a parabolic relationship where the power is calculated from the underpinning force-velocity curve, which is an inverse, hyperbolic relationship (Figure 2-8).

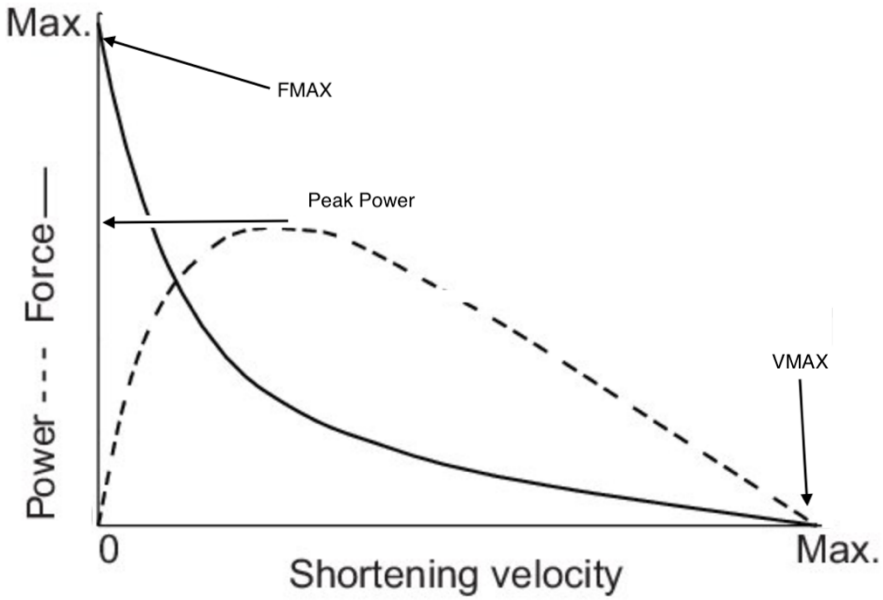

Figure 2-8: Power-velocity (dotted line) and inverse, hyperbolic force-velocity (solid line) of a muscle as first proposed by A.V. Hill (1938). Taken and adapted from Lindstedt (2016). Peak power, maximal force (FMAX), maximal shortening velocity (VMAX).

The measure of interest in the concentric power-velocity relationship is peak power (Figure 2-8), which is underpinned by maximal isometric force (F_{MAX}), maximal shortening velocity (V_{MAX}) and the degree of curvature of the force-velocity relationship. If any of those three variables are manipulated, it affects the force-velocity relationship and, consequently, the power-velocity relationship and peak power (Cormie *et al.*, 2011).

The same relationships are exhibited in sprint cycling, which are almost exclusively formed of concentric contractions with two main distinctions. Firstly, the relationships are described as P-C (rather than power-velocity) and T-C (rather than force-velocity) relationships. Secondly, sprint cycling T-C relationships have largely been reported to be an inverse linear relationship rather than an inverse hyperbolic relationship, as is seen in force-velocity (Figure 2-9; Arsac *et al.*, 1996; Driss *et al.*, 2002; Dorel *et al.*, 2005). The reasons for this difference are somewhat unclear but they share features of other multi-joint movements, such as the leg press (Bobbert, 2012), that uses a number of muscle groups. It has been suggested that the linear relationship may be due to external factors such as segmental forces, momentum and centripetal forces, rather than physiological factors, that 'add' to the torque production and give it its inverse, linear qualities at intermediate cadences (Bobbert, 2012).

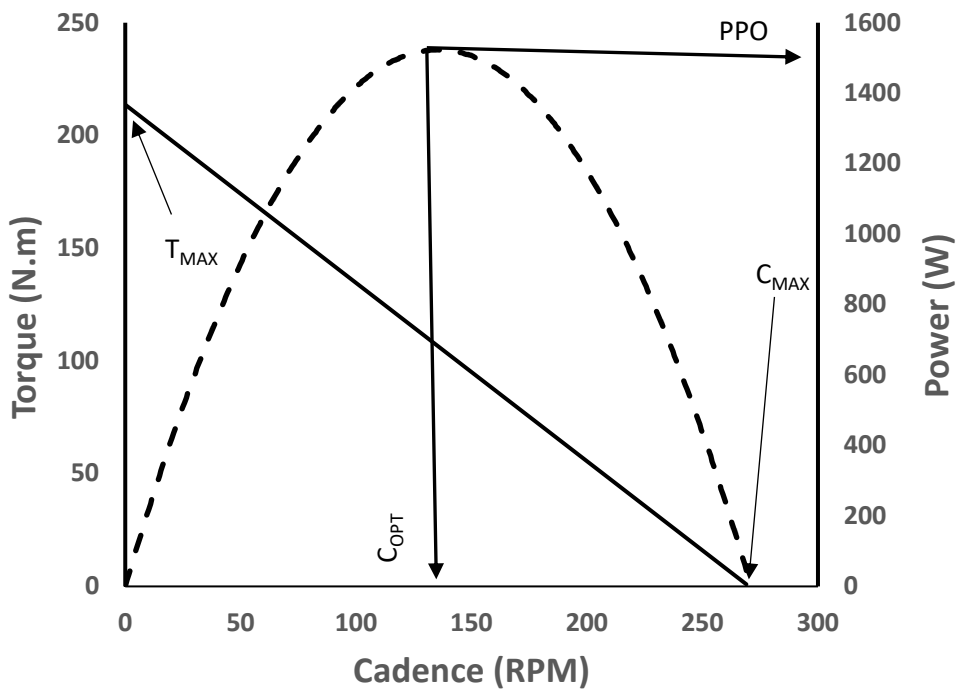

Figure 2-9:An example of a parabolic power-cadence (dotted line) and inverse linear torque-cadence (solid line) relationship in sprint cycling. Peak power output (PPO), optimal cadence (COPT), maximal torque (TMAX) and maximal cadence (CMAX) are annotated

PPO is the apex of the P-C relationship, which is formed in a short time frame (< 7 s) and before metabolic fatigue occurs (Gardner *et al.*, 2007). The cadence at PPO (known as optimal cadence; C_{OPT}) is also thought to be a measure of interest to infer surrogate changes in co-ordination, muscle fibre distribution and/or functional properties of the muscle (Hautier *et al.*, 1996; Hintzy *et al.*, 1999). Changes in the P-C cadence relationship and, consequently, PPO and C_{OPT} are determined by alterations of the underpinning T-C relationship. Due to the linear nature of the T-C relationship, changes in maximum torque (T_{MAX}) and maximal cadence (C_{MAX}) are needed to manipulate changes in PPO and C_{OPT}. Therefore, improvements in PPO in sprint cycling can be achieved through increasing T_{MAX} and/or C_{MAX} (Figure 2-10).

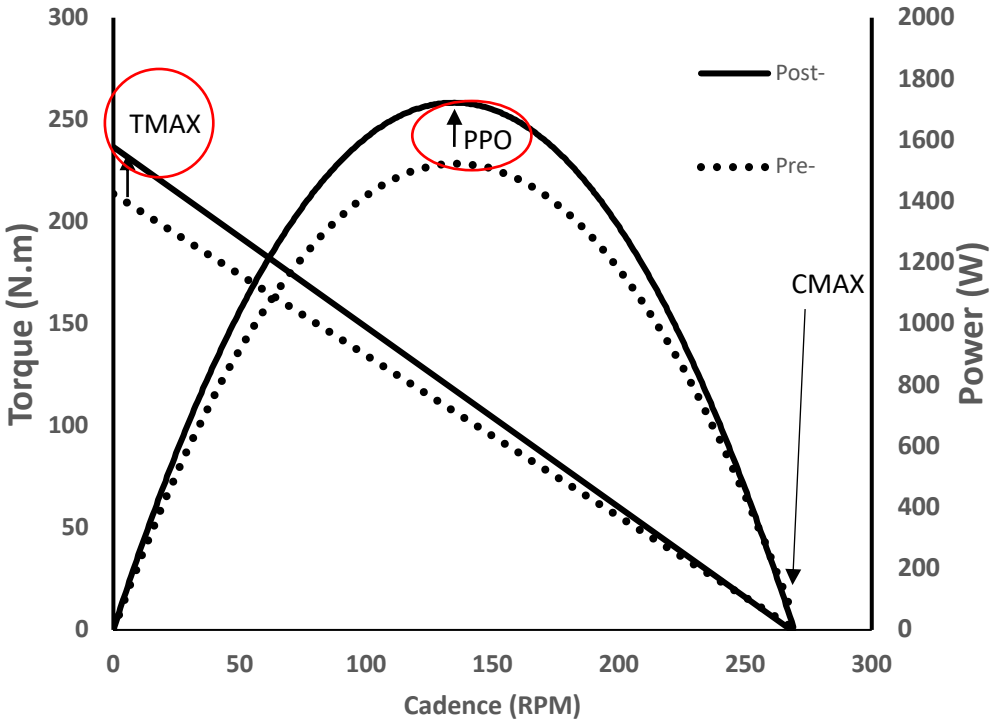

Figure 2-10: A hypothetical example of changing the torque-cadence relationship by improving maximum torque (TMAX) whilst maximal cadence (CMAX) remains constant, leading to a consequential increase in peak power output (PPO)

2.7 Physiology of the Power- and Torque-Cadence relationships

The inverse relationship between T-C (and/or force-velocity) is related to the anaerobic muscle contraction and relaxation mechanics at the cellular level (Hughes, 2003). The mechanism of muscle contraction occurs in the sarcomeres, which are the most basic unit of muscle. Sarcomeres are composed of thick and thin filaments which are required for muscle contraction and relaxation.

2.7.1 Overview of Muscle Contraction

Initially, the contraction of skeletal muscle is started when an action potential reaches the axonal terminal of an alpha motor neuron. This causes small vesicles of acetylcholine (ACh) to be released and diffuse across to the synaptic cleft and binds to specific receptors on the sarcolemma. This leads to sodium ions (Na^+) channels to open and consequently an influx of Na^+ into the sarcolemma that generates an action potential. The action potential spreads and depolarises the rest of the membrane, including the transverse tubules (t-tubules). Once the t-tubules are depolarised, calcium ions (Ca^{2+}) are released from the sarcoplasmic reticulum to the cytoplasmic reticulum. The released Ca^{2+} (with the presence of ATP) initiates muscle contraction by binding to troponin-tropomyosin located on the actin filaments. This continually exposes the myosin-binding site that allows cross-bridge formation and tension as the muscle contracts with the energy released from ATP, allowing myosin cross-bridge movement. Cross-bridge activation continues as the concentration of Ca^{2+} remains high by binding to the troponin-tropomyosin complex, which exposes the myosin-binding site. This process continues until the muscle shortens to reach its anatomical limit.

The cessation of muscle contraction occurs when signalling from the motor neuron halts. This causes repolarisation of the sarcolemma and T-tubules. The consequence is that the Ca^{2+} channels in the sarcoplasmic reticulum close and the tropomyosin becomes safeguarded due to Ca^{2+} ions being pumped back into the sarcoplasmic reticulum. As such, no cross-bridges can be formed. Also, muscle contraction reduces or ceases during fatigue when ATP is depleted (Jones *et al.*, 2004).

2.7.2 Muscle Contraction: Sliding Filament Model

The more detailed mechanism of muscle contraction that is most commonly used is known as the sliding filament theory, which was first proposed in the mid-1950s (Hanson & Huxley, 1953; Huxley & Niedergerke, 1954). As already mentioned in the previous section, the sarcomeres are composed of myosin (thick) and actin (thin) filaments. The sliding filament theory suggests that the length of filaments remain relatively constant, with the cross-bridge cycling explaining the molecular changes in sarcomere length. Each myosin filament is composed of two main components: a tail and a head. The head of the myosin molecule has a site that binds to an actin myosin-binding site to form cross-bridges and an ATPase site that hydrolyses ATP. The cross-bridge cycle has five main steps (McArdle *et al.*, 2010):

1) The head of the myosin chain is in its excited state by having ADP and P_i attached to it. It then binds to the myosin binding site on the actin filament.
2) Once bound to the myosin binding site, the P_i is released, leaving ADP attached to the myosin head. This liberates energy that is used to pivot the

myosin head toward the middle of the sarcomere and pulls the actin filament attached with it. This is known as the 'power stroke'.

3) This then puts the myosin head in a low-energy form (as it has ADP bound to it) and remains bound to the actin subunit until another ATP molecule binds to the myosin head.

4) Once ATP becomes available and binds to the myosin head it induces a conformational change that detaches the myosin head from the actin filament.

5) The ATPase associated with the myosin head then hydrolyses the ATP in the myosin head, allowing the myosin head to unbind from the actin filament. This allows the 'cocking' of the myosin head in its high-energy state, allowing the process to start again.

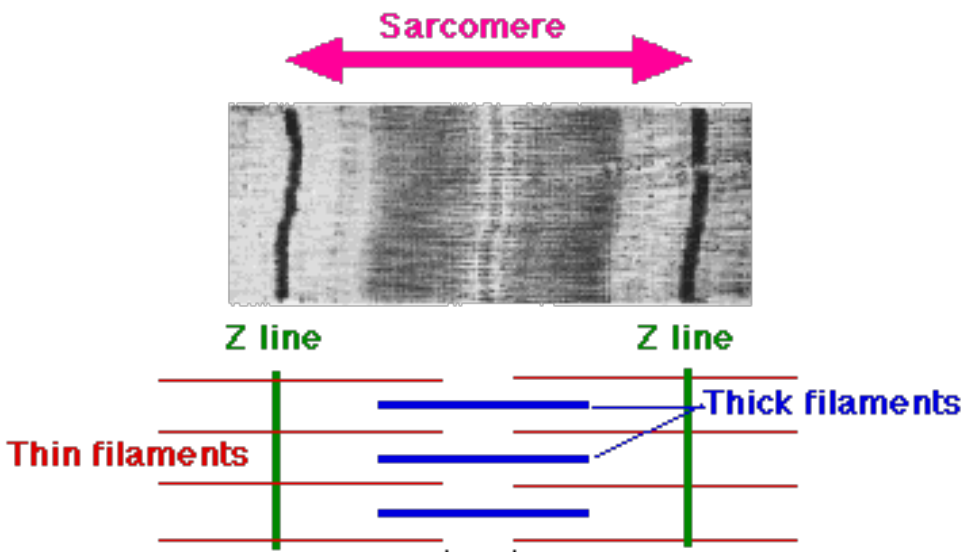

Figure 2-11: A picture of a sarcomere unit with a schematic impression below it highlighting the actin (thin) and myosin (thick) filaments. Taken from Jones (2004)

2.7.3 The Role of Muscle Contraction Mechanics in the Power-Cadence and Torque-Cadence Relationships

In both force-velocity and T-C paradigms, force production is related to the number of cross-bridge attachments and detachments (known as cycles). As the velocity of the muscle contraction increases, the time available for cross-bridges to attach and detach, as well as ATP stores, decreases. Consequently, the total number of cross-bridges attached decreases with the increasing velocity of muscle shortening. Thus, force production decreases as the velocity of the contraction increases and power is maximised at a combination of 'submaximal' force/torque and velocity/cadence values, leading to the inverse T-C relationship and parabolic P-C relationship (Hughes, 2003). Any manipulation of the T-C and P-C relationship is likely to involve either changes in the number of sarcomeres (for high torque/low cadence) and/or changes in cross-bridge cycling mechanisms (for low torque/high cadence).

2.8 Neural Factors

The mechanical output of a muscle group is not exclusively determined by muscle morphology. The nervous system is responsible for the activation level of the muscles, which can influence maximal force production (Review: Folland & Williams, 2007) and power production (for review, see Cormie *et al.*, 2011). It has been inferred that neural factors (and muscle activation) do play a role in sprint cycling ability (Akima *et al.*, 2005). This sub-section will briefly review the basic concepts and involvement of the nervous system that may play a role in sprint cycling.

The nervous system can be divided into the central (CNS) and peripheral (PNS) systems, which are both involved during voluntary muscle contraction. The CNS initiates the process of muscle activation by eliciting action potentials from the neurons

of the primary motor cortex to the spinal cord. Once the action potential exits in the spinal cord, it enters the PNS and, in particular, the alpha motor neurons until the action potentials reach the intended muscle(s) to be activated. The action potentials are transmitted by depolarising alpha motor neuron(s). If the stimulus breaches a threshold, Na^+ gated ion channels open, allowing a big enough influx of Na^+ ions to cause the cell to depolarise. Once peak voltage is reached, K^+ gated ion channels open, allowing the outflux of K^+ ions, causing polarisation. By the time the K^+ ion channels close, the cell's potential falls below resting potential. This is known as being in a hyperpolarised state. Once hyperpolarised, the cell then enters its refractory period, where the resting potential is restored by the passive Na^+ - K^+ pumps that move Na^+ ions to outside of the cell and K^+ ions inside. A single motor unit typically innervates hundreds of muscle fibres in multiple locations (McArdle *et al.*, 2010).

Force produced by a muscle is related to the number and type of motor units recruited. According to the size principle, as the force from maximal voluntary contractions increases, motor units are recruited in size order (Mcphedran *et al.*, 1965). As such, larger motor neurons that innervate the muscle fibres capable of higher force generation are recruited after the low force generating motor units. Recruitment of high threshold motor units is highly beneficial to maximal force production through the innervation of a large number of high force-producing muscle fibres. As such, the ability to promptly engage high-threshold motor units potentially affects maximal torque, maximal cadence and, consequently, PPO in sprint cycling.

The rate of action potential impulses reaching the motor neuron endplate to transmit acetylcholine from the motor neuron to the muscle fibre is known as motor unit firing frequency. Particularly in the applied field where movements are dynamic, it is only theorised that maximum motor unit firing frequency is the cause of the

improvement in neuromuscular performance. It is thought that increasing the motor unit firing frequency can improve PPO by increasing the magnitude of force from a muscle contraction that in turn increases the rate of force development.

Motor unit synchronization occurs when two or more motor units are activated concurrently more frequently than expected for independent random processes. Although it is yet to be convincingly demonstrated, synchronization has been hypothesized to augment force production and positively influence the explosive strength.

2.9 Measurement of the Neural System

Needle electromyography is arguably an insightful and mechanistic method available to assess the neural system. However, it can only be carried out during isometric contractions because of its invasive nature, making it useful in closed laboratory settings, whilst not appropriate for use during dynamic, ballistic maximal movements. Alternatively, surface electromyography (EMG) can be used with dynamic movements to assess the nervous system. Electrodes placed on the overlying skin of the muscle in question can detect the electrical activity of the underlying muscle. Aside from the non-physiological factors that influence the EMG signal (such as placement), there are two physiological areas of the nervous system that influence EMG measurements: 1) fibre membrane properties, such as average muscle fibre conduction velocity; and 2) motor unit properties, such as the number of recorded motor units, motor unit synchronisation and distribution of motor unit firing frequency.

The relationship of the neural system and power output during a 30 s maximal 'all-out' sprint cycling effort has been indirectly associated using EMG (Stewart *et al.*, 2011). The average muscle fibre conduction velocity, which was assessed using EMG

from linear array techniques, showed a positive and significant relationship between power output during the 30 s maximal 'all-out' sprint cycling test and the average muscle fibre conduction velocity (r = 0.57), whilst no change was seen for root-mean-square EMG amplitude (rmsEMG). The findings from this experiment suggest that from a neural perspective, firing frequency coupled with recruitment and elongation of high threshold motor units could be key factors in PPO during maximal cycling (Stewart *et al.*, 2011).

Due to the number of physiological factors that influence the EMG signal, the exact change in any of the aforementioned physiological factors cannot be isolated. Accordingly, it makes EMG a relatively global and crude measure of the nervous system. It is the membrane depolarisation and, more specifically, the overall change in membrane voltage (which includes motor units, muscle fibres and fibre type) that is cumulatively measured by EMG. This means that whilst the probability of the neural factors playing a role in PPO during sprint cycling is high, the likelihood of a) making an association with EMG amplitude and PPO, and b) extracting the specific neural factors that are linked to PPO might be small because of the nature and limitations of EMG (Farina *et al.*, 2014).

2.10 Laboratory Assessments of the Power-cadence relationships in Sprint Cycling

There are a number of methods of measuring P-C relationships in the sprint cycling domain. Whilst portable instrumented cranks that measure power in the field have been used (Gardner *et al.*, 2005, 2007, 2009) and validated when trying to form P-C and T-C relationships during training and competition (Gardner *et al.*, 2007), laboratory-based assessments still provide the most controlled method of assessing

physiological sprint cycling ability by minimising any lateral technical movements and isolating the physiological ability to generate power (Bertucci *et al.*, 2005). There are two protocols that measure P-C and T-C relationships: acceleration and isovelocity.

2.10.1 Acceleration Method

The acceleration method usually starts from a desired cadence or from a stationary start (i.e. cadence at zero). Upon the investigator's cue, participants are required to accelerate the cranks as hard and as fast as possible, trying to reach the highest cadence possible within the time allocated (usually < 7 s). The resistance can be provided either via a friction belt or an isoinertial load from the flywheel (see Figure 2-12 for an example) or a combination of both - all of which are summarised elsewhere (Martin *et al.*, 1997).

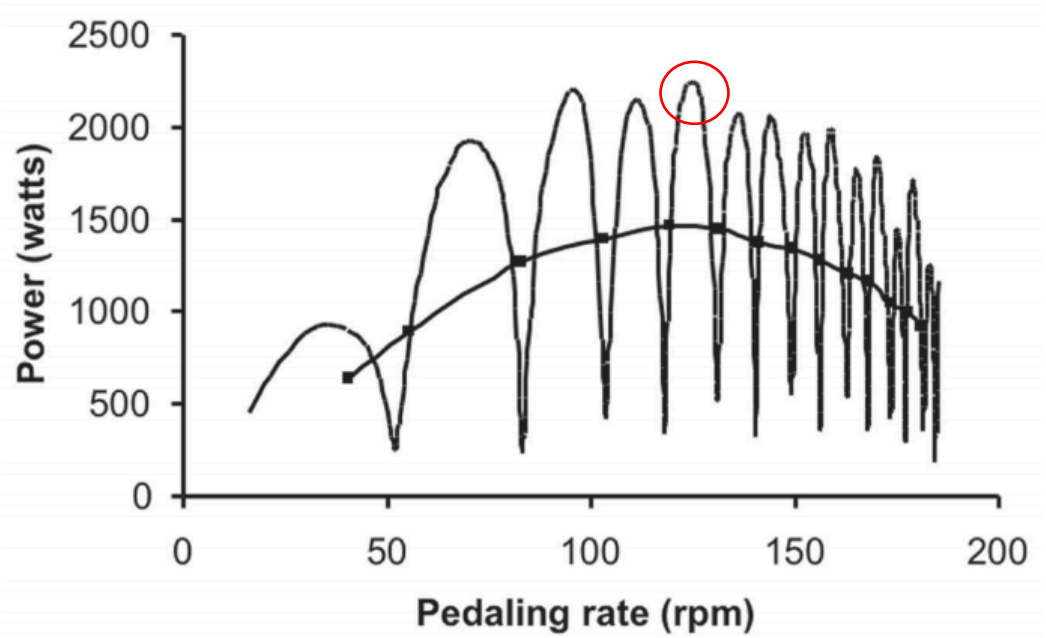

Figure 2-12: The raw power-cadence relationship in an acceleration sprint cycling test. The average power-cadence relationship which is represented over a revolution is shown by the filled squares. The circle represents the highest instantaneous power of any revolution. Taken from Martin et al. (2006)

They are thought to mirror the type of efforts in track sprint cycling as they usually involve maximal accelerations either from a stationary start (e.g. Team Sprint and 500/1000 m TT) or during efforts in the individual events such as the keirin or match sprint (Gardner *et al.*, 2005, 2007). Irrespective of which method is chosen, there are two approaches that investigators can use to ascertain P-C and T-C relationships. Firstly, a number of efforts are used, with at least three to four efforts starting from different cadences and resistance levels, which are normally relative to body mass (Arsac *et al.*, 1996; Dorel *et al.*, 2005, 2012). Secondly, it has been validated by Martin and colleagues that simply using isoinertial resistance from the flywheel alone can establish P-C and T-C relationships in a single bout (Martin *et al.*, 1997). Due to the ease of the test being administered, lack of preparation and easy replication, coaches at British Cycling and practitioners at the English Institute of Sport prefer the isoinertial protocol when assessing P-C and T-C relationships, when using the acceleration method.

2.10.2 Isovelocity Method

Isovelocity methodology involves participants sprinting at a constant pre-determined cadence. When using one effort to measure PPO, investigators have used a pre-determined cadence approximate to where PPO is typically achieved (between 110 – 130 RPM). However, this does not give any indication of changes in P-C and T-C relationships. As such, a number of isovelocity efforts across the cadence spectrum effort can be used to form P-C and T-C relationships (Baron *et al.*, 1999; McDaniel *et al.*, 2014). The latter is the preferred isovelocity method; it gives more insightful physiological measurements as it can provide a number of 'fatigue-free' efforts at

difference cadences which can establish torque- and P-C relationships (see Figure 2-13 for an example).

Traditionally, participants have to get the ergometer up to the desired cadences by pedalling against a large gear ratio and flywheel, which might add fatigue that affects the effort and potentially any subsequent efforts. However, the ergometer used to perform isovelocity efforts at the English Institute of Sport uses a motor to spin the flywheel up to the pre-determined cadence, and so the participant can cycle up to that cadence with minimal resistance before it brakes them at that the set cadence. This will be further discussed in the following chapter.

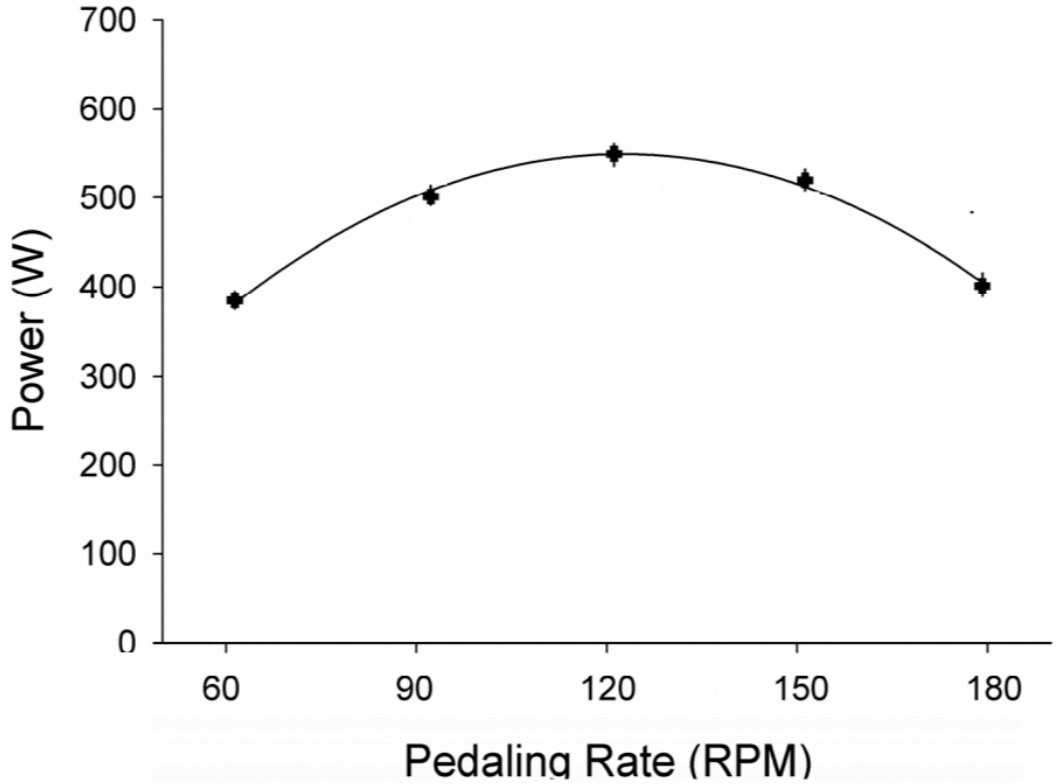

Figure 2-13: An example of a power-cadence relationship formed from isovelocity sprint testing. In this example, the pre-determined cadences were 60, 90, 120, 150 and 180 RPM. Adapted from McDaniel et al. (2014)

2.11 Previously Reported Laboratory Peak Power Output, Power- and Torque-cadence Relationships During Maximal Sprint Cycling

There are a number of studies that have measured different aspects of the P-C and/or T-C relationships using both acceleration and isovelocity techniques in laboratory testing. The majority of studies used healthy and physically active individuals without previous cycling experience (Martin *et al.*, 1997; Akima *et al.*, 2005; Mendez-Villanueva *et al.*, 2007; Leong *et al.*, 2014) or cyclists that were endurance trained (Martin *et al.*, 2000; Bertucci *et al.*, 2005, 2005; Rønnestad *et al.*, 2010). Experiments have seldom recruited (elite) track cyclists for studies that involve sprint cycling physiology and/or performance (Dorel *et al.*, 2005, 2012; Gardner *et al.*, 2005, 2007, 2009).

2.11.1 Peak Power Output (PPO)

The most commonly used measure that is reported to assess sprint cycling measurements in experiments is PPO. Martin and colleagues investigated the effects of PPO across human lifespan using different age groups. In the 20–30 year age category, 38 participants who were either physically active and/or moderately-trained endurance cyclists performed a maximal sprint acceleration test. Group PPO was reported as 1322 ± 38 W (Martin *et al.*, 2000). Rønnestad *et al*. (2010) reported similar PPO (1306 ± 81 W) in a comparable group of road cyclists prior to starting an intervention (Rønnestad *et al.*, 2010). However, using a similar cohort, two studies from the same research group reported significantly lower PPO group averages of 876 ± 164 W and 951 ± 194 W, which included participants who regularly participated in MTB, road and triathlon races (Buttelli *et al.*, 1996, 1997).

Studies have assessed PPO using the isovelocity method. Baron *et al.* (1999) reported PPO (normalised to body mass) as 15.3 ± 1.7 W/Kg using 60 male sports science studies. Other studies have also investigated mechanical power output but have reported instantaneous peak power output, which is defined as the highest power output within a revolution (Sargeant *et al.*, 1981). As instantaneous power output is not relevant for this thesis, it has not been considered.

In the elite and national level track sprint cycling population, Dorel *et al.* (2005) reported a group average of 1600 ± 116 W, which ranged between 1830 – 1460 W (Dorel *et al.*, 2005). Conversely, Gardner and colleagues reported a slightly higher PPO in a similar group of elite track sprinters, with an average PPO of 1791 ± 169 W and a range of 2092 – 1536 W (Gardner *et al.*, 2007). However, these were performed as stationary starts "out of the saddle", which can generate up to 8 – 12% more power in comparison to seated starts because of the increase in maximal torque production (Bertucci *et al.*, 2005; Martin *et al.*, 2007).

2.11.2 Maximum Torque (T_{MAX})

T_{MAX} values are less commonly reported as most studies focus on PPO as the measure of interest, and T_{MAX} is more difficult to measure as it has to be calculated by dividing power by angular velocity (after being converted from cadence). The acceleration method has reported healthy and physically active participants to have T_{MAX} average values of 203 ± 9 N·m (Martin *et al.*, 1997). For endurance trained participants, lower T_{MAX} values (164 ± 27 N·m) were reported when using the acceleration method (Buttelli *et al.*, 1996).

Dorel and colleagues reported 236 ± 19 N·m and a range of 215 – 270 N·m in a cohort of 12 elite cyclists (Dorel *et al.*, 2005). Gardner *et al*. (2007) reported a higher

group average (266 ± 20 N·m) and range (291 – 242 N·m) in a similar group of elite track sprint cyclists (Gardner *et al.*, 2007). Both studies used the acceleration method, but the results reported from Gardner and colleagues are likely to be inflated because, as mentioned above, they were performed out of the saddle, which can contribute between 8 – 12% additional power output (Bertucci *et al.*, 2005; Martin *et al.*, 2007).

2.11.3 Optimal Cadence (C_{OPT}) & Maximal Cadence (C_{MAX})

Optimal cadence has been reported to range between 115 – 139 RPM. When the isovelocity test was used, healthy and physically active participants exhibited C_{OPT} of 115 ± 9 RPM (Baron *et al.*, 1999). When using the acceleration method, the same cohort achieved PPO at 127 ± 14 RPM (Martin *et al.*, 1997). In healthy and/or endurance trained athletes, a similar C_{OPT} of 122 ± 2 and 124 ± 8 RPM (Buttelli *et al.*, 1996, 1997) was reported. Two different studies have reported the C_{OPT} in elite track cyclists. Gardner and colleagues had group averages of 128 ± 7 RPM with a range of 137 – 121 RPM (Gardner *et al.*, 2007), whilst Dorel *et al*. (2005) reported C_{OPT} 129 ± 5 RPM with a range of 141 – 123 RPM.

Healthy participants, when performing the isovelocity sprint test, have shown to have C_{MAX} values at 236 ± 22 RPM (Baron *et al.*, 1999). When similar cohorts performed an acceleration sprint test, C_{MAX} values generally ranged between 230 – 240 RPM: 237 ± 5, 222 ± 21 and 236 ± 22 (Buttelli *et al.*, 1996, 1997; Baron *et al.*, 1999). Elite track sprinters generally have higher C_{MAX} values at 260 ± 9 RPM, ranging between 282 – 247 RPM (Dorel *et al.*, 2005).

2.12 Physiological Factors Influencing the Power-Cadence and Torque-Cadence Relationship

The mechanisms influencing the force-velocity relationship in single muscle groups, such as the knee extensors, are complex and multi-factorial. Different studies have suggested a number of factors including mixed muscle fibre-type composition (Thorstensson *et al.*, 1976); muscle size (MacDougall *et al.*, 1977; Narici *et al.*, 1996*b*); architectural characteristics (such as pennation angle, fascicle length and muscle thickness) (Gans & de Vree, 1987); and a range of neural factors (Sale, 1988).

In sprint cycling, the physiological underpinnings of PPO, P-C and T-C relationships are poorly understood and largely limited to either cross-sectional studies using small cohorts of endurance trained cyclists (Rønnestad *et al.*, 2010) or in untrained participants (Hintzy *et al.*, 1999; Driss *et al.*, 2002; Akima *et al.*, 2005; Leong *et al.*, 2014). However, there have been a number of studies that have at least, in part, suggested potential determinants (Stone *et al.*, 2004; Akima *et al.*, 2005; Dorel *et al.*, 2005), but have used surrogate measurements to draw their conclusions.

2.12.1 Maximal Voluntary Contractions & Explosive Strength Contractions

A cross-sectional study by Driss *et al.* (2002) used a group of trained male volleyball players to demonstrate that peak isometric maximal voluntary torque of the knee extensors exhibited a strong relationship with PPO (r = 0.75). In the same data collection, explosive strength assessments of the knee extensors also showed a similar positive relationship to PPO (r = 0.81). Furthermore, there were identical relationships between peak force produced during maximum voluntary contractions (r = 0.73) and explosive strength measures (r = 0.79) with T_{MAX} (Driss *et al.*, 2002).

Another cross-sectional study examined the relationship of peak force and explosive strength measures from an isometric mid-thigh pull with sprint cycling performance assessments in the laboratory and using the time taken to perform a 25 m sprint from a stationary start on the track. The relationship between PPO and peak force from isometric mid-thigh pull showed similar relationships (r = 0.74 – 0.90) to Driss *et al*. (2002) (Stone *et al.*, 2004). Furthermore, the top six riders who scored the highest in peak force for the isometric mid-thigh produced high PPO (absolute and normalised to body mass) as well as faster 0 – 25 m standing start times in comparison to the six riders who scored the lowest strength for isometric mid-thigh pull. This study concluded that off-bike/gym-based resistance exercises to develop maximal strength and explosive strength are important in improving sprint cycling performance (Stone *et al.*, 2004).

A 12-week heavy resistance training programme was introduced to a group of trained endurance road cyclists. An increase in maximal force produced in an isometric half-squat and PPO was significantly higher after the intervention and, in comparison to experiments, cyclists that performed the same endurance training but without resistance training (Rønnestad *et al.*, 2010). The findings from Rønnestad *et al.* started to investigate a "cause and effect" relationship, seeing an improvement in strength being related to sprinting ability. However, the major limitation of this study was trained endurance riders who had no previous experience in (track) sprint cycling and resistance training were used, so the question still remains whether the same observations can be found in track sprint cyclists who are experienced in resistance training.

These studies (Driss *et al.*, 2002; Stone *et al.*, 2004; Rønnestad *et al.*, 2010) give a good insight into the importance of maximal strength and explosive strength in a

general capacity (using isometric mid-thigh pull), as well as being muscle specific (knee extensors), for sprint cycling performance. However, the determinants of strength are also multi-factorial, and a better understanding of the physiological underpinnings of strength (particularly in the sprint cycling domain) would be beneficial to optimising training.

2.12.2 Muscle Morphology

Skeletal muscle is responsible for locomotion, which is largely done by producing force (and power). It has been well-documented that prolonged strength training results in increases in muscle mass. Increases in muscle mass equates to increases in sarcomeres, the basic unit of muscle. By definition, an increase in sarcomeres results in more contractile material being available and, therefore, increases the ability to produce more force.

Jones and Pearson (1969) proposed a crude method to estimate muscle mass (plus bone) just by using a tape measure and skin-fold callipers (Jones & Pearson, 1969). This method was used to establish a significant and positive association with T_{MAX} and, consequently, PPO in elite track sprinters (Dorel *et al.*, 2005). An anatomical cross-sectional area, which is normally captured by magnetic resonance imaging, is defined as the largest cross-sectional image of a muscle. Though it is a surrogate measure of muscle volume, it is a far better estimate of muscle volume than if using a tape measure. Irrespective of the fibre type composition, the maximal force generated by a single muscle fibre is directly proportional to its anatomical cross-sectional area (Jones *et al.*, 2004).

Untrained individuals show large and significant changes in muscle mass when they undertake prolonged track sprint cycling training (Ema *et al.*, 2016) and/or

prolonged strength training (Narici *et al.*, 1996*b*). However, resistance training and improvement in strength (and consequently muscle) are the foundation stones of an experienced track sprint cyclist's training programme. Ahtiainen and colleagues examined changes in strength and cross-sectional area fractions of the quadricep femoris over a 21-week strength training programme (Ahtiainen *et al.*, 2003). Two cohorts participated in this study: strength-trained individuals and physically active participants who did not have any experience in strength training. The findings showed that from baseline, the untrained individuals showed bigger relative improvements in isometric strength at 14 and 21 weeks, whilst the strength trained participants only showed a significant increase in strength from baseline at 21-weeks. In addition, fractional cross-sectional area assessment of the quadriceps femoris showed that after 21 weeks, increases in the cross-sectional area for five out of the eight slices from baseline in the non-strength trained individuals compared to two of the eight slices examined from the strength trained individuals. However, it must be noted that maximum strength and cross-sectional area slices were all significantly greater in the strength trained individuals. In any case, Ahtiainen *et al.* suggested that it is harder to elicit and/or detect the same improvements in strength and muscle in chronically strength trained individuals (Ahtiainen *et al.*, 2003), which track sprint cyclists are considered to be.

Whilst it is generally accepted that a close relationship between muscle force and anatomical cross-sectional area (ACSA) exists, previous studies have reported inconsistent results whether or not the force per unit of ACSA is affected by training (Maughan *et al.*, 1984; Sale *et al.*, 1987). This discrepancy is partly explained by the measurement of cross-sectional area (CSA) i.e. whether it is ACSA or physiological cross-sectional area (PCSA). The CSA measurements should be made physiologically

rather than anatomically because ACSA does not account for any pennate muscle fibres. As such, muscle volume is which encompasses PCSA and fascicle length is thought of as an index of specific tension and exhibits the strong relationships with muscle power (Fukunaga *et al.*, 2001). However, no study has conducted the 'gold standard' measure of muscle (muscle volume of individual muscle groups rather than a cross-sectional area using MRI) using highly trained and/or elite (sprint) cyclist and no assessment has been made as to what degree it influences sprinting ability. The question remains whether hypertrophy or, in particular, a muscle group is linked with sprinting ability in elite level riders of any level, and/or whether the relationship is still meaningful when using experienced resistance/strength trained participants.

2.12.3 Muscle Architecture

Muscle architecture can be defined as the arrangement of muscle fibres relative to the axis of force generation (Lieber & Fridén, 2000). Ultrasound has been shown to be an accessible, reliable and valid method to assess muscle architecture *in vivo* (Henriksson-Larsen *et al.*, 1992; Kwah *et al.*, 2013; Ema *et al.*, 2013). Brightness mode (B-mode) ultrasound can be used to capture images of muscle architecture. Images are formed by reflecting ultrasonic waves off the collagen rich fascia septa that are located between muscle fascicles (which is a bundle of muscle fibres surrounded by perimysium). The cross-section of a muscle fibre/fascicle is composed of myofibrils which are made up the basic contractile unit of muscle, sarcomeres. The length of muscle fascicles and their orientation to the line of work and/or connective tissue/tendon influences the mechanical properties (i.e. force production and shortening velocity) of the muscle. From this, there are three main measurements of interest: 1) pennation angle, 2) fascicle length, and 3) muscle thickness (Figure 2-14).

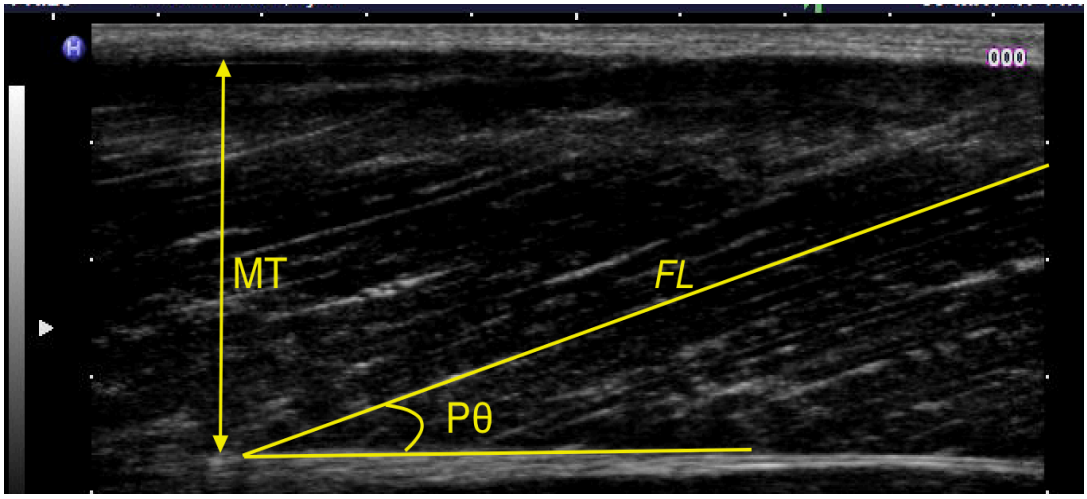

Figure 2-14: An example of B-mode ultrasound to measure muscle architecture of vastus lateralis: Pennation angle (Pθ), fascicle length (FL) and muscle thickness (MT). Fascicle lengths may need to be extrapolated. Image taken from Study 4

The angle of insertion of the fascicles relative to the line of work or tendon is known as the pennation angle (Rutherford & Jones, 1992). The pennation angle increases as more muscle sarcomeres are packed in parallel and can attach to a given area of aponeurosis or tendon within the same anatomical cross-sectional area (which increases the physiological cross-sectional area) and, consequently, produces higher force (Jones *et al.*, 2004). Furthermore, pennation angle allows the calculation of PCSA. In more detail, the magnitude of muscle fibre area perpendicular to the longitudinal axis of the muscle multiplied by the cosine of the angle of pennation gives PCSA. This exceeds the ACSA which simply measures the area of muscle perpendicular to the longitudinal plane of the muscle. Accordingly, PCSA represents the maximal number of acto-myosin cross-bridges that can be activated in parallel making the force producing capabilities of a muscle related to its angle of pennation (Aagaard *et al.*, 2001). A study by Leong *et al.* investigated the effect of PPO and muscle architecture of VL and RF after a chronic eccentric cycling training intervention using untrained participants (Leong *et al.*, 2014). The results suggested

that improvements in PPO could be associated with increases in the pennation angle and muscle thickness of VL and RF. However, there were *only* eight participants who completed the study, none had any previous cycling experience, and there were no controls to compare the intervention against. No other studies have examined the relationship between the pennation angle and sprint cycling ability.

Muscle fascicle length is the second measure of muscle architecture when using ultrasound. It can be defined as the distance between the insertions of the fascicle into the deep and superficial aponeuroses (Narici *et al.*, 1996*a*). Several studies have previously referred to fascicle length as muscle fibre length (Brand *et al.*, 1981; Lieber & Baskin, 1981). The number of sarcomeres that are arranged in series is related to maximal shortening velocity (i.e. V_{MAX}) as an increase in sarcomeres simultaneously contracting in series increases muscle fibre shortening velocity. As V_{MAX} is a determinant of peak power at muscle level (Section 2.3; Cormie *et al.*, 2011), it can be assumed that an increase in fascicle length could increase V_{MAX} and hence lead to an increase in peak power. Fascicle length and its relation to sprint cycling performance is yet to be investigated, but two cross-sectional studies have reported that sprint runners have longer fascicles than marathon runners (Abe *et al.*, 2000), and that fascicle length is associated to 100 m sprint running performance amongst trained athletes (Kumagai *et al.*, 2000).

The final measure in muscle architecture assessment is muscle thickness. It can be simply defined as the distance between the superficial and deep aponeurosis (Narici *et al.*, 1996*a*). Cross-sectional studies have displayed positive and significant relationships of muscle thickness to other measurements of muscle, such as Dual-energy X-ray absorptiometry (DXA; Takai *et al.*, 2014); anatomical cross-sectional area (measured from MRI) (Abe *et al.*, 1997); and muscle volume (Miyatani *et al.*,

2002; Franchi *et al.*, 2018*a*). When trying to assess longitudinal percentage changes in muscle thickness with anatomical cross-sectional area, a positive and significant relationship was displayed ($r = 0.69$; $p < 0.01$). However, when percentage changes of muscle thickness were compared to percentage changes in muscle volume, the relationship did not reach significance ($r = 0.33$; $p = 0.21$) (Franchi *et al.*, 2018*a*). It was concluded that muscle thickness is a good estimate of the anatomical cross-sectional area as it is site-specific rather than encompassing a whole muscle. The study by Leong *et al.* also assessed changes in muscle thickness of the VL and RF with changes in PPO before and after a chronic eccentric cycling intervention Along with the increase in the pennation angle (see above), the results also linked increases in muscle thickness of the VL and RF with PPO in untrained healthy participants.

2.12.4 Muscle Fibre Type

As mentioned earlier, one of the influences on C_{OPT}, C_{MAX} and consequently peak power output of a muscle is thought to be muscle fibre type proportion. Per CSA, type I (slow twitch) and type II (fast twitch) muscle fibres exhibit similar maximal force production properties. However, fast twitch muscle fibres are characterised by short cross-bridge cycle times that are underpinned by high sarcoplasmic reticulum and ATPase activity. Consequently, fast twitch fibres correspond to higher shortening velocities and have 5 – 10-fold more power per cross-sectional area unit in comparison to slow twitch making type II fast-twitch fibres being associated with higher C_{OPT} (and C_{MAX}) and could theoretically PPO.

2.13 Investigations and Aims

As previously discussed, PPO is the biggest physiological determinant of performance in track sprint cycling. The underpinning P-C and T-C relationships determine PPO but, despite this being well established, the number of studies that have investigated the physiological determinants have been limited to either cross-sectional studies that have used rudimentary methods of physiological estimates or interventions that have used more detailed measurements but have been limited by either using healthy participants or endurance trained participants as opposed to track sprint cyclists who are experienced in resistance training. As PPO is produced in the 'fatigue-free' state and within in the first 7 s of commencing maximal cycling, it predominantly uses the alactic energy system. Thus, the mechanisms that underpin PPO are a combination of the muscular and neuromuscular systems. In light of the literature presented, the overarching aim of this thesis is to understand the physiological determinants of PPO in sprint cycling. More specifically, this thesis is broken down into five investigations that specifically address the following aims:

2.13.1 Chapter 4 - Study 1

Title: Isovelocity vs Isoinertial Sprint Cycling Methods for Establishing the Power-Cadence and Torque-Cadence Relationships

Aims: To compare the magnitude and reliability of PPO, T_{MAX}, C_{MAX} and C_{OPT} measured from P-C and Torque-Cadence relationships using isovelocity and isoinertial sprint cycling methods

2.13.2 Chapter 5 – Study 2

Title: Maximum Voluntary Isometric Torque Production for Task specific and Single-joint Muscle groups and their Relation to Peak Power Output in Sprint Cycling

Aims: To establish relationships between maximal voluntary torque production from isometric single-joint and cycling-specific tasks and assess their ability to predict PPO

2.13.3 Chapter 6 – Study 3

Title: Reliability of Traditional and Task Specific Reference tasks to assess Peak Muscle Activation during two different Sprint Cycling Tests

Aims: 1) to compare the magnitude and between-session reliability of peak muscle activation, assessed with EMG amplitude, during two different sprint cycling tests (isovelocity and isoinertial); 2) to compare the magnitude and between-session reliability of EMG amplitude during two different reference tasks (a series of isometric single joint vs isometric cycling maximum voluntary contractions) in order to; 3)

establish if normalisation of EMG amplitude during sprint cycling to reference tasks improves measurement reliability.

2.13.4 Chapter 7 – Study 4

Title: Physiological Determinants of Peak Power Output in Sprint Cycling: A Cross-Sectional Study of Elite Cyclists.

Aims: To examine the relationship of a range of putative neuromuscular determinants (muscle volume, architecture and neuromuscular activation) with cycling PPO and then to compare and characterise the sprint performance and physiological measurements of elite sprint and endurance cyclists.

2.13.5 Chapter 8 – Study 5

Title: Isometric vs. Traditional Resistance Training in Elite Track Sprint Cyclists.

Aims: 1) investigate and compare the changes of power-cadence and torque-cadence relationships, along with selected neuromuscular measurements, between traditional resistance training and an isometric maximum strength cycling protocol, prescribed alongside track sprinters habitual training; and 2) whether any changes in the physiological measurements can predict changes in sprinting ability (i.e. PPO).

CHAPTER 3

GENERAL METHODS

3.1 Introduction

General methods applied to the studies within the thesis are explained in this chapter. Any specific methods used in individual studies are outlined in their respective chapters.

3.2 Pre-Test Procedures

3.2.1 Ethical approval

Prior to the commencement of data collection, ethical approval for each study was obtained from the Department of Sport, Exercise and Rehabilitation Research Ethics Committee.

3.2.2 Participants

Trained cyclists were recruited for the first three studies, whilst elite level cyclists were recruited for the final two. The participants read an information sheet and provided written informed consent prior to testing (Appendix 11.1). The participants also completed a health questionnaire (see Appendix 11.2) that included (where necessary) specific questions relating to the safety of electrical stimulation and magnetic resonance imaging. Participants were excluded if they reported any contra-indicated health issues. Participants were thoroughly familiarised before any formal testing procedures and were instructed not to take part in strenuous exercise 24 h prior to the testing sessions. Participants were instructed to avoid drinking alcohol the day before a test, refrain from caffeine on test days, and avoid eating 2 h prior to testing. It was vital to make provisions for caffeine ingestion as it has been shown that caffeine can alter neuromuscular function with effects occurring at numerous sites along the motor pathway (Gandevia & Taylor, 2006).

3.3 Apparatus and Procedures

3.3.1 Anthropometry

All testing procedures were either conducted at the English Institute of Sport Laboratory in Manchester or at the British Cycling Velodrome gymnasium in the National Cycling Centre, Manchester. Each participant's date of birth was recorded and then converted to a decimal age. Stature was measured to the nearest 0.1 cm using a stadiometer (Seca 220, Seca Limited, Birmingham, UK). Participants were asked to stand with their back, buttocks and heels touching the stadiometer and with their head orientated in the Frankfurt plane (orbital and tragion horizontally aligned). Participants were asked to inspire fully while stature was taken as the distance from the floor to the vertex of the head. Body mass (kg), while wearing minimal clothing, was measured to the nearest 0.1 kg using calibrated electronic scales (Seca 220, Seca Limited, Birmingham, UK).

3.3.2 Cycling Ergometer

The two different sprint cycling methods were performed on the same modified SRM ergometer (Schoberer Rad Messtechnik, Jülich, Germany) that was adjusted to match the participants' track bike position with 'drops' or if they did not ride the track, adjusted to their 'upright' road position.

The ergometer itself was modified to have a braking module to control the motor to increase the acceleration of the flywheel to match the velocity of the prescribed cadence for isovelocity sprints (Figure 3-1 and 3-2). This allowed the participants to pedal without resistance (i.e. with just the mass of both of their legs) until they reached the pre-determined pedalling rate. Participants wore their own cycling shoes and pedals (fitted to the ergometer), and were instructed to perform each

recorded effort in the saddle whilst using the 'drop' handlebars. The ergometers used in the thesis are presented in Figure 3-1 and 3-2. Both were identical in function and use, but the ergometer in 3-2 was used in the final study as it was easier to transport, modify and had fewer exposed components.

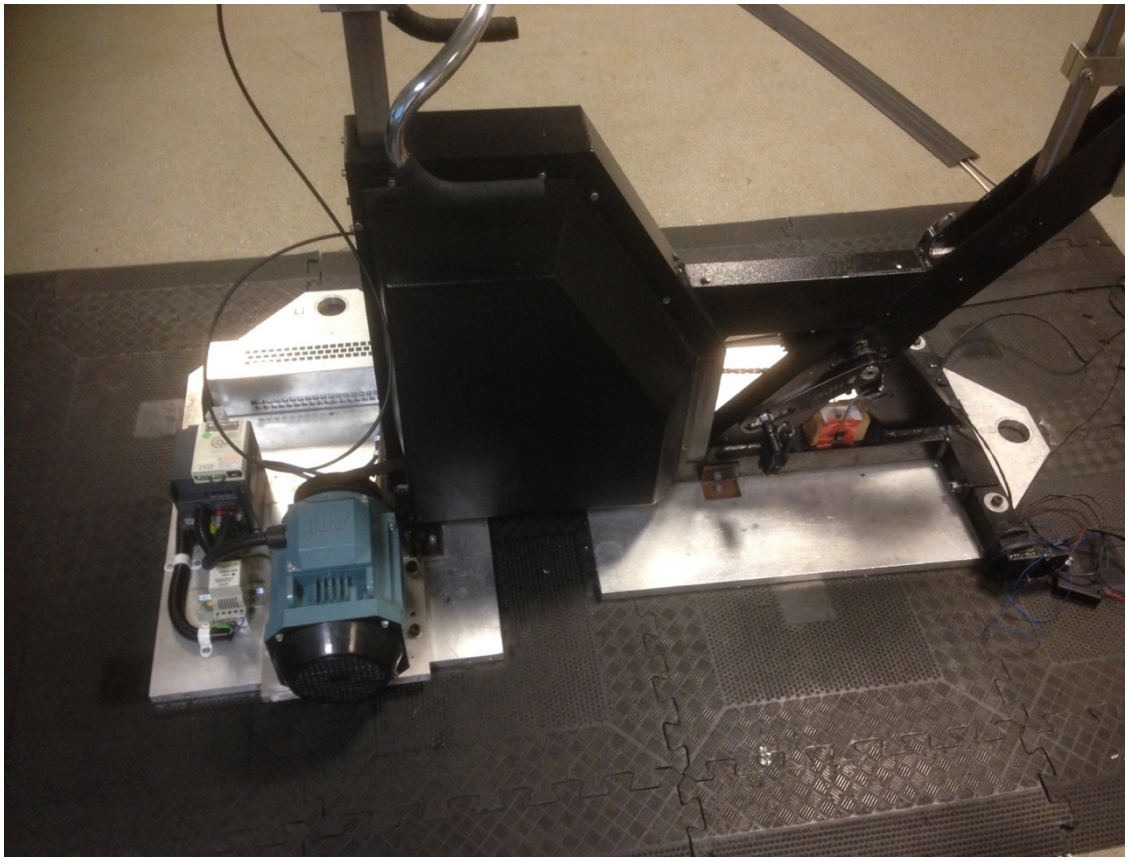

Figure 3-1: The set-up of the modified SRM ergometer used for studies 1, 2, 3 and 4. A 2.2kW motor was controlled by a braking module which moved the flywheel up to the desired cadence which was controlled by the power control. A reed switch was positioned at bottom dead centre of the non-drive side crank to indicate when the drive-side crank was at top dead centre, which was used to synchronise the crank data with the surface EMG traces.

3.3.2.1 Isovelocity Sprints

The isovelocity sprint method could hold participants at different pre-determined cadences. The cadence was kept constant by using a braking module and a 2.2 kW motor; riders could increase power output by increasing the torque throughout the crank revolution. The investigator gave a 3 s countdown and the subjects performed a 4 s maximal effort. Prior to each effort, the motor speed was

brought up to match the desired cadence. The volunteers were then instructed to pedal lightly below the prescribed cadence and told to 'attack the effort as fast and as hard as possible' throughout each sprint. The investigator gave a 3 s countdown and the subjects performed a 4 s maximal effort (to ensure at least three complete revolutions at maximal efforts) at each cadence, with 3 min of passive rest between each effort. The number of efforts and the cadence(s) of each effort are described in the individual chapters.

Figure 3-2: For the final study, the modified SRM ergometer was altered to conceal the mechanical equipment from the participants.

3.3.2.2 Isoinertial Sprints

A constant isoinertial load disc (4.6 kg) and an intermediate gear ratio (front 53; rear 15) were used for these sprints. Prior to each sprint, the flywheel was brought to a complete standstill and participants assumed the starting position of their cranks (typically, they had their front leg between 45 – 90° from top dead centre) and position on the 'drop' handlebars, ready to sprint. Participants were reminded to achieve the 'highest cadence possible by pedalling as hard and as fast as possible' and 'attack the effort as hard and fast as possible' before a 5 s countdown to a maximal sprint. After 6 s the investigator verbally terminated the test (Dorel *et al.*, 2012). Participants performed two sprints 8 min apart. The sprint with the highest derived (interpolated) PPO was used for analysis.

3.3.3 Power Measurement

The original SRM cranks were replaced with 170 mm instrumented cranks (Factor cranks, Beru Factor 1, Diss, Norfolk, United Kingdom) to record instantaneous torque, crank angle and angular velocity from both the right and left cranks (Factor Cranks, BF1 Systems, Diss, UK), sampled at 200 Hz. The data were wirelessly transmitted to and recorded on a wireless data logger (BF1 Systems, Diss, UK). Crank data from the data logger were subsequently imported into Spike2 software (CED, Cambridge, UK) and analysed offline using custom scripts to calculate mean torque, power and cadence per revolution from top dead centre to top and dead centre.

3.3.4 Isometric Torque measurement

3.3.4.1 Measurement of Torque of different Muscle Groups

When measuring peak torque of maximum voluntary contractions of muscle groups, a calibrated dynamometer (Biodex, System 4 Pro, New York, USA) was used.

This was a commercially available dynamometer that can perform isometric or isokinetic contractions, which allows a number of muscle groups to be assessed, and which can easily be manipulated to assume different positions to fit joint angles and fulfil the investigator's needs. As such, the single-joint, unilateral isometric (ISO-SINGJT) maximum voluntary contractions (MVC) were performed using a calibrated dynamometer. Participants performed the MVCs seated and strapped across the hips and chest in the sagittal plane, in four different positions. These were selected because these joint angles were described as the angle of peak torque production for each muscle group (Ericson, 1986; Rouffet & Hautier, 2008). These MVCs were performed in the following order with the right limb always assessed first: neutral plantar extension or anatomical zero (0°), hip 45° in extension, knee 70° in extension (Figure 3-3) and 50° in flexion where 0° was full extension of the knee. Regression analysis from the calibrations was used to convert the raw analogue signals (mV) to torque.

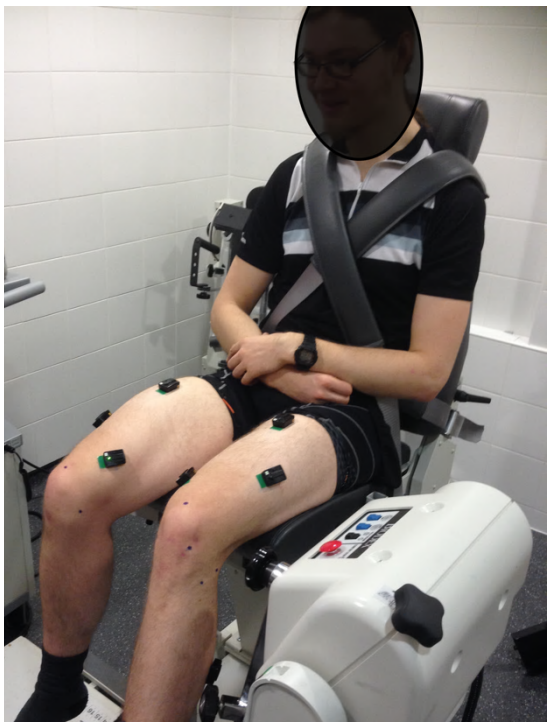

Figure 3-3: A participant between maximal voluntary contractions of the left knee extensor on the Biodex Dynamometer for studies 1, 2 and 3.

3.3.4.2 Measurement of Maximum Isometric Torque of Knee Extensors

When specifically measuring the isometric torque of the knee extensors, and in particular maximum voluntary torque and explosive contractions to measure maximal torque up to 200 ms, a custom-built isometric dynamometer was made in accordance with previous recommendations (Maffiuletti *et al.*, 2016); this was used in the final study. Participants were seated with the hip joint angle positioned at ~125° and the knee joint angle positioned at ~115° (full extension for both hip and knee was assumed to be 180°). The chair had a long, rigid back-rest to provide full back and head support. The lack of padding on the test rig minimised any compliance and distensibility of the dynamometer. This is shown in Figure 3-4. All the components were tightly fixed onto the dynamometer, and three separate industry-standard polyester seatbelts with adjustable automotive seatbelt latchets were independently used to tightly fasten the participants to the dynamometer: two seatbelts went over each shoulder and contralateral to the hip and one was fastened over the hip (Figure 3-4).

A calibrated S-beam strain gauge (Force Logic, Swallowfield, UK) was used to measure force at the ankle. Regression analysis from the calibration was used to convert the raw analogue signals (mV) to force. A metal cuff attached to the strain gauge was positioned perpendicular to the tibia and attached to the ankle (~15% of tibial length above the medial malleolus). Another two straps, 40 mm in width and made of reinforced canvas webbing, were placed over the cuff to further secure it. The analogue force signal from the strain gauge was amplified (×370) and sampled at 2,000 Hz using an external analogue-to-digital (A/D) converter (Micro 1401; CED, Cambridge, UK) and recorded with Spike2 computer software (CED, Cambridge, UK). In the offline analysis, force data were low-pass filtered at 10 Hz using a fourth-order zero-lag Butterworth filter, gravity corrected by subtracting the baseline force

and multiplying by the lever length i.e. the distance from the knee joint space to the centre of the ankle strap, to calculate knee joint torque values.

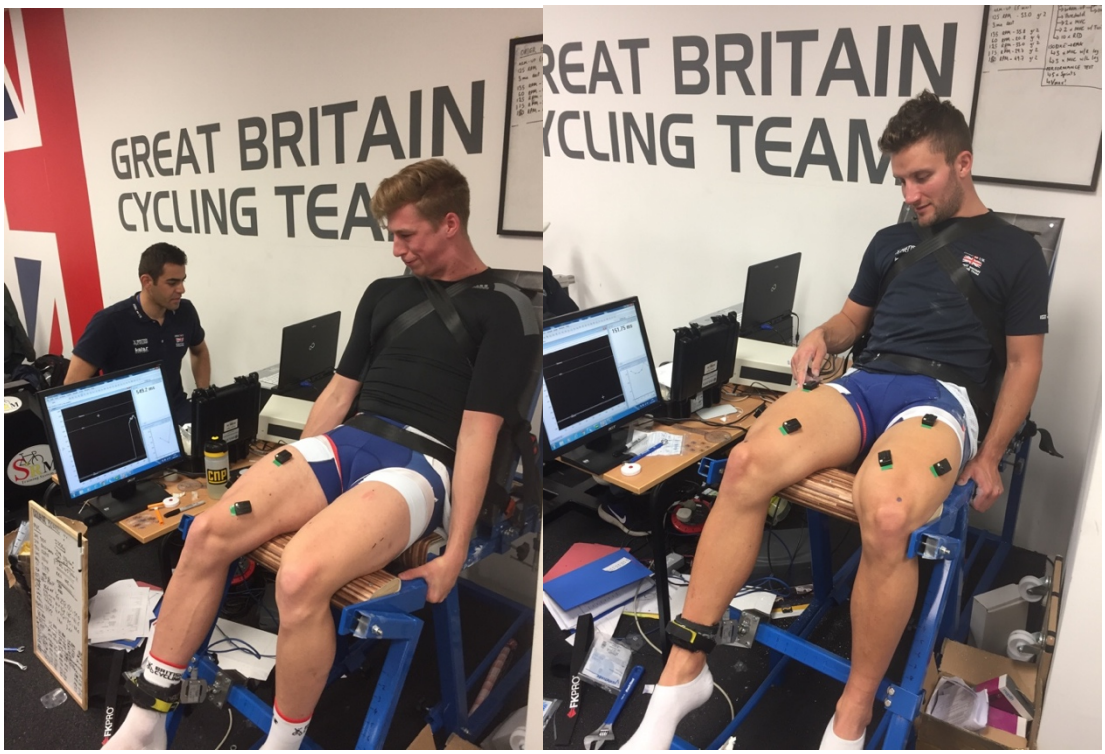

Figure 3-4: Two participants on a custom-made dynamometer that was designed to minimise compliance for study 5. This allows good measurements of isometric maximal and explosive contractions

In total, 10 explosive isometric contractions of the knee extensors were performed. They were instructed to extend their knee "as fast and hard as possible" for 1 s upon hearing a verbal cue from the investigator. Each contraction was separated by 30 s rest. The cyclists were instructed to avoid any countermovement or pre-tension. This was monitored by the investigators, who were using a custom-made script to detect any deviation from the baseline that could also see the force-time track in real-time. Biofeedback to the cyclists was provided by virtue of a real-time force-time curve on a monitor. This provided the cyclists with a visual display to provide information for two main reasons: 1) it informed them as to whether any pre-tension or

countermovement was made; 2) it provided the force recorded at 200 ms to act as a source of motivation and gauge for previous and subsequent efforts.

3.3.4.3 Maximum Isometric Cycling Torque Production

Most instrumented cranks do not start measuring and/or recording mechanical data until the crank arms have completed a full revolution, which is normally around 50 RPM when commencing an effort from a stationary start (Gardner *et al.*, 2007). However, the instrumented cranks used in this thesis (Factor Cranks, BF1 Systems, Diss, UK) continually record torque upon being manually switched on, meaning that they can also measure torque isometrically. Isometric efforts on a bicycle have previously been investigated as a reference task for EMG (Albertus-Kajee *et al.*, 2010) and as a method to elicit post-activation potentiation for sprint cycling performance (Munro *et al.*, 2017), but none have measured and/or presented torque production.

A custom-made ergometer (BAE Systems, Farnborough, UK) was modified to record isometric force by using a car jack clamp that was attached to the ergometer and was fitted with a rubber stopper that pressed against the flywheel. The crank arms were positioned at 3 and 9 o'clock or 90° clockwise and anti-clockwise from top dead centre (TDC). The ergometer was adjusted to fit the cyclists' geometric bike position and all participants used their own clipless shoes and pedals (Figure 3-5). Once in position, the participants were instructed to try to pedal the ergometer with both legs. After pilot testing, participants were asked to rest their forearms on the 'tops' of the handlebars to ensure that movement from the upper body contribution and lower body joint angles were minimised. The data was wirelessly transmitted and recorded on to a "Flogger" (BF1 Systems, Diss, UK) at 192 Hz and analysed by off-line software (Spike2, CED, Cambridge, UK) using custom-made scripts. Prior to performing any

efforts, a seatbelt was positioned on the first contact point of their left buttock and the seat with a 1.25 kg weight placed on the other end to ensure the cyclists stayed in the saddle; if they got out of the saddle, the belt weight would fall to the floor and the effort would not be recorded.

3.3.5 Muscle Architecture Measurement

Assessments of muscle architecture were performed by using brightness-mode ultrasound (B-mode) images. B-mode images are formed by using a flat-faced transducer from piezoelectric crystals that are in a parallel formation. Once an alternating current is applied to the piezoelectric crystals, they grow and shrink, depending on the voltage that is run through it. The alternating current causes the crystals to vibrate at a high speed and to produce ultrasound waves. The waves then bounce back off the object under investigation, hit the piezoelectric crystals and cause the mechanical energy produced from the sound vibrating the crystals to be converted back into electrical energy. The properties of the reflection (i.e. the time between when the sound was sent and received, the amplitude and the pitch of the ultrasound waves upon their return) are then plotted as a series of dots to produce a two-dimensional image.

In this thesis, a linear array transducer (5-10 MHz scanning width 92 mm and depth 65 mm, EUP-L53L; Hitachi EUB-8500) was used to form B-mode images of the superficial muscle. Water-soluble transmission gel was used to coat the transducer that was positioned with minimal pressure on the skin. This acted as a conductive medium between the transducer and skin. Images were captured with the transducer placed on the medial longitudinal line of the muscle while positioned on the skin over the VL at 50% of femur length (from the knee joint space to the greater trochanter) to correspond with the area of greatest anatomical CSA. The transducer was orientated perpendicular to the skin and parallel to the fascicular path.

Figure 3-5: Image of a rider that has had the cranks of a custom-made ergometer made isometric and in position to have their muscle architecture measured using B-mode ultrasound. When performing the ultrasound scan, participants had thighs exposed by rolling up any obstructive clothing.

In this thesis, the participants assumed different positions to have their muscle architecture of the vastus lateralis assessed. In Chapter 8, a custom-made (UK Sport Innovations, UK) cycling ergometer that had its geometry altered to fit the participants cycling position in an identical position to section 3.3.4.3 & Figure 3-5 was employed. In Chapter 9, the muscle architecture assessments were performed when the

participants assumed more ‘standard’ positions, as described in section 3.3.4.2 (Figure 3-4). These specific protocols are described in more detail in the relevant chapters. Irrespective of the anatomical positioning of the participants, the measurements were consistent throughout the study. Muscle thickness was measured as the distance between the superficial and deep aponeurosis, the pennation angle was the angle of insertion of the fascicles relative to the line of work or tendon, and the fascicle length was the distance between the insertions of the fascicle into the deep and superficial aponeuroses. With regard to fascicle length, despite a longer transducer being used, there were incidences when the full fascicles did not fit in the field of view. When this was the case, the linear extrapolation method was used (Ando *et al.*, 2014).

Two-dimensional B-mode ultrasound images of relaxed muscles have been shown to be reliable and valid measures of muscle architecture (Kwah *et al.*, 2013). However, in this thesis only images around the ACSA/muscle belly of the vastus lateralis (i.e. at 50% of the muscle length) were captured and analysed. Whilst this has been extensively done over the past 25-years, there are two limitations to this approach. First, despite being a reliable and valid measure, it is not in a contracted state (which is more applicable for force production) and muscle architecture measure have been shown to alter during contraction (Fukunaga *et al.*, 1997). This could give a more applicable or ecological measure of the muscle architecture. Second, it has been shown the muscle architecture measures vary within an individual muscle and a better representation of the muscle architecture of the vastus lateralis would be to use extended field of view imaging which merges a sequence of images (Franchi *et al.*, 2018*b*) and taking a series of measurements throughout the muscle.

3.3.6 Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI) is considered the 'gold standard' when quantifying skeletal muscle (Engstrom *et al.*, 1991; Cruz-Jentoft *et al.*, 2010). It measures muscle (and other body tissue) by using a magnet to orientate the spin of the protons, and then electromagnetic waves are applied that excite the protons of the water molecules in the body's tissue. During relaxation (or the return to the original spin orientation), receiver coils collect the radio frequency waves that are emitted from the protons. The pattern of the radio frequencies is then used to generate digital images that are two-dimensional single slice images of the region of interest. The different tissues are then differentiated by colour, with skeletal muscle exhibiting a light grey colour.

The two-dimensional cross-sectional images can be used to identify anatomical CSA or the volume of a muscle can be estimated by producing a three-dimensional estimate of the muscle(s) in question by using multiple slice acquisition (Narici *et al.*, 1992; Erskine *et al.*, 2009). The advantages associated with MRI are its high repeatability and validity, as well as its ability to distinguish individual muscles or muscle groups. Whilst these advantages are also seen in computer tomography, an MRI does not involve radiation exposure to the participants or patients, making it safe to use with multiple exposures in a short period of time. The main disadvantage associated with MRI usage is the high financial burden incurred to gain access and operate it, meaning accessibility is limited. Furthermore, trained technicians are required to operate it, and the analysis of the data is onerous and time-consuming. Mobile MRI scanners can be hired by the day, assuming there is an adequate power-supply and permission has been granted by the landowner. In this thesis, a mobile MRI scanner (1.5 T Signa HDxt; Alliance Medical Limited, Warwick, UK; Figure 3-6) was

hired for two separate days and used in Chapter 7 to measure the muscle volume of the thigh (quadriceps femoris and hamstrings). T1-weighted axial images of each thigh originating at the anterior-superior iliac spine and finishing at the knee joint space (scan parameters: time of repetition = 600 ms; time to echo = 14 ms; image matrix 512 pixels × 512 pixels; field of view 260 mm × 260 mm; slice thickness = 5 mm; and interslice gap = 5 mm) were recorded. An array of fish-oil capsules were attached using micro-pore surgical tape on and around the anterior-superior iliac spine and knee joint space as done previously (Massey *et al.*, 2018). This was to help the operator orientate any overlapping blocks during the analysis stage. Before undertaking the scans, the participants were asked to complete a questionnaire and hold a brief conversation with the technician to ensure they could safely undergo an MR scan (Appendix 11.3).

Figure 3-6: Image of the exterior of the mobile MRI scanner unit used in this thesis

3.3.7 Dual-energy X-ray absorptiometry (DXA)

Dual-energy X-ray absorptiometry (DXA) provides information on whole and regional body composition in three different areas: bone mineral, fat mass and fat-free (muscle) mass. DXA scans are carried out by producing photons at two different energy levels that pass through and diminish at rates relative to the different body tissue compositions. The unique elemental profiles of bone, fat, and fat-free non-bone (i.e. muscle) tissue allow for each of the three tissue types being quantified. The development of fan beam DXA scanners means that multiple radiation detectors, rather than the two found in conventional first-generation pencil beam DXA scanners, have greatly reduced the time for a DXA scan to be performed: from ~25 mins for pencil beam DXA scanners to ~5 mins for fan beam. If age and BMI were included in the calculations, fat-free (i.e. muscle mass) estimations were shown to be validated when compared to computer tomography scans.

There is a body of evidence to suggest that muscle mass estimates of DXA exhibit moderate to strong associations with MRI measurements (Fuller *et al.*, 1999; Freda *et al.*, 2009; Maden-Wilkinson *et al.*, 2013; Tavoian *et al.*, 2019). Other advantages of using DXA include its ease of use and low-cost as well as the prompt delivery of results, particularly when compared to MRI. The output or results are also relatively easy to interpret. The disadvantages of DXA include radiation exposure (0.04 to 0.86 mrem); however, this is still a low dose particularly when the average daily exposure to radiation is ~1.69 mrem. Also, while results are easy to interpret, DXA cannot distinguish between individual muscle groups and the 'quality of muscle', making the results less detailed and cruder in comparison to MRI. Lastly, the use and/or accuracy of the fat-free assessments when using DXA to assess muscle mass longitudinally has been questioned (Haderslev *et al.*, 2005; Delmonico *et al.*, 2008).

In comparison to other measures of muscle (for example, MRI) which directly measure muscle, DXA measures are somewhat of an indirect measure of muscle which is referred to as 'fat-free mass'. Initially, bone and fat measures are done made and then the remainder is categorised as 'fat-free' mass which could explain why it is unsuitable for monitoring muscle mass longitudinally.

In the final experimental chapter of this thesis, total lean body mass (TLBM) and cumulative lower body lean mass (LBLM) were recorded using a fan beam DXA scanner (Lunar iDXA, GE Healthcare, Madison, WI) before and after a 6-week training intervention. More detail of the protocol is described in the respective chapter.

3.3.8 Surface Electromyography

EMG can be used to study the muscle function through inquiry of the electrical signal the muscles emanate (Basmajian & De Luca, 1985). As already mentioned in Section 2.9, EMG is easy to administer, electrodes being placed on the overlying muscle to detect and record the cumulative electrical contribution made by the active motor units. The EMG traces give a more holistic measure of the motor units and/or neural system as it depends on the membrane properties of the muscle fibres as well as the timing of the motor unit action potentials, meaning that the EMG is a reflection of the peripheral and central properties of the neuromuscular system (Farina *et al.*, 2014). Throughout this thesis, a wireless EMG system (Trigno, Delsys Inc., Boston, MA, USA) was used whenever EMG measurements were taken. This system possessed up to 16 portable wireless EMG sensors (inter-electrode distance = 10 mm, head size = 24 mm × 11 mm × 6 mm) that had four silver bar electrodes, an integrated amplifier, and it communicated with the 'base station' through radio frequency. Double-sided adhesive tape that was specifically made for the wireless electrodes

(Delsys Inc., Boston, MA, USA) was used to directly attach the wireless electrodes to the skin. Prior to attaching the electrodes to the targeted muscles, the area was marked using the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) guidelines (Hermens *et al.*, 2000). The skin was then prepared by shaving the targeted area by using a disposable razor, then lightly abrading it with sandpaper and subsequently cleaning it using a disposable ethanol wipe. Once the ethanol had dried, the electrodes were placed on the skin overlaying the targeted muscles. In this thesis, the vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), bicep femoris (long head; BF), gluteus maximus (GM) and gastrocnemius lateral head (GL) were assessed, and EMG electrodes were attached to the respective muscles on both the right and left side of participants. Surface EMG signals were amplified (×1000), band-pass filtered (20-450 Hz), and sampled at 2,000 Hz using an external analogue-to-digital data acquisition system (Micro 1401, Cambridge Electronic Design, Cambridge, UK) and a PC utilising Spike2 software (version 7.11, CED, Cambridge, UK). Examples of these are shown in Figures 3-4; 3-5; 3-7.

Figure 3-7: A participant performing a maximal voluntary contraction of the right knee extensor with wireless surface EMG electrodes attached on their vastus lateralis, vastus medialis and rectus femoris. The screen facing the participant gives real-time feedback on their effort, as well as a comparison to their previous efforts.

3.3.9 Evoked twitch force

Direct (or Galvanic) current is a unidirectional electrical current that can be suddenly applied or suddenly discontinued, and which can be used to activate the muscle directly without involving the peripheral nerve(s). Though this type of stimulation was first reported over 200 years ago using dead frogs' legs, it is now widely used for therapeutic purposes and experimental research. Direct current is

passed through the body tissue by means of two stimulating pads placed on the surface of the skin.

Evoked twitch force is used in the final experimental chapter of this thesis (Chapter 8). Participants were 'connected' to a constant-current stimulator (DS7AH, Digitimer Ltd., Welwyn Garden City, Hertfordshire, UK) that administered the single direct current pulses by using 50 mm disposable self-adhesive stimulation surface electrodes (A.CF5000, Digitimer Ltd., Welwyn Garden City, Hertfordshire, UK). The surface electrodes were placed midway between the iliac crest, which acted as the anode, and the greater trochanter and above the femoral nerve high in the femoral triangle, which acted as the cathode (Sidhu *et al.*, 2009).

Single direct current pulses delivered by the electrical stimulator can be manipulated in three different ways: 1) the frequency of stimulation, which denotes the number of pulses that are delivered per second; this can be from 1 Hz upwards 2) the duration of each pulse, which is measured in microseconds (μs); and 3) the intensity of current, which is expressed in milliamps (mA) or voltage (V; Low & Reed, 2000). In Chapter 8, single (1 Hz) electrical stimuli (200 μs duration) were delivered separately to both the left and right femoral nerves to assess knee-extensor contractility (Figure 3-8). With regards to intensity, supramaximal motor nerve stimulation was sought and twitch responses were obtained from the relaxed knee-extensors during the increase of stimulator intensity. To determine the level of supramaximality, two stimulations separated by 30 s were delivered during an incremental protocol beginning at 50 mA; thereafter, the intensity of stimulation was increased by 25 mA until a plateau was evident in the potentiated twitch force, indicating maximum depolarisation of the femoral nerve. To account for activity-dependent changes in axonal excitability and to ensure that supramaximal level of stimulation was achieved,

all stimulations in this thesis were delivered at 130% of the participant's resting motor threshold (Burke, 2002).

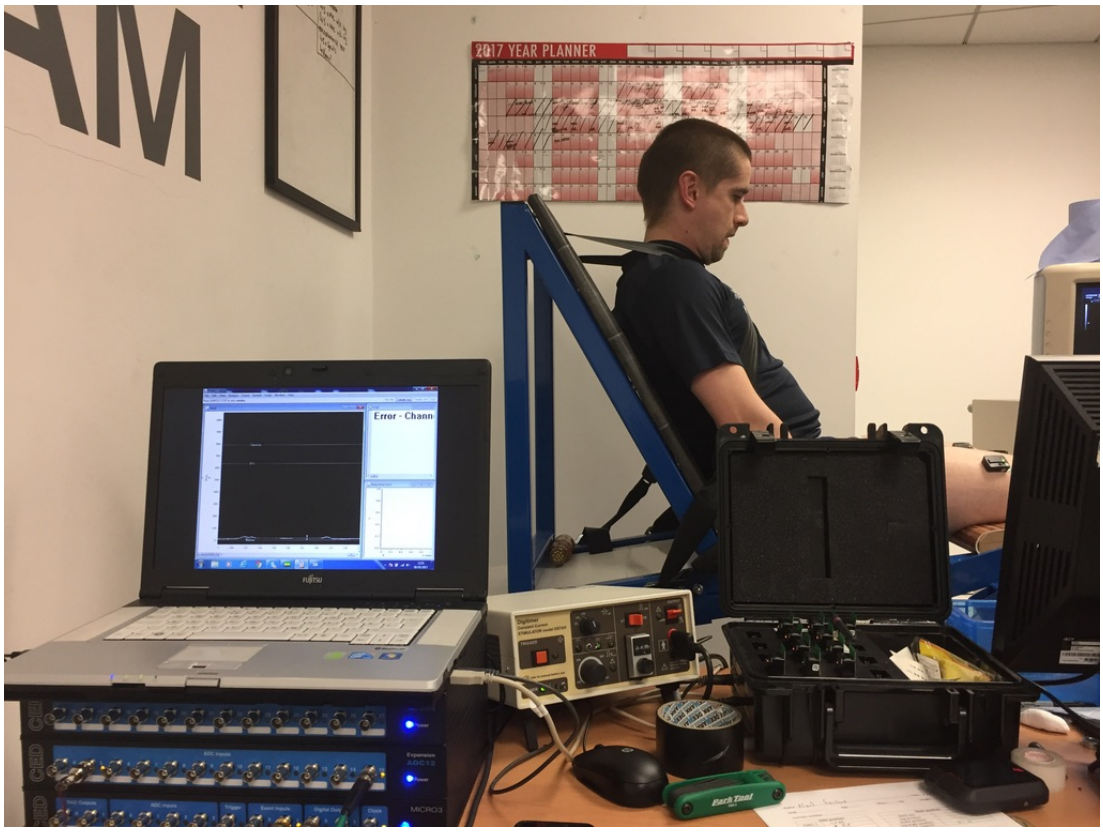

Figure 3-8: Investigators point of view when carrying out muscle function testing in final experimental data collection of surface EMG, electronic stimulator and custom-built dynamometer. Ultrasound machine in background of right photo

Once the level of electrical stimulation was established, potentiated quadriceps twitch force was obtained immediately after maximal contractions ($Q_{tw.pot}$) at rest. Maximal voluntary contractions (SIT) of the knee extensors were also performed to assess voluntary activation, which is defined as "the level of neural drive to a muscle during exercise" (Merton, 1954). This was attained by delivering a single stimulus to the femoral nerve at peak force during an MVC (see section 3.3.4.1) to evoke a twitch-like rise in force. Once the MVC ceased and rest force returned to resting baseline for 2 s, another single stimulus was delivered. Voluntary activation was estimated by

comparing the amplitude of the interpolated twitch evoked by the peripheral stimulus during the MVC to the amplitude of the evoked twitch during the resting potentiated twitch delivered immediately afterwards by using the following equation (equation 1):

$$\text{Voluntary Activation (\%)} = (1 - SIT/\ Q_{tw.pot}) \times 100 \text{ (equation 1)}$$

Equation 1 is the standard reference method to measure voluntary activation. However, in Chapter 8, the participants were strength trained sprint cyclists and when observing the MVC force traces during the familiarisation trials, predicting when peak force would occur was inconsistent both between within session efforts and between riders. As such, if $Q_{tw.pot}$ was not administered at peak force then a different 'correction' formula was used to calculate voluntary activation, as has previously been done by Stronjnik and Komi (Strojnik & Komi, 1998):

$$AL = 100 - D * (1T/\ MVC_{MAX})/Q_{tw.pot} * 100 \text{ (Equation 2)}$$

Where MVC_{MAX} is the maximum voluntary torque produced without the twitch, D is the difference between the torque level just before the delivery of the single twitch (1T) and the maximum torque produced during the single twitch. An example trace where the 'correction' formula is used is shown in Figure 3-9.

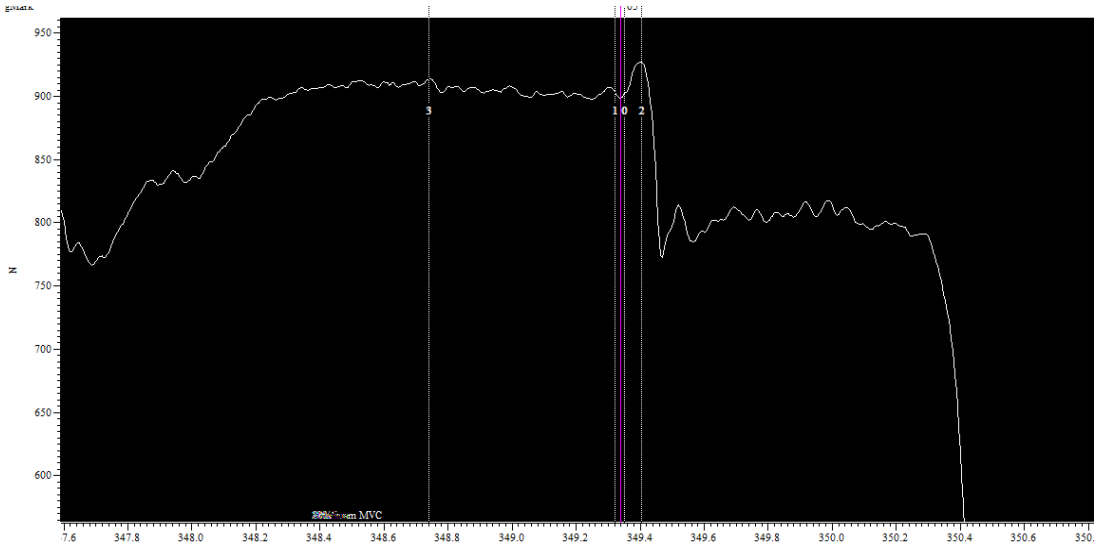

Figure 3-9: An example of force-duration trace of the knee extensor from an elite track sprinter. Peak voluntary force is attained (3) before the potentiated twitch stimulus is administered (0). The rise between (0) and (2) is the consequence of potentiated quadricep twitch. Note: force (N) is on the y-axis and time(s) is on the x-axis.

CHAPTER 4

ISOVELOCITY VS ISOINERTIAL SPRINT CYCLING TESTS FOR POWER- AND TORQUE-CADENCE RELATIONSHIPS

4.1 Introduction

Peak power output (PPO) can be defined as the highest measure of mechanical power produced measured at the cranks over a revolution during a short maximal effort (<7 s) (Seck *et al.*, 1995; Martin *et al.*, 1997; Gardner *et al.*, 2007). In sprint cycling, PPO occurs at the apex of the largely parabolic P-C relationship, where power is the product of the torque and cadence and which has been widely documented as having an inverse linear T-C relationship (Arsac *et al.*, 1996; Martin *et a* 1997; Driss *et al.*, 2002; Gardner *et al.*, 2007). Typically, PPO and the respective optimal cadence (i.e. cadence at PPO; C_{OPT}) occurs at ~50% of the extrapolated axis intercepts of maximum torque (T_{MAX}) and cadence (C_{MAX}) (Driss *et al.*, 2002; Gardner *et al.*, 2007; Driss & Vandewalle, 2013*a*). PPO and the underlying P-C and T-C relationships, specifically T_{MAX}, C_{MAX} and C_{OPT}, are widely used to monitor and understand/improve sprint cycling ability.

There are two main laboratory methods used to measure PPO and establish P-C and/or T-C relationships in sprint cycling: 1) the isoinertial method, which involves participants pedalling maximally against a constant load from a stationary or rolling start (Arsac *et al.*, 1996; Martin *et al.*, 1997). The aim is to achieve the highest cadence as quickly as possible and typically involve isoinertial resistance, provided by accelerating a flywheel, sometimes with additional frictional resistance; and 2) the isovelocity method, which involves a series of maximum efforts against a range of fixed, pre-defined cadences (Sargeant *et al.*, 1981; McDaniel *et al.*, 2014). Both methods have been used extensively to monitor sprint cycling performance as they are relatively easy to conduct and have been shown to provide valid measurements of PPO.

The isoinertial method, with its changing cadence throughout, is considered highly relevant to track sprint cycling (Martin *et al.*, 1997; Gardner *et al.*, 2007) and

can be assessed in a single effort, although familiarisation is recommended regardless of cycling experience (Martin *et al.*, 2000). In contrast, the isovelocity method typically involves a number of 3-4 s maximal sprints, each at a pre-defined cadence (Sargeant *et al.*, 1981; Baron *et al.*, 1999; McDaniel *et al.*, 2014). This method involves the collection of more data during a greater number of efforts.

Previously, isovelocity and isoinertial methods had been compared, the results demonstrating that both methods had very good levels of reliability for measuring PPO (Spearman's correlation coefficient 0.97 – 0.98) (Baron *et al.*, 1999), and that the isovelocity method measured higher PPO than the isoinertial method (using a combination of flywheel and frictional resistance) (Baron *et al.*, 1999). In previous studies that have made comprehensive assessments of T-C and P-C relationships, measurements have only been carried out on one sprint cycling test (Martin *et al.*, 1997; Gardner *et al.*, 2007; Mendez-Villanueva *et al.*, 2007; Jaafar *et al.*, 2015). In addition, there have been no studies that compare two different sprint cycling tests and assess the performance measurements in depth (i.e. PPO, T_{MAX}, C_{MAX} and C_{OPT}), along with meaningful reliability measurements (i.e. coefficient of variation), using the same ergometer with trained cyclists.

Such information would inform coaches, practitioners and clinicians whether these sprint cycling methods can be compared (i.e. used interchangeably), and are stable for inter-individual comparisons and longitudinal monitoring. Accordingly, the aim of this investigation was to compare the magnitude and reliability of PPO, T_{MAX}, C_{MAX} and C_{OPT} measured from isovelocity and isoinertial sprint cycling methods.

4.2 Methodology

4.2.1 Participants

Twenty trained male cyclists volunteered to participate (mean ± SD age, 27 ± 5 yr; stature, 183.1 ± 8.4 cm; mass, 84.1 ± 11.1 kg). All the participants were engaged in between 5-24 h of training per week, and were regularly competing in various disciplines from sprint track to road endurance cycling and at a range of competitive standards, according to British Cycling categorisation, from '3rd Category' to 'Elite Category'. With the exception of four cyclists, all had track accreditation and regularly competed in a track league. All testing was done during the track cycling season. Following approval from Northumbria University Research Ethics Committee and having undergone health screening for possible contraindications to the protocol, the participants provided written informed consent prior to the experimental procedures. The cyclists were instructed to avoid caffeine and food for 3 h prior to testing and to avoid strenuous exercise in the 36 h before each session.

4.2.2 Study Design

The cyclists attended the laboratory on four separate occasions, separated by 2-7 days, each conducted at the same time of day (± 1 h). All laboratory sessions were identical; however, the first two visits were classed as familiarisation to ensure all the cyclists were fully accustomed to the testing procedure, as had previously been suggested (Mendez-Villanueva *et al.*, 2007), and the last two were experimental (measurement) sessions.

The cyclists performed on a modified cycling ergometer as described in Chapter 3.3.2 and 3.3.3. All completed a standard 10-minute warm-up, pedalling at 100–150 W and 80–90 RPM. Subsequently, they performed, in a randomised

crossover order, both the isovelocity sprint method and isoinertial sprint method during the experimental sessions. There was at least 15 minutes of passive rest between the two sprint methods in order to get full recovery before commencing the subsequent test. Warm-up and both sprint cycling methods were performed on the same modified SRM ergometer (Schoberer Rad Messtechnik, Jülich, Germany), as described in Chapter 3.3.2.

4.2.3 Isovelocity Sprint Cycling Test

The isovelocity sprint protocol is described in more detail in Chapter 3.3.2.1. For this experiment, five maximal isovelocity cycling sprints at 60, 110, 120, 130 and 180 RPM were performed. The order of cadences was randomly assigned for every visit.

4.2.4 Isoinertial Sprint Cycling Test

The isoinertial sprint cycling testing method was identical to that described in Chapter 3.3.2.2.

4.2.5 Data Analysis

For the isovelocity method, the revolution with the highest average power output at each pre-determined cadence was used to form the P-C and T-C relationships. For the isoinertial method, the effort with the highest PPO was used for analysis, and the first five revolutions from the onset of crank movement were analysed. This ensured the same number of revolutions (data points) were used to form the P-C and T-C relationship with each method. Individual P-C relationships were fitted with a quadratic function and the values of power and cadence at the apex were defined as

PPO and C_{OPT}, respectively. Individual T-C relationships were fitted with a linear function and extrapolated in both directions to calculate axis intercepts at zero cadence (T_{MAX}) and zero torque (C_{MAX}).

Data are presented as mean ± SD or mean (90% CI). When assessing the magnitude of the performance measurements (PPO, T_{MAX}, C_{MAX} and C_{OPT}) between sprint cycling methods, data from both experimental sessions were averaged to give criterion values for each method. Subsequently, a paired t-test was used to assess whether any of the differences between the measurements between the respective methodologies (i.e. isovelocity vs isoinertial for PPO, T_{MAX}, C_{MAX} and C_{OPT}) were significant. A Pearson's product–moment correlation analysis was carried out to report the strength of the relationships. To interpret the magnitude of the relationship (r) between both sprint cycling method measurements, the following scale was used: <0.1, trivial; 0.1– 0.29, small; 0.3– 0.49, moderate; 0.5– 0.69, large; 0.7– 0.89, very large; and 0.9–1.0, almost perfect. (Hopkins *et al.*, 2009).

4.2.6 Statistical Analysis

All the performance measurements of the two sprint cycling methodologies had their between-session reliability assessed by 1) using a paired t-test to establish whether any between-session differences were significant; 2) the coefficient of variation (CV%) (which was calculated by SD/mean); 3) using a paired t-test to assess any significant differences between the CV% of respective measurements for both tests; 4) calculating the intraclass correlation coefficient (ICC); 5) Standard Error of Estimate (SEE) was used to interpret the strength of the relationships of respective measures between tests. Previously, a CV of ≤ 5.0% was considered good between-

session reliability for performance tests (Buchheit *et al.*, 2011), and significance was set at $p < 0.05$.

4.3 Results

The two methods produced significant differences in the P-C and T-C relationships, as indicated by all four metrics of these relationships (Figure 4-1 and Table 4-1). PPO was higher (45 W, 3.8%) with the isoinertial method than the isovelocity method (1242 ± 196 W vs. 1197 ± 203 W; $p < 0.001$). The isovelocity method produced higher C_{OPT} (124 ± 11 RPM vs. 117 ± 11 RPM; $p < 0.001$) and C_{MAX} (248 ± 22 RPM vs. 236 ± 19 RPM; $p = 0.002$); however, a lower T_{MAX} (173 ± 26 N.m. vs. 198 ± 34N.m; $p < 0.001$) was recorded. Despite these differences in the outcome measurements from the two methods, near perfect (PPO $r = 0.97$; T_{MAX} $r = 0.94$) or very large relationships (C_{OPT} $r = 0.85$; C_{MAX} $r = 0.74$) were seen between the two methods (Figure 4-2 and Table 4-1).

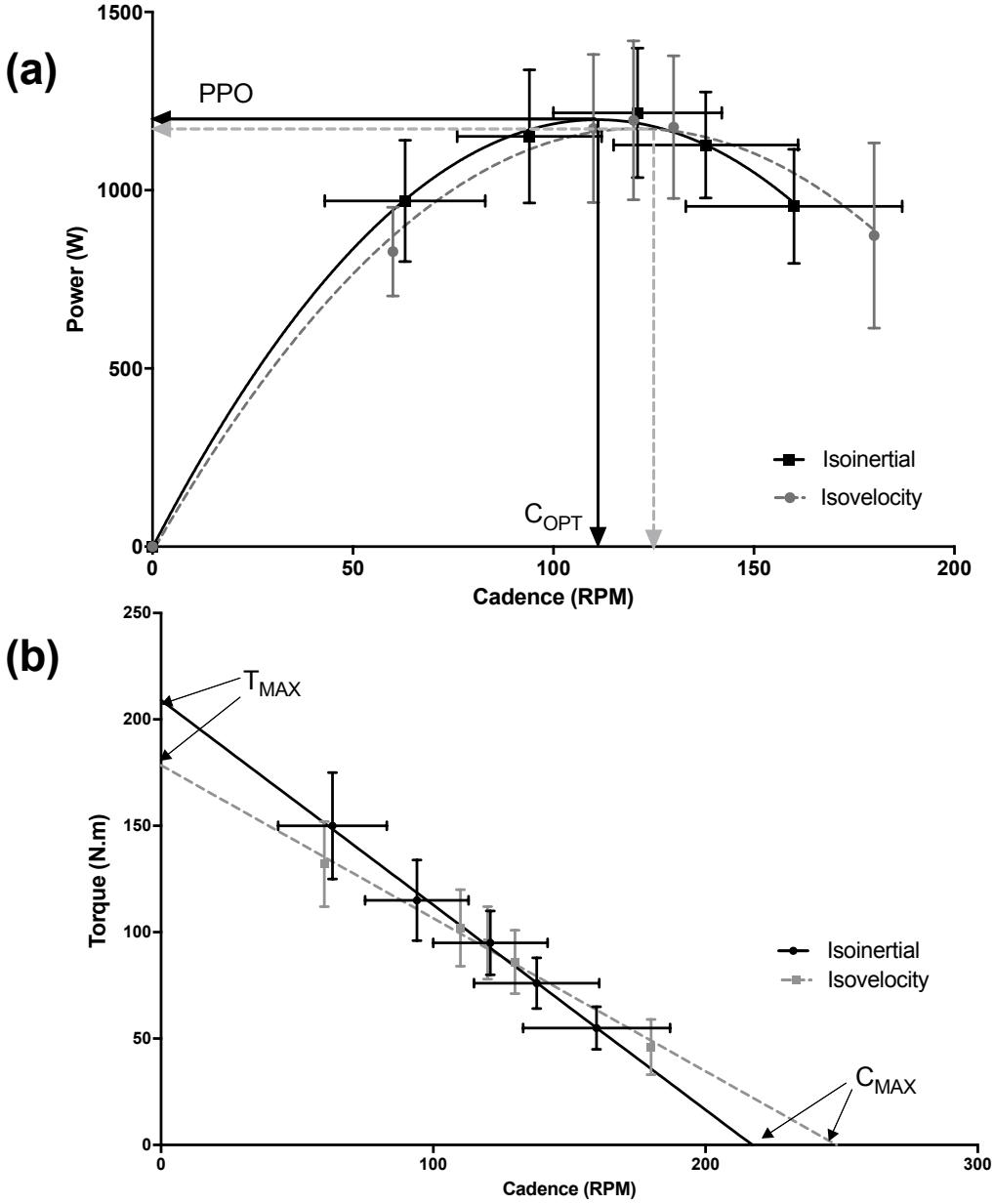

Figure 4-1: (a) Power-cadence relationship of both isoinertial and isovelocity sprint cycling methods. The apex of the parabolic relationship represents peak power output (PPO) and cadence at PPO represents optimal cadence (C_{OPT}); (b) Torque-cadence relationship of isoinertial and isovelocity sprint cycling tests. The linear relationships have been extrapolated to the axis intercepts in order to calculate maximal torque (T_{MAX}) and cadence (C_{MAX}). Data are presented as mean ± SD (n=20)

All measurements for the two sprint cycling methods were consistent and similar (i.e. unchanged) between the first and second experimental sessions (Table 4-2). All measurements for both tests were categorised as having good levels of between-session reliability (i.e. CV ≤ 5.0%); there were no differences in reliability (CV%) between the two methods and the ICC was measured at or above 0.75 for all measurements of both methods. The results are detailed in Table 4-2.

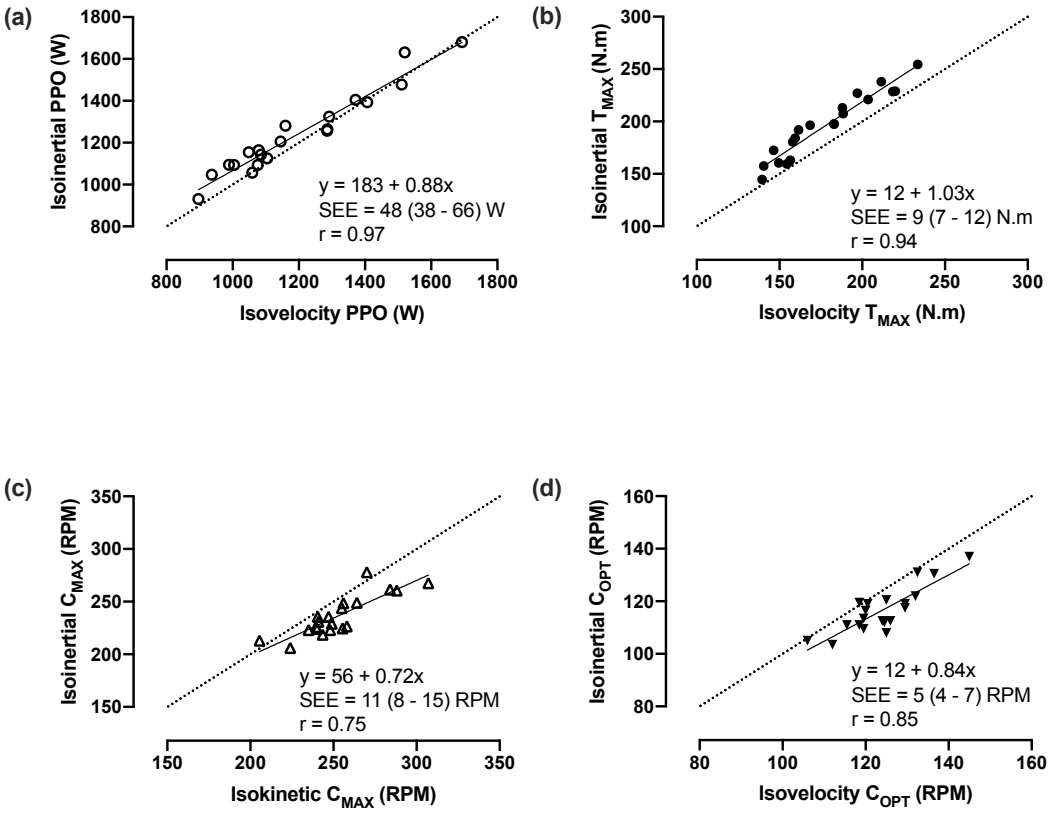

Figure 4-2: Relationships of (a) peak power output (PPO); (b) Maximal Torque (T_{MAX}); (c) Maximal cadence (C_{MAX}); (d) Optimal cadence (C_{OPT}) from isoinertial and isovelocity sprint cycling tests (n = 20). All figures are presented with equations for the linear relationships, Standard error of estimate (SEE) (with 90% confidence intervals, Pearson's correlation coefficient (r) *and have a line of identity which is represented by the dotted line.*

*Table 4-1: Magnitude of isovelocity and isoinertial sprint cycling methods for the measurements of peak power output (PPO), optimal cadence (COPT), maximal torque (TMAX) and maximal cadence (CMAX). Overall mean difference (Diff.); Pearson correlation coefficient (r) and respective r rating; * denotes significant difference to other respective sprint cycling method.*

	Isovelocity	Isoinertial	p-value	Diff.	r	r Rating
PPO (W)	1197 ± 203*	1242 ± 196*	<0.001	45	0.97	Almost perfect
C_{OPT} (RPM)	124 ± 11*	117 ± 11*	<0.001	7	0.85	Very Large
T_{MAX} (N.m)	177 ± 28*	198 ± 34*	<0.001	25	0.94	Almost Perfect
C_{MAX} (RPM)	248 ± 19*	236 ± 26*	0.002	12	0.75	Very Large

Table 4-2: Between session reliability from experimental lab visit 1 (Exp 1) and lab visit 2 (Exp 2) (n = 20) of isoinertial and isovelocity peak power output (PPO), maximal torque (T_{MAX}), maximal cadence (C_{MAX}), optimal cadence (C_{OPT}); p-value which evaluates whether there are any significant differences between Exp 1 and Exp 2 with respective measurements; Coefficient of variation (CV); p-value of CV that assesses any significant difference between the CV of a measurement between respective methods; intraclass correlation (ICC).

		Exp 1	Exp 2	Between Session p =	Between Session CV, %	Between Methods CV% p =	Between Session ICC (90% CI)
PPO (W)							
	Isoinertial	1237 ± 86	1248 ± 86	0.442	2.9	0.601	0.98 (0.96 - 0.99)
	Isovelocity	1203 ± 87	1192 ± 98	0.466	2.7		0.96 (0.92 - 0.98)
C_{OPT} (RPM)							
	Isoinertial	117 ± 9	116 ± 9	0.358	3.5	0.283	0.80 (0.61 - 0.90)
	Isovelocity	125 ± 10	123 ± 9	0.157	2.7		0.73 (0.50 - 0.87)
T_{MAX} (N.m)							
	Isoinertial	197 ± 33	198 ± 34	0.764	4.4	0.499	0.87 (0.73 - 0.94)
	Isovelocity	178 ± 31	177 ± 28	0.604	3.6		0.94 (0.87 - 0.97)
C_{MAX} (RPM)							
	Isoinertial	238 ± 22	235 ± 19	0.381	3.1	0.377	0.83 (0.66 - 0.92)
	Isovelocity	253 ± 24	252 ± 27	0.782	4.0		0.83 (0.67 - 0.92)

4.4 Discussion

Both the P-C and T-C relationships measurements were different between the two methods of assessing sprint cycling performance, and thus these methods cannot be used interchangeably. The isoinertial method produced a more vertically orientated T-C relationship with a higher T_{MAX} and lower C_{MAX}, and consequently a P-C relationship further to the left that had a lower C_{OPT} and also a higher PPO, in comparison to the isovelocity method. Nonetheless, there were very large to near perfect relationships between the measurements taken during both methods (r = 0.75 - 0.97). The data in this study also showed high levels of between-session reliability (i.e. CV ≤ 5.0% and ICC ≥ 0.75) when measuring PPO, C_{OPT}, T_{MAX} and C_{MAX} with both methods.

The isoinertial method showed significantly higher PPO (~45W). In addition, the isoinertial method showed higher T_{MAX} and lower C_{MAX} in comparison to the isovelocity method. The C_{OPT} was also achieved at different cadences depending on the method, being higher for isovelocity than isoinertial (124 vs. 117 RPM), although C_{OPT} with both methods was in the range of previously reported values (between 110 - 130 RPM) (Beelen & Sargeant, 1991). The observation that every measure (i.e. PPO, T_{MAX}, C_{OPT} and C_{MAX}) was different between the methods of assessing sprint cycling strongly suggests that these methods cannot be used interchangeably to ascertain changes in the P-C and T-C relationships.

Our finding of higher PPO and T_{MAX} using the isoinertial method and higher C_{MAX} and C_{OPT} with the isovelocity method was largely in contrast to a previous study that reported PPO and C_{OPT} to be higher with the isoinertial method with no differences in T_{MAX} and C_{MAX} (Baron *et al.*, 1999). The major differences between the experiments were two-fold. Firstly, the acceleration method (i.e. flywheel plus friction) was used

instead of the isoinertial sprint test. Secondly, the participants had no previous experience of cycling. Therefore, the discrepancy between this study and that of Baron and colleagues may be linked to one or both of those factors. (Baron *et al.*, 1999)

The lower isoinertial C_{OPT} and C_{MAX} may potentially be attributed to potential fatigue accumulated throughout the isoinertial effort. It has been suggested that fatigue in maximal cycling is revolution dependent rather than time dependent, and power output can reduce at a rate of 0.5% per revolution (Tomas *et al.*, 2010). The P-C relationship of the isoinertial method was established in 5 revolutions, hence the power output could be reduced by 2.0 -2.5% by the fifth revolution. In comparison, the addition of the motor during isovelocity assessment allowed participants to pedal with no resistance until they had achieved the pre-required cadence, meaning that the isovelocity efforts are relatively fatigue-free due to the minimal effort involved in accelerating to the required cadence and analysis of the single highest revolution at each velocity/sprint. Collectively, this could contribute to the higher isovelocity C_{OPT} and C_{MAX} compared to the isoinertial method, and thereby provide a better indication of the actual C_{OPT} and C_{MAX}. Additionally, the methodology of calculating power output can be attributed to the difference in P-C and T-C relationships between PPO methods. Torque and cadence in cycling are calculated by multiplying mean torque and cadence per revolution (Martin *et al.*, 1997). Isoinertial cycling, unlike isovelocity cycling, is not performed under fixed cadences and the change in cadence/acceleration of the flywheel throughout the effort is neither constant nor linear. Therefore, cadence, when measured by averaging over a revolution, reads higher in an isoinertial effort compared to isovelocity efforts and, we suggest, over-estimates the actual physiological PPO, but underestimates C_{MAX} and, therefore, C_{OPT}. Isovelocity cycling minimises the effect of potential fatigue and eradicates variable changes in cadence. If

these explanations are correct, it suggests that isovelocity cycling is a better method of establishing a fatigue-free physiological measure of P-C and T-C relationships in sprint cycling.

Between-session reliability of the measurements from both sprint cycling methods was classed as good (≤ 5.0%), and there were no differences in CV between the two methods. These levels of good reliability are consistent with other studies where they have had a similar number of familiarisation sessions when assessing PPO using similar sprint cycling methods (Martin *et al.*, 1997; Baron *et al.*, 1999; Mendez-Villanueva *et al.*, 2007). Previous studies that have reported reliability have mainly focused on reporting PPO (Martin *et al.*, 1997, 2000; Mendez-Villanueva *et al.*, 2007) and in one case, C_{OPT} has been reported (Martin *et al.*, 2000). None has specifically focused on the reliability of T_{MAX} and C_{MAX}. Martin and colleagues suggested that irrespective of experience in cycling, familiarisation with the task is recommended to produce reliable PPO (Martin *et al.*, 2000). Yet, they also suggested that irrespective of their cycling experience, no significant differences were measured in C_{OPT} between sessions or efforts. Due to the good reliability of both methods of assessing sprint cycling in the current study, either method could be effective for monitoring cycling performance (PPO) and the underlying P-C and T-C relationships (T_{MAX}, C_{MAX} and C_{OPT}).

The isoinertial load of the flywheel (4.6 kg) and gear ratio (3.5:1) used in this experiment were somewhat lower than those that have previously been used (up to 8.4 kg and 7.4:1) (Seck *et al.*, 1995; Gardner *et al.*, 2007), making the inertial load of the isoinertial method considerably lower than in previous experiments. Based on our pilot work, the flywheel load and gear ratio used in this experiment were selected to produce a similar number of full revolutions (i.e. 5) during the isoinertial sprints as those

prescribed for the isovelocity sprints. In addition, the recruitment of the participants was thought to be a homogenous sample. However, a broad range of P-C and T-C measures were recorded where the range differed over two-fold for some measures (e.g. PPO). As such, the results should be used with caution as a broad range could have exaggerated the relationship when comparing sprint tests.

4.5 Conclusion

Both isoinertial and isovelocity sprint cycling tests presented good reliability when measuring PPO, P-C and T-C relationships but when monitoring and comparing any measurement, the tests should not be used interchangeably. The results from this Chapter suggest that the between-session reliability of performance measurements, of both isovelocity or isoinertial sprint cycling tests, are suitable for use in the remainder of this thesis as long as one is consistently used when comparing data. As both exhibit similar reliability, the next chapter will assess which sprint test (if any) is more suited for use with surface EMG during PPO and if isometric reference tasks can improve the between-session reliability.

CHAPTER 5

RELIABILITY OF TRADITIONAL AND TASK SPECIFIC REFERENCE TASKS TO ASSESS PEAK MUSCLE ACTIVATION DURING TWO DIFFERENT SPRINT CYCLING TESTS

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5.1 Introduction

Sprint cycling lab tests typically are short in duration (< 7 s) and maximal in effort in order to measure peak mechanical power output (PPO) (Dorel *et al.*, 2005; Martin *et al.*, 2007) and associated biomechanical and physiological aspects of performance. Two lab tests are commonly used to measure PPO in sprint cycling. Firstly, isoinertial accelerations, where the participant pedals maximally against a constant inertial load for 5 – 7 s from a stationary start with the aim of accelerating the pedals to the highest cadence as quickly as possible (Martin *et al.*, 1997). Secondly, the isovelocity method, which involves maximal sprinting at a constant, pre-determined cadence for 3 – 4 s (Sargeant *et al.*, 1981; Baron *et al.*, 1999).

Neuromuscular activation is considered an important determinant of PPO and, consequently, sprint cycling performance (Driss & Vandewalle, 2013). However, there has been little research undertaken to understand the degree to which muscle activation, which can be assessed with EMG measurements, influences PPO, or how neuromuscular activation changes with training. Before addressing these questions, it is important to establish if there are any differences in EMG amplitude between sprint cycling tests (isoinertial vs. isovelocity), the reliability of EMG amplitude measurements during sprint cycling tests, and whether the reliability of EMG measurements during sprint cycling tests can be improved by normalisation to an independent reference task. This will inform the interpretation and meaningfulness of any potential differences between athletes and/or changes in EMG/muscle activation with training.

The normalisation of EMG during a performance task, in this case sprint cycling, to EMG during separate reference tasks, typically a series of isometric maximum voluntary contractions (MVCs) with each muscle group, is a widely

recommended approach. The purpose of normalisation is to reduce the influence of variable signal recording conditions of between-participants and -days, thereby improving reliability and reducing between-subject and between-session variability (Vera-Garcia *et al.*, 2010; Burden, 2010; Farina *et al.*, 2014). However, isometric MVCs with each of the muscle groups of both legs involved in cycling (potentially flexors and extensors of the hip, knee and ankle joints of each leg, thus 12 distinct isometric strength tests) is a laborious and time-consuming protocol. It also relies on additional equipment (e.g. an isokinetic dynamometer). These single joint/muscle group MVCs also lack task specificity as they are typically performed at different joint angles and involve activation of single muscle groups, when compared to cycling. A novel reference task of isometric cycling involves measuring all the cycling muscle groups simultaneously in each contraction (extensors of the front leg and flexors of the rear leg). This is more specific to cycling, whilst also being a much more time efficient reference task (2 isometric strength tests, with each leg in front and rear positions). However, this idea has yet to be compared to traditional dynamometry in terms of whether it produces equivalent EMG amplitude values and reliability.

Accordingly, the aims of the experiment were: 1) to compare the magnitude and between-session reliability of peak muscle activation, assessed with EMG amplitude during two different sprint cycling tests (isovelocity and isoinertial); 2) to compare the magnitude and between-session reliability of EMG amplitude during two different reference tasks (isometric single joint vs isometric cycling MVCs) in order to; 3) establish if normalisation of EMG amplitude during sprint cycling to reference tasks improves measurement reliability.

5.2 Methodology

5.2.1 Participants

Twelve trained male cyclists initially volunteered to take part in this study. However, only participants with complete performance and EMG data sets were analysed (i.e. EMG data collection for all muscle groups, for both limbs, for all reference tasks and performance tasks over both sessions). Eight participants were excluded as more than two groups of electrodes had completely detached from the skin during both experimental visits. As such, the data of twelve cyclists are presented (mean ± SD age, 27 ± 5 yr; stature, 182.9 ± 8.2 cm; mass, 84.0 ± 10.9 kg). The cyclists were predominantly competing in regional or national level track and road race competitions and all had been competitively racing for over three years. Following approval from Northumbria University Research Ethics Committee, the participants provided written, informed consent prior to the experimental procedures. The cyclists were instructed to avoid caffeine and food for 3 h prior to testing and to avoid strenuous exercise in the 36 h before each session.

5.2.2 Protocol Overview

The participants attended the laboratory on four separate occasions; the first two visits were for familiarisation, followed by experimental session 1 (Exp 1) and experimental session 2 (Exp 2), each separated by 2-7 days, and conducted at the same time of day (± 1 h). Familiarisation and experimental sessions were identical apart from the recording of EMG during the experimental visits. Experimental sessions started with the placement of the EMG electrodes followed by the measurement of unilateral isometric single joint (ISO-SINGJT) maximal voluntary contractions

(MVCs) of four different muscle groups - the plantar flexors, hip extensors, knee extensors and knee flexors of each leg - using an isometric dynamometer (Biodex, System 4 Pro, New York, USA). For each muscle group, the right leg was always assessed first and then the left leg, before moving on to the next muscle group. Following a passive rest period of 20 minutes, the participants then performed three MVCs of the isometric cycling task (ISO-CYC) with each leg as the front leg. Subsequently, the participants had a passive rest period of 10 minutes and then completed a standard 10-minute warm-up on a modified cycle ergometer (Schoberer Rad Messtechnik, Jülich, Germany) (100–150 W, 80–90 revolutions per minute [RPM]). They then performed, in a randomised crossover order, isovelocity and isoinertial sprints. The isovelocity sprint involved a maximal effort of 120 RPM (with the ergometer in 'isovelocity mode') and the isoinertial sprints involved two maximal sprints accelerating from a stationary start with only the flywheel inertia as resistance.

5.2.3 Surface Electromyography

Neuromuscular activation during all exercise tasks was measured using a wireless surface EMG system (Delsys Trigno® Wireless EMG systems, Boston, MA, USA). EMG electrodes were placed each leg over the GM, RF, VL, VM, BF and GL as described in section 3.3.8.

5.2.4 EMG Reference Task: Isometric Single Joint Dynamometry

Single-joint unilateral isometric (ISO-SINGJT) MVCs were performed using a calibrated dynamometer (Biodex, System 4 Pro, New York, USA) as described in Chapter 3.3.4.1. With each muscle group of each leg, the participants completed three warm-up contractions of progressive intensity before performing three MVCs, lasting

3-5 s each, separated by 60 s rest, with a further 5 minutes rest between muscle groups/legs. Prior to performing the MVCs, the participants were reminded to perform the MVC "as hard as possible". Real-time bio-feedback, a torque-time trace displayed in front of the participant and verbal encouragement were given throughout the MVCs. The real-time analogue torque signal was recorded by the same data acquisition system as for the EMG recordings in order to synchronise the mechanical and electrical data.

5.2.5 EMG Reference Task: Multiple Joint Isometric Cycling Task

Participants performed the multiple-joint isometric cycling task (ISO-CYC) as described in chapter 3.3.4.3. The ergometer was adjusted to match the riders habitual cycling position. Once the cyclists mounted the ergometer and attached their shoes using their clipless pedals, their forearms were positioned on the crossbar of the handlebars. The cranks were always first orientated with the right crank forward at 90° clockwise/at the 3 o'clock position from top dead centre (TDC), and thus the left crank at 270° clockwise from TDC. Once in position, the participants were instructed to try to 'pedal forwards as hard as possible with both legs whilst remaining in the saddle' (i.e., the front leg pushing down and the rear leg pulling up, simultaneously; Figure 3-5). After three progressive warm-up contractions, the participants performed 3 MVCs, each lasting 3 s, that were separated by 60 s of rest. After 5 minutes of passive rest, the crank positions were reversed, with the left crank positioned forward at 90° from TDC.

5.2.6 Sprint Cycling Methods

Both sprint cycling methods were performed on the same modified SRM cycle ergometer as described in chapter 3.3.2 (and 4.2.3 as well as 4.2.4). In addition, the same torque, cadence and power measurements were collected using the equipment detailed in chapter 3.3.3. The participants wore their own cycling shoes and pedals

(fitted to the ergometer), and were instructed to perform each recorded effort in the saddle whilst using the 'drop' handlebars.

5.2.6.1 Isovelocity Sprints

The protocol was identical to that described in more detail in section 3.3.2.1. For this experiment, maximal isovelocity cycling was performed at a constant cadence of 120 RPM. This cadence was chosen as this the cadence where PPO is typically achieved. (Dorel *et al.*, 2010; Elmer *et al.*, 2011).

5.2.6.2 Isoinertial Sprints

The isoinertial sprint protocol was identical to that which was previously described in chapter 3.3.2.2. However, the sprint with the highest mechanical power output over a revolution (PPO) was used for analysis.

5.2.7 Data Analysis

For both sprint tests, PPO was identified as the highest mechanical power output averaged over a complete revolution (from TDC to TDC) for each test, and subsequently used for EMG analysis (see Figure 5-1 as an example of an isoinertial sprint test torque trace and an EMG channel). PPO and cadence at PPO (for the isoinertial sprint test [cadence at PPO for the isovelocity sprint test was held at 120 RPM]) were recorded.

For the ISO-CYC reference tasks, the efforts with the highest peak instantaneous cumulative (i.e. sum of right and left crank) mechanical torque output (for each side) was used for EMG analysis and for the ISO-SINGJT reference task; the

effort with the highest peak torque for each muscle group during the respective efforts was used for EMG analysis.

The isometric reference tasks had EMG signals processed as root-mean-square EMG amplitudes (rmsEMG) with an epoch duration of 200 ms, and the peak rmsEMG value was used. It has been suggested that when assessing isometric MVCs, time intervals shorter than 200 ms significantly reduces reliability (Buckthorpe *et al.*, 2012; Del Vecchio *et al.*, 2018).

For the sprint cycling tests, peak rmsEMG was assessed as the highest rmsEMG during a 90º sector of crank displacement (i.e. ¼ of a revolution) during the revolution where PPO was achieved (measure from TDC to TDC) (Figure 5-1). Therefore, isovelocity sprints which were at a constant 120 RPM used a 125 ms epoch (as that is the time window equivalent to a 90º sector). For the isoinertial sprints, the revolution (measure from TDC to TDC) where mechanical PPO was achieved was used for analysis. The cadence was initially calculated by dividing 60 by the time taken from TDC to TDC. Then the time window equivalent to a 90º sector was used for rmsEMG analysis. This ensured that all EMG measurements during both tests were assessed over a consistent range of motion despite different velocities. Normalising the reference tasks (i.e. ISO-SINGJT or ISO-CYC) to the performance tasks was done by dividing the peak rmsEMG value of the performance task (of specific muscle) by the peak rmsEMG value from the reference task (of said muscle). The resultant fraction was then expressed as a percentage.

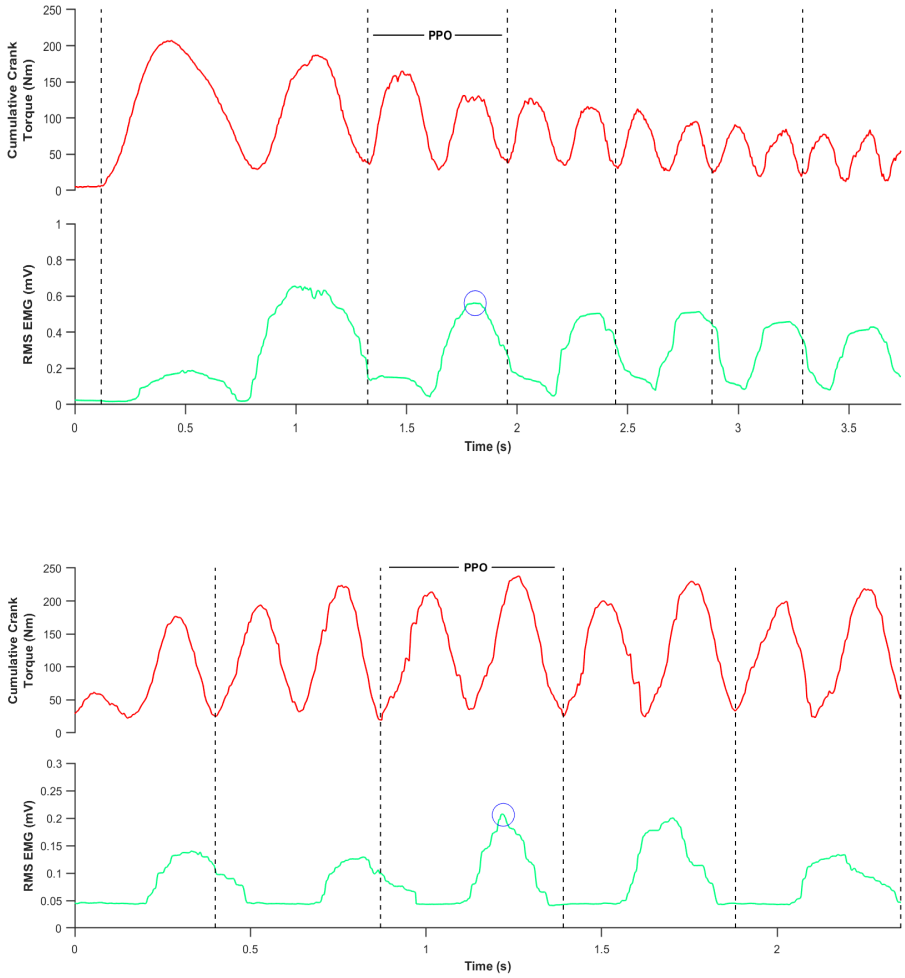


Figure 5-1: An example of a cyclists torque trace of the isoinertial sprint cycling test (above) and isovelocity sprint cycling test (below) with the respective rmsEMG trace of the right vastus lateralis. The dotted vertical lines represent each full revolution and time taken to complete each revolution was calculated (i.e. cadence [RPM]). Power (Watts) is expressed over a revolution and calculated as the product of average torque over each full revolution and cadence. The revolution where peak power output (PPO) was achieved was analysed and peak rmsEMG was measured, over the highest 90°sector, from six muscles of each leg.

5.2.8 Statistical Analysis

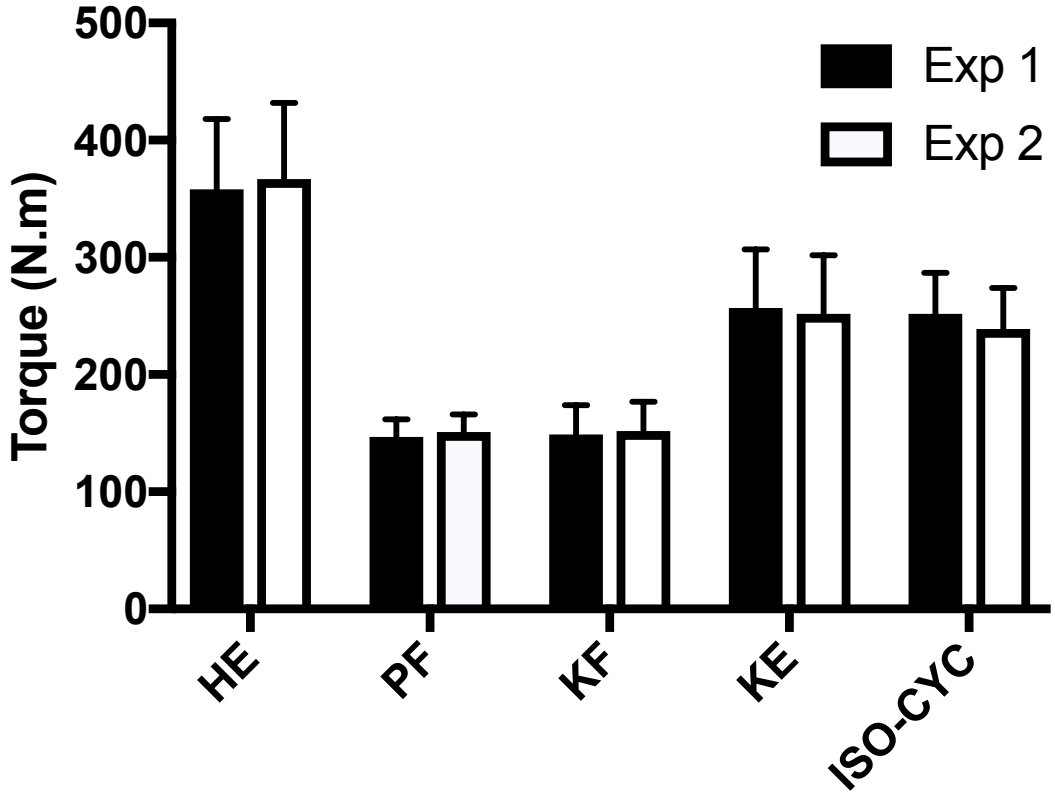
Data were presented as mean (± SD). Paired t-tests were used to ascertain whether between-session differences were significant for the following functional/performance measurements: PPO from both isovelocity and isoinertial sprint tests, cadence at PPO for the isoinertial test, peak torque for each muscle group for ISO-SINGJT and peak torque for ISO-CYC. Between-session reliability was measured by calculating the coefficient of variation (CV) (which was calculated by standard deviation/average) for all the aforementioned measurements. The CV of PPO

was also compared between methods, as well between both experimental sessions using a paired t-test. A one-sample t-test was used to measure any difference between cadence at PPO from the isoinertial test and the cadence from the isovelocity test (i.e. 120 RPM). Magnitude of peak rmsEMG when produced during both reference tasks, as well as when normalised to both sprint tests, was carried out by 1) paired t-test 2) Pearson correlation coefficient I with ratings as follows: <0.1 trivial, 0.1 – 0.29 small, 0.3 – 0.49 moderate, 0.5 – 0.69 large, 0.7 – 0.89 very large, 0.9 – 1.0 almost perfect. Between-session reliability when involving absolute peak rmsEMG values were carried out by 1) a paired t-test to assess any significant differences between-sessions 2) calculating the intra-class correlation coefficient (3,1) (ICC) 3) CV. Due to the naturally higher variability of EMG, CV was described by modifying the categories used in previous research. In this case, the categories are as follows: "good" (<10%), "acceptable" (10.0 – 19.9%), "weak" (20.0 – 29.9%) and "very weak" (≥ 30.0%). The level of significance was set at $P \leq 0.05$.

5.3 Results

Functional (performance) outcome measurements, specifically PPO during both sprint cycling tests and peak torque values during ISO-SINGJT and ISO-CYC tasks, revealed no significant differences between-sessions (Figure 5-2 & 5-3). The isoinertial sprint test produced higher PPO (Figure 5-3; +5.8%; $p = 0.0151$), but the reliability of PPO measured with both tests was similar (between-session CV for isovelocity and isoinertial was 2.0 vs 3.0 %, respectively; $p = 0.1554$). For the isoinertial sprint cycling test, cadence at PPO was 122 ±10 RPM (CV of 2.4%) and thus similar to the optimum cadence for PPO during the isovelocity sprints (120 RPM; $p = 0.575$). ISO-SINGJT peak torque had between-session CV values of 3.9% (knee

extensors), 7.1% (knee flexors), 8.1% (hip extensors) and 8.2% (plantar flexors), whilst ISO-CYC peak cumulative torque had a between-session CV of 5.8%.



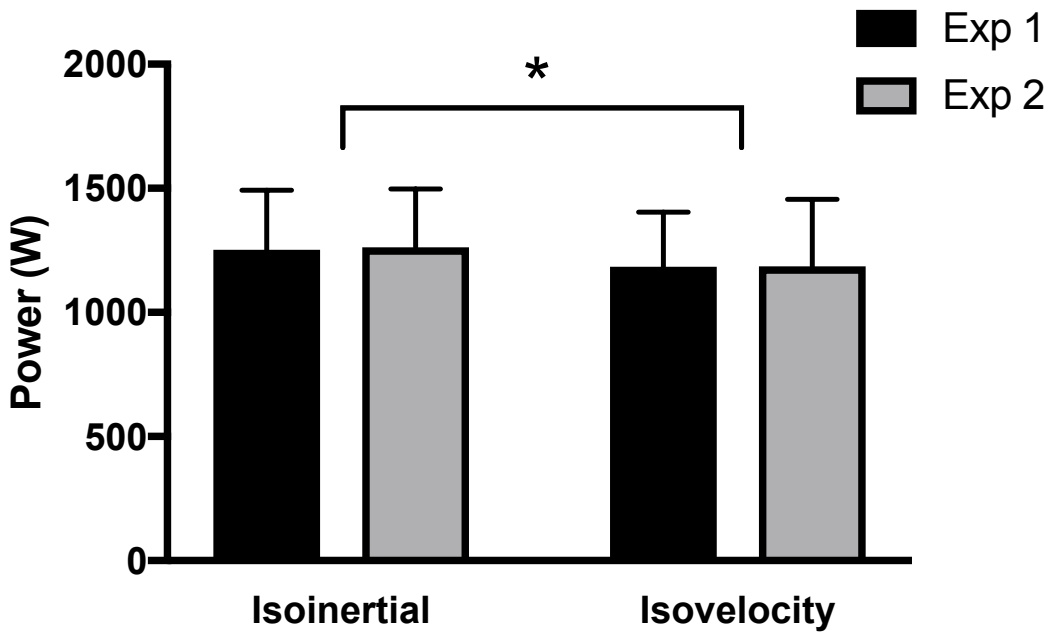


*Figure 5-3: Comparison of between session reliability of peak power output during isoinertial and isovelocity sprint tests. No significant differences were observed for both isovelocity (1184 ± 220 W vs. 1185 ± 270 W; p = 0.8826) and isoinertial (1253 ± 240 W vs. 1262 ± 236 W; p = 0.2399). When the peak power output was compared between sprint tests the difference reached significance (p = 0.0151); * denotes significant difference between isovelocity and isoinertial.*

No significant differences in peak rmsEMG were seen for respective muscle groups at PPO between both sprint tests. The reliability and between-session CV values of absolute peak rmsEMG during the isovelocity and isoinertial sprint tests were similar for five muscle groups (GL, BF, VL, VM and RF), but the GM peak rmsEMG during the isoinertial sprints was less reliable than in the isovelocity sprints (9.0 vs 22.5%; p = 0.007; Table 5-1).

Peak rmsEMG for ISO-CYC was significantly lower than ISO-SINGJT for 3 out of 6 muscle groups (GL -20% p = 0.0068; BF -34% p = 0.0002; RF -28% p = 0.0154), with similar values for GM (37% p = 0.2431), VM (-4% p = 0.04615) and VL (-18% p = 0.0712; Table 5-2). There were moderate to very large relationships between peak rmsEMG assessed with the two reference tasks. With the exception of GM during ISO-SINGJT, no significant differences of peak rmsEMG were seen for either reference tasks between experimental sessions. All muscle groups for both reference tasks

showed acceptable levels of between-session reliability (i.e. CV between 10 – 20%) with the exception of BF during ISO-SINGJT and RF during ISO-CYC, which both exhibited weak (high) CV values. There were no differences in the reliability (CV) of peak rmsEMG for any of the six muscle groups in the isovelocity and isoinertial sprint tests (Table 5-1 & 5-3).

*Table 5-1: Absolute peak rmsEMG values (mV) during experimental sessions 1 (Exp 1) and 2 (Exp 2) of gluteus maximum (GM), gastrocnemius (GL), long head bicep femoris (BF), vastus lateralis (VL), vastus medalis (VM) and rectus femoris (RF) at PPO during isovelocity and isoinertial sprint cycling tests. Paired t-tests were used to identify significant differences between Exp 1 and Exp 2 (Between Session), between isovelocity vs. isoinertial sprint methods for each muscle group, and between session CV (%). Respective CV rating, as well as between-session ICC, are also presented significance p < 0.05; * denotes significant difference between isovelocity and isoinertial*

	Exp 1	**Exp 2**	**Between-Session**	**Between-Session**	**CV Rating**	**Between-Session**	**Average**	**Isovelocity vs Isoinertial**	
	mV	**mV**	**p =**	**CV, %**		**ICC**	**mV**	**Average p =**	**CV p =**
GM									
Isovelocity	0.222 ± 0.169	0.221 ± 0.164	0.940	9.0*	Good	0.98	0.222 ± 0.166	0.656	0.0068
Isoinertial	0.240 ± 0.252	0.221 ± 0.170	0.494	22.5*	Weak	0.92	0.231 ± 0.210		
GL									
Isovelocity	0.291 ± 0.085	0.264 ± 0.089	0.148	13.6	Acceptable	0.80	0.277 ± 0.087	0.839	0.687
Isoinertial	0.294 ± 0.122	0.255 ± 0.088	0.067	15.1	Acceptable	0.84	0.274 ± 0.105		
BF									
Isovelocity	0.162 ± 0.068	0.158 ± 0.074	0.475	6.9	Good	0.97	0.160 ± 0.071	0.587	0.180
Isoinertial	0.162 ± 0.076	0.168 ± 0.067	0.441	11.4	Acceptable	0.94	0.165 ± 0.071		
VL									
Isovelocity	0.436 ± 0.122	0.414 ± 0.127	0.484	15.1	Acceptable	0.67	0.425 ± 0.124	0.718	0.112
Isoinertial	0.397 ± 0.172	0.438 ±0.151	0.245	21.3	Weak	0.78	0.417 ± 0.161		
VM									
Isovelocity	0.641 ± 0.246	0.555 ± 0.199	0.913	21.7	Weak	0.38	0.598 ± 0.223	0.700	0.724
Isoinertial	0.581 ± 0.226	0.438 ± 0.151	0.913	19.0	Acceptable	0.62	0.584 ± 0.213		
RF									
Isovelocity	0.185 ± 0.076	0.199 ± 0.074	0.428	15.0	Acceptable	0.86	0.192 ± 0.075	0.236	0.462
Isoinertial	0.220 ± 0.144	0.200 ± 0.082	0.438	19.3	Acceptable	0.77	0.210 ± 0.113		

*Table 5-2: Absolute peak rmsEMG values (mV) during experimental sessions 1 (Exp 1) and 2 (Exp 2) of gluteus maximum (GM), gastrocnemius (GL), long head bicep femoris (BF), vastus lateralis (VL), vastus medalis (VM) and rectus femoris (RF) during both isometric reference tasks: single-joint dynamometry (ISO-SINGJT) and isometric-cycling (ISO-CYC). Paired t-tests were used to identify significant differences between Exp 1 and Exp 2 (Between-Session), between methods (ISO-SINGJT vs. ISO-CYC for each muscle group) and between session CV (%). Respective CV rating, as well as between-session ICC, are also presented. The relationship I and relationship rating between the two methods is also given; * denotes significant difference between peak rmsEMG between reference tasks; # denotes significant difference of muscle group between experimental session of the same reference task.*

	Exp 1	**Exp 2**	**Between-Session**	**Between-Session**	**CV Rating**	**Between-Session**	**Average**	**ISO-SINGJT vs ISO-CYC**		**Relationship**	**Rating**
	mV	**mV**	**P=**	**CV, %**		**ICC**	**mV**	**Average p =**	**CV p =**	**r**	
GM											
ISO-SINGJT	0.160 ± 0.076	0.199 ± 0.094	0.0410#	15.5	Acceptable	0.92	0.174 ± 0.083	0.2431	0.4851	0.81	Very Large
ISO-CYC	0.265 ± 0.252	0.212 ± 0.108	0.2574	15.5	Acceptable	0.72	0.239 ± 0.078				
GL											
ISO-SINGJT	0.304 ± 0.082	0.295 ± 0.054	0.6956	15.4	Acceptable	0.46	0.299 ± 0.059*	0.0068	0.8747	0.60	Large
ISO-CYC	0.254 ± 0.101	0.226 ± 0.061	0.2135	14.5	Acceptable	0.66	0.240 ± 0.075*				
BF											
ISO-SINGJT	0.233 ± 0.073	0.218 ± 0.056	0.2929	20.8	Weak	0.77	0.225 ± 0.061*	0.0002	0.0570	0.73	Very Large
ISO-CYC	0.145 ± 0.070	0.153 ± 0.070	0.5444	10.7	Acceptable	0.86	0.149 ± 0.067*				
VL											
ISO-SINGJT	0.430 ± 0.201	0.442 ± 0.110	0.7985	15.8	Acceptable	0.50	0.436 ± 0.138	0.0712	0.5562	0.38	Moderate
ISO-CYC	0.378 ± 0.134	0.335 ± 102	0.2180	15.8	Acceptable	0.60	0.356 ± 0.105				
VM											
ISO-SINGJT	0.637 ± 0.213	0.607 ± 0.169	0.6486	11.4	Acceptable	0.33	0.622 ± 0.155	0.4615	0.2099	0.78	Very Large
ISO-CYC	0.619 ± 0.249	0.574 ± 0.157	0.4401	18.6	Acceptable	0.61	0.597 ± 0.184				
RF											
ISO-SINGJT	0.271 ± 0.113	0.272 ± 0.117	0.9628	15.2	Acceptable	0.92	0.272 ± 0.117*	0.0154	0.3778	0.60	Large
ISO-CYC	0.207 ± 0.101	0.185 ± 0.080	0.2009	23.4	Weak	0.85	0.196 ± 0.087*				

Table 5-3: Reliability of normalised EMG against the two reference tasks (isometric single-joint dynamometer [ISO-SINGJT] and isometric cycling [ISO-CYC]) for the gluteus maximum (GM), gastrocnemius (GL), long head bicep femoris (BF), vastus lateralis (VL), vastus medalis (VM) and rectus femoris (RF) between experimental session 1 (Exp 1) and 2 (Exp 2). P-value of paired t-test, intraclass correlation (ICC), coefficient of variation (CV%) and respective CV% rating; One-way ANOVA was used to measure any significant difference from respective CV% of absolute rmsEMG, normalised ISO-SINGJT and normalised ISO-CYC; † denotes significant difference from CV% of respective absolute peak EMG reliability; # denotes significant difference from respective sprint methods.

ISOVELOCITY normalised to ISO-SINGJT (%)

	Exp 1	Exp2	Between-Session p =	ICC	CV%	CV% Rating	Average
GM	166 ± 47	154 ± 68	0.582	0.38	24†	Weak	131 ± 42
GL	134 ± 69	115 ± 38	0.275	0.60	22†#	Weak	124 ± 54
BF	99 ± 24	95 ± 40	0.642	0.70	17	Acceptable	97 ± 32
VL	146 ± 58	151 ± 87	0.790	0.78	22	Weak	149 ± 73
VM	167 ± 94	139 ± 56	0.483	0.21	28	Weak	153 ± 75
RF	95 ± 24	121 ± 49	0.153	0.55	18	Acceptable	108 ± 37

ISOINERTIAL normalised to ISO-SINGJT (%)

	Exp 1	Exp 2	Between-Session p =	ICC	CV%	CV% Rating	Average
GM	162 ± 96	153 ± 68	0.776	0.46	32†	Very weak	157 ± 82
GL	125 ± 54	110 ± 30	0.361	0.47	20#	Weak	118 ± 42
BF	93 ± 29	97 ± 35	0.581	0.81	15	Acceptable	95 ± 32
VL	140 ± 70	162 ± 89	0.261	0.77	28	Weak	151 ± 79
VM	136 ± 54	147 ± 51	0.558	0.48	25	Weak	142 ± 53
RF	107 ± 39	117 ± 37	0.542	0.56	21	Weak	112 ± 38

ISOVELOCITY normalised to ISO-CYC (%)

	Exp 1	Exp2	Between-Session p =	ICC	CV%	CV% Rating	Average
GM	128 ± 44	133 ± 40	0.710	0.51	16	Acceptable	179 ± 42
GL	197 ± 129	165 ± 46	0.361	0.46	33†#	Very weak	181 ± 87
BF	173 ± 50	169 ± 34	0.775	0.74	11	Acceptable	171 ± 42
VL	172 ± 67	185 ± 66	0.623	0.30	25	Weak	179 ± 66
VM	192 ± 117	146 ± 65	0.338	0.28	24	Weak	169 ± 91
RF	135 ± 43	139 ± 37	0.764	0.39	16	Acceptable	137 ± 40

ISOINERTIAL normalised to ISO-CYC (%)

	Exp 1	Exp 2	Between-Session p =	ICC	CV%	CV% Rating	Average
GM	116 ± 45	133 ± 51	0.342	0.51	21	Weak	125 ± 48
GL	197 ± 118	160 ± 41	0.235	0.50	35†#	Very weak	179 ± 80
BF	162 ± 61	179 ±39	0.346	0.53	18	Acceptable	170 ± 50
VL	162 ± 85	200 ± 66	0.158	0.56	30	Very weak	181 ± 75
VM	151 ± 52	154 ± 58	0.891	0.26	26	Weak	153 ± 55
RF	150 ± 58	143 ± 48	0.759	0.16	29	Weak	146 ± 53

5.4 Discussion

The three principle findings of the experiment were: 1) peak rmsEMG at PPO during both sprint cycling tests was similar for the six muscle groups assessed; 2) of the two reference tasks, ISO-SINGJT produced significantly higher peak rmsEMG values for 3 out of 6 muscle groups, but there was similar between-session reliability for both reference tasks; and 3) the reliability of peak rmsEMG during sprint cycling (isovelocity or isoinertial) was not improved by normalisation to either reference task (ISO-SINGJT or ISO-CYC).

From a performance (functional) perspective, PPO was significantly higher in the isoinertial sprint test in comparison to the isovelocity sprint test, whilst cadence at PPO was similar for both sprint tests. The parabolic P-C and underpinning inverse linear T-C relationships in sprint cycling imply that the underpinning functional difference of PPO between the two tests is torque production. There is a well-established relationship between muscle activation and torque/force production (Lippold, 1952; Balshaw *et al.*, 2018). Despite this, no significant difference was measured between peak rmsEMG during PPO of the isovelocity and isoinertial sprint cycling methods. This suggests that the difference between the tests may be rooted in performance test methodology. For example, isoinertial sprint tests are not performed under fixed pre-determined cadences, and they involve accelerating the flywheel (and cranks). This acceleration is neither constant nor linear, and the inverse T-C relationship means the torque output at the same point(s) of each crank cycle is reduced (Figure 5-2). As no difference was measured between cadence at PPO, it implies that the torque, when measured by averaging over a revolution, reads higher in an isoinertial effort compared to isovelocity efforts. Furthermore, different co-ordination

strategies rather than maximal neuromuscular activation may influence PPO between both sprint tests.

The reliability (between session CV) of absolute peak rmsEMG values was similar for isoinertial and isovelocity cycling for 5 (GL, VL, VM, RF and BF) out of 6 muscle groups. Only GM exhibited lower reliability during isoinertial vs isovelocity sprints (Table 5-1). The conditions might be expected to produce more reliable results by virtue of constant muscle shortening velocity rather than the non-linear acceleration of isoinertial sprints (Figure 5-2).

Three muscle groups (RF, BF and GL) had higher peak rmsEMG during ISO-SINGJT MVCs in comparison to ISO-CYC MVCs, but three other muscles (GM, VL, VM) showed similar values for the two reference tasks. The discrepancy between the references tasks for some muscles is likely due to the fact that the multiple joint ISO-CYC is limited by torque production of some muscles (i.e. the weakest links in this mechanical situation), which are maximally activated, whilst other muscles are not fully activated in comparison to an isolated single joint task.

No significant difference was measured between the reliability of reference tasks for each respective muscle group. Generally, the reliability for each muscle during either ISO-SINGJT or ISO-CYC was rated as acceptable, with the only exceptions being BF ISO-SINGJT and RF ISO-CYC, which were rated as weak. None of the between-session reliability measurements was rated as good, which can be due to three main possibilities: 1) Between-session reliability of the functional outcomes of the reference tasks. With the exception of KE (3.8%), all the reference tasks scored a CV over 5.0% (7 – 8%) indicating poor levels of functional performance between-sessions (Buchheit *et al.*, 2011). This suggests a poor functional task reliability could contribute to the poor between-session reliability 2) Amplitude cancellation that

comes about from the stochastic nature of EMG with the increase in (voluntary) force production. This is particularly pertinent during MVCs, when motor unit activity is underestimated by EMG due to the increasing number of simultaneous overlapping positive and negative phases of action potentials, resulting in increased variability (Farina *et al.*, 2014). 3) Number of electrodes. This experiment used one electrode per muscle group and though they were averaged over both muscle groups over both legs, it has been suggested that increasing the number of EMG electrodes over a muscle group might help improve reliability, particularly during MVCs (Balshaw *et al.*, 2017). Of course, this becomes inherently less practical, more complex, more time consuming, and, hence, more difficult to deliver in applied situations

Other investigators also attribute the high levels of variability to various factors, including: psychological/motivational factors (Yang & Winter, 1983; Heinonen *et al.*, 1994; Bamman *et al.*, 1997; Ball & Scurr, 2010); synergetic muscle contribution (Miaki *et al.*, 1999); and fatigue onset (Yang & Winter, 1983; Heinonen *et al.*, 1994).

The most notable finding in this part of the experiment was that, overall, absolute peak rmsEMG values during sprint cycling had better, or at least similar levels of reliability, in comparison to normalised EMG values (irrespective of the reference task). Whilst this finding is similar to some previous research (Buckthorpe et al., 2012), it is contrary to recommendations that investigators should use normalising tasks to limit the between-session reliability and improve reliability of EMG during a (performance) task (Yang & Winter, 1983; Knutson *et al.*, 1994; Kashiwagi *et al.*, 1995; Lehman, 2002). The findings from this experiment suggested that the reliability exhibited when using absolute EMG values is at least as good as the reliability shown when using isometric MVCs as reference tasks. This questions the use of isometric

MVCs as normalisation procedures when assessing sprint cycling, and indicates that absolute values may be at least as reliable as normalised EMGs when wanting to measure changes longitudinally.

In any case, the most plausible reason as to why the between-session reliability of peak rmsEMG values of the majority of the muscles during both sprint cycling tests is not significantly better with a normalising task is likely mathematical. The problem is that both performance and reference tasks exhibit inherent variability. Combining them will exacerbate reliability rather than improve it and, thus, the bias would remain within the EMG amplitude rather than be removed from it.

EMG amplitude can be viewed as a basic measure of neural activation. However, there are limitations related to its inferences with neural drive as it has been reported that it may be poorly associated with motor unit recruitment (Del Vecchio *et al.*, 2017), and it is the combination of both neural drive and the properties of the action potentials, without the possibility of distinguishing between the two, that makes EMG amplitude, at best, a very crude estimate of neural drive (Farina *et al.*, 2014). Currently, technological limitations mean that instruments are not advanced enough to measure discharge rates of motor units and recruitment thresholds during dynamic movements. However, highly accurate decomposition EMG has recently been reported to estimate changes in average conduction velocity with a high degree of accuracy (Del Vecchio *et al.*, 2017), but this is yet to be done in dynamic movements. Additionally, to get a better understanding of muscle activation and recruitment strategies during the crank cycle, inverse dynamics can be used in conjunction with EMG to understand the contribution (positive or negative) of each muscle group throughout the crank cycle and the magnitude of contribution.

5.5 Conclusion

The main findings of this experiment were three-fold: 1) peak rmsEMG values during PPO did not differ between sprint cycling tests and between-session reliability was similar for all muscle groups with the exception of GM, which exhibited better reliability for the isovelocity method; 2) when peak rmsEMG was compared for both normalising tasks, peak rmsEMG was higher for 3 (GL, BF and RF) out of 6 muscle groups in comparison to ISO-CYC. From a reliability perspective, no difference was seen for any muscle group between both methods; 3) neither normalising task improved between-session reliability when compared to absolute rmsEMG values.

The work from this chapter addresses the thesis aims by trying to establish the between-session reliability (and as such, the suitability) of surface EMG and whether the addition of maximal isometric reference tasks improves reliability. The findings suggest that isometric maximum voluntary contractions as reference tasks do not improve between-session reliability and that EMG reliability was poor. and perhaps may be unsuitable for use during sprint cycling efforts. As the between-session reliability generally scored better for isovelocity sprint tests, this will be used to measure PPO, P-C and T-C relationships in the forthcoming chapters. The next chapter will investigate which muscle groups are associated with and can predict PPO.

CHAPTER 6

THE RELATION BETWEEN PEAK POWER OUTPUT IN SPRINT CYCLING AND MAXIMUM VOLUNTARY ISOMETRIC TORQUE PRODUCTION

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6.1 Introduction

First described by Hill in 1938, mechanical power produced by muscle is the consequence of force production and shortening velocity (Hill, 1938). These two variables share a hyperbolic inverse relationship with peak concentric mechanical power being achieved at approximately a third of maximal shortening velocity and maximum concentric force (Edman, 1979). From an applied perspective, maximal power output acts as one of the main physiological determinants and predictors of performance in sports such as running (Bundle & Weyand, 2012), rowing (Ingham *et al.*, 2002) and jumping (Grassi *et al.*, 1991; Ferretti *et al.*, 1994). Similarly, from a sprint cycling perspective, mechanical peak power output (PPO) at the crank level acts as a primary physiological determinant of performance (Dorel *et al.*, 2005; Weyand *et al.*, 2006; Martin *et al.*, 2007).

Torque (the cycling equivalent of force) and cadence (the cycling equivalent of shortening velocity) are inversely related, however; unlike the descriptions of Hill, they are linearly, not hyperbolically, related. As such, PPO is achieved at approximately half of the maximum extrapolated torque (T_{max}) and maximum extrapolated cadence (C_{max}), which is reported to occur ~120 rpm (Samozino *et al.*, 2007); however, conceptually, an increase in T_{max} and/or C_{max} could result in an increased PPO and, by inference, performance.

To date, evidence to suggest what physiologically underpins PPO and sprint cycling performance is limited to estimated lean leg volume (Dorel *et al.*, 2005). Other studies have used non-sporting populations to significantly correlate fat free mass (Duché *et al.*, 2002) and isometric quadriceps strength (Driss *et al.*, 2002). Despite Driss and colleagues reporting strong correlations between maximal voluntary contractions (MVCs) during isometric knee extension in relation to both T_{max} ($r = 0.73$)

and PPO (r = 0.75) in sprint cycling, there seems to be a plethora of data associating isometric MVCs with dynamic performance, providing varied results. Typically, correlations range between 0.3 and 0.6, whilst perhaps unsurprisingly, much stronger relationships have been observed (r = 0.76 – 0.97) when the isometric MVC has a great degree of specificity to the dynamic performance task (for review: Wilson & Murphy, 1996). Typically, non-specific tasks that isolate single-joint muscle groups have been used to determine performance, but these are of limited use given the performance action is often very different to the surrogate measure; therefore, a task specific measure would be conceptually better (Wilson & Murphy, 1996). This is exemplified in using maximum isometric force in a bench press test to predict performance in shotput throwers, where a poor relationship was observed (r = 0.22) as the isometric task lacked specificity to the 'dynamic' performance measure. Notwithstanding, maximum isometric force was strongly correlated with (dynamic) bench press 1RM (r = 0.78) due to the performance and isometric task being very similar (Murphy *et al.*, 1994), which further illustrates the issue of task specificity.

The limitation of the study carried out by Driss et al., (2002) was that it was limited to the knee extensors only, whereas sprint cycling is a compound movement and uses all major muscle groups in the lower limbs to produce impulse (Dorel *et al.*, 2012). Consequently, it is important to investigate, and therefore gain, greater understanding of whether other muscle groups (beyond knee extensors) contribute to PPO and sprint cycling performance. Building on the work from Chapter 5, the isometric EMG reference tasks were used to measure maximum torque. Consequently, investigating maximal strength using a cycling-specific isometric task in comparison to a single joint isometric task could inform coaches, practitioners and athletes about

non-specific cycling strength vs. cycling-specific cycling strength in relation to sprint cycling ability.

The aims of this study were two-fold. Firstly, we examined the yet untested relationship of maximal strength of different major lower body cycling muscles using isometric single-joint dynamometry with PPO and whether they can predict PPO. Secondly, we assessed whether an isometric cycling-specific task would be a better predictor of sprint cycling performance than isolated isometric single-joint muscle group tasks.

6.2 Methodology

6.2.1 Participants

Twenty male cyclists volunteered to take part in the study (mean ± SD age, 27 ± 5 yr; stature, 183.1 ± 8.4 cm; mass, 84.5 ± 11.1 kg). Cycling training experience and rider category varied across the participants, but all were engaged in between 5-24 h of training per week and were regularly competing in various disciplines from sprint track to road endurance cycling, from British Cycling's 'Category 3' up to the 'Elite category' of national level riders. The cyclists were free from injury, as assessed by a health screening questionnaire. Following institutional ethics committee approval, the cyclists provided written informed consent prior to any experimental procedures.

6.2.2 Study Overview

Participants attended two familiarisation sessions prior to the two experimental sessions. All lab sessions were identical, whereby participants completed the same protocol on each lab visit. Lab visits were separated by at least 1 and not more than 7 d. Cyclists were asked to report to the laboratory in a hydrated state, to avoid caffeine

and food for 3 h prior to testing, and to avoid intense exercise in the 24 h before each session. Firstly, the participants performed isolated, isometric, single-joint MVCs with four different muscle groups (knee extensors, knee flexors, hip extensors and plantar flexion) on a dynamometer. Subsequently, after 15 minutes of passive rest, participants performed a series of cycling-specific, multi-joint isometric MVCs on an instrumented, custom made cycling ergometer. Lastly, a maximum isovelocity P-C protocol was performed to measure PPO.

6.2.3 Isometric Dynamometry

The isometric dynamometry was performed identically to that in Chapter 4 as it was part of the same data collection.

6.2.4 Cycling-Specific Isometric Protocol

The multi-joint cycling-specific isometric (ISO-CYC) MVCs were performed on a custom-made cycling ergometer (BAE Systems, London, UK). As already stated, , the protocol was used in the previous chapter (Chapter 5) and described further in the general methods section (chapter 3.4.3.3) as it formed part of the same data collection.

6.2.5 Isovelocity Sprint Cycling Testing

The isovelocity sprint test protocol was identical to that presented in chapter 3.3.2.1 and Chapter 4 (.2.4) as it was part of the same data collection.

6.2.6 Data Processing

Torque from the dynamometer was sampled (2,000 Hz) and fed directly into a data acquisition system (Micro 1401, CED, Cambridge, United Kingdom) and the

accompanying PC utilizing Spike2 software (CED, Cambridge, United Kingdom). Of the three MVCs, the highest peak torque value (from the isometric dynamometry) for each individual muscle group was recorded. As the performance task (sprint cycling) uses both limbs, peak torque values were averaged for both right and left muscle groups for each experimental session and then averaged again over both experimental sessions. Likewise, peak torque values from right and left cranks in all ISO-CYC efforts were extracted and averaged for both sessions and then averaged between sessions.

Data from the power cranks was measured and recorded as per Chapter 3.3.3. For the isovelocity PPO sprints, the first three full revolutions (from TDC to TDC) of each effort at the pre-determined cadence were recorded and analysed; the revolution with the highest mean torque (and, therefore, power) was used. Then, the five power outputs at each pre-determined cadence were averaged between sessions, a quadratic regression P-C relationship was plotted and PPO was interpolated at the apex of the curve, as has been done previously (Arsac *et al.*, 1996; Gardner *et al.*, 2007).

6.2.7 Statistical Analysis

All data are reported as mean (± SD) unless otherwise stated. A Shapiro-Wilk test of the measurements showed that the data were normally distributed and suitable for parametric testing. The relationship between PPO and peak torques for different muscle groups in isometric dynamometry MVCs and the ISO-CYC were calculated by using a Pearson's product moment correlation. Pearson's correlation coefficients were defined as previously described by Buchheit and colleagues: trivial (0.0), small (0.1), moderate (0.3), strong (0.5), very strong (0.7), nearly perfect (0.9), and perfect (1.0) (Buchheit *et al.*, 2010). Any correlation greater than r = 0.50 was used in a step-wise

linear regression to predict PPO from peak torque values from isometric dynamometry of the relevant muscle groups. If any were seen as significant predictors, they were placed in another step-wise linear regression against ISO-CYC to determine whether a more task specific or a non-skilled task best predicts PPO. All statistics were performed on SPSS (IBM Corp., Armonk, N.Y., USA).

6.3 Results

The average mechanical PPO was measured at 1197 ± 215 W (Figure 6-1). In relation to PPO, the maximum isometric strength of the knee extensors showed a very strong relationship ($r = 0.71$; $p < 0.01$). Strong relationships were also observed between the knee flexors ($r = 0.53$; $p = 0.02$) and the hip extensors ($r = 0.56$; $p = 0.01$) and PPO, with a trivial non-significant relationship between ankle extensors and PPO ($r = -0.03$; $p = 0.89$). The relationship between PPO and ISO-CYC (Figure 6-2) had a very strong relationship ($r = 0.87$; $p < 0.01$).

All isometric dynamometry muscle groups that were assessed (apart from the plantar extensors) were entered into a step-wise regression model and significantly predicted PPO ($F_{(3, 19)} = 16.06$, $p = 0.001$, $R^2 = 0.47$). However, only peak torque from the isometric knee extension contributed significantly to the prediction, accounting for 47% of the variation in PPO ($p = 0.001$). Knee flexion ($p = 0.460$) and hip extension ($p = 0.507$) did not contribute meaningfully to the prediction. Accordingly, peak torques of knee extensors and ISO-CYC were put into a subsequent step-wise regression model and PPO was significantly predicted ($F_{(2, 19)} = 23.55$, $p < 0.001$, $R^2 = 0.77$). Only the peak isometric torque from ISO-CYC added statistical significance to the prediction, accounting for 77% of the variation ($p = 0.001$). Knee extension did not contribute significantly to the relationship ($p = 0.389$).

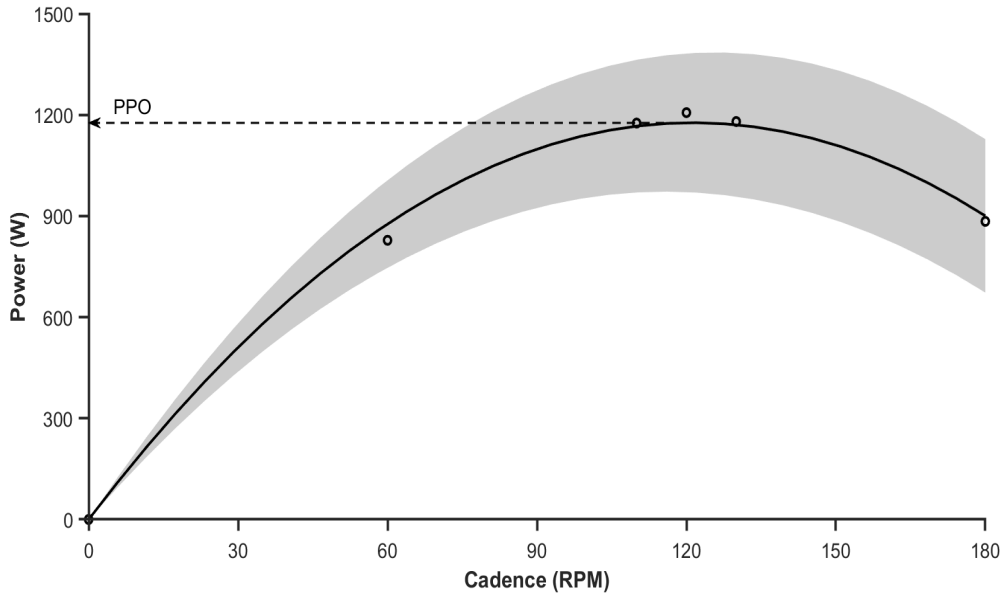

Figure 6-1: Power-cadence relationship of second order polynomial was formed after performing maximal sprints at 60, 110, 120, 130 and 180 RPM; $R^2 = 0.996$; $y = -0.081x^2 + 19.35x - 13.96$); Mechanical peak power output (PPO) was interpolated and measured at 1108 ± 215 W. The hollow circles represent the means at the respective cadences and shaded area represents the standard deviation.

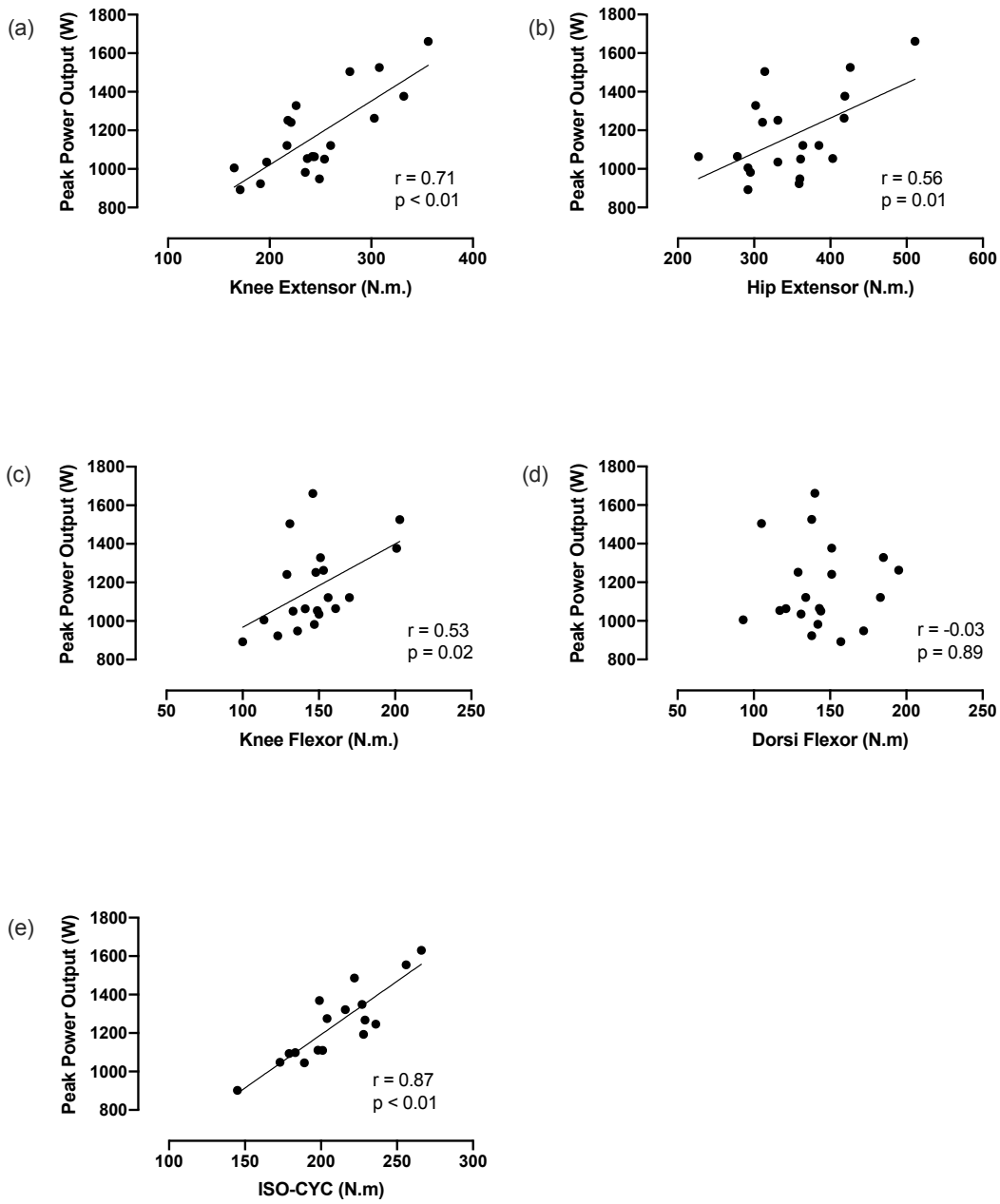

Figure 6-2: Relationship between (a) peak isometric strength of knee extensors and mechanical peak power output (PPO), (b) peak isometric strength of hip extensors and PPO, (c) peak isometric strength of knee flexors and PPO, (d) peak isometric strength of ankle extensors and PPO, (e) peak isometric torque cycling-specific torque (ISO-CYC) and PPO.

6.4 Discussion

The purpose of this study was two-fold. Firstly, to establish whether maximal torque produced from single joint isometric dynamometry can significantly predict PPO in sprint cycling. Secondly, to determine how single joint isometric dynamometry

compares to a cycling-specific isometric task in predicting PPO. With respect to the first aim, of all the major lower body muscle groups that were assessed using isometric single joint MVC, peak torque produced by the knee extensors was shown to be a significant predictor of PPO. However, with respect to the second aim, when peak torque from the knee extensors was compared to peak torque produced by ISO-CYC, it was the cycling-specific measure of maximal strength that was shown to be the only significant predictor of PPO.

With ISO-CYC being the best predictor of PPO and, therefore, having the potential to predict sprint cycling performance, it builds on the growing body of evidence that task specific isometric contractions are a better predictor of performance than non-skilled single-joint tasks like isometric dynamometry. The ISO-CYC is easy to perform, is a more familiar task to trained cyclists and, in comparison to dynamometry, is significantly cheaper. Furthermore, should the instrumented cranks be on their own bikes, it can be performed almost anywhere. The disadvantage of using an isometric compound movement like ISO-CYC, as opposed to an isolated single joint MVC, is that it does not provide sufficient information to ascertain which muscle groups are responsible for any changes that may be observed.

Previously, instrumented cranks have been able to provide P-C (and T-C) relationships as an accurate means of modelling cycling performance in the laboratory, which may be later reflected in field performances (Gardner *et al.*, 2007). However, though this may be thought of as a more ecologically valid task, it involves a large technical/biomechanical component that makes it hard to quantify the true physiological changes in the strength of the muscle groups. Isometric tasks such as single-joint dynamometry (in this case, knee extensor assessment) can provide valuable information about strength changes in targeted muscle groups. This means

that it can act as an abstract measurement of strength that is far removed from the task, can be monitored by coaches and practitioners to provide information on meaningful changes in physiological strength relative to a key performance measurement, as well as provide valuable feedback on the efficacy of previous training or indeed inform the prescription and monitoring of future training programming.

The findings from the single joint dynamometry concur with previous work that has shown a similar strong relationship between isometric MVC of the knee extensor and PPO. The hip extensors and knee flexors displayed large and significant relationships to PPO, but they did not significantly add to the regression model that already included the knee extensors. No relationship between maximal plantar flexor strength with PPO was observed, which is contrary to the high muscle activation levels of the plantar flexors during maximal sprint cycling (Dorel *et al.*, 2012). A possible explanation for this finding could either that plantar flexor strength may be more cycling/task specific than a general non-specific abstract strength measurement and/or may provide some evidence that the planar flexors are involved in the transfer of mechanical energy from the proximal muscles to the crank (Raasch *et al.*, 1997).

A plausible suggestion as to why knee extensors are the only significant single joint predictors of PPO could be because the superficial mono-articular muscles of the quadriceps (i.e. VM and VL) are maximally activated when peak torque is achieved around the crank cycle (Dorel *et al.*, 2012). Thus, stronger knee extensors are critical for high instantaneous torque and, therefore, PPO. Nevertheless, irrespective of why the knee extensors are the best predictor of PPO, peak torque from ISO-CYC MVCs provides a task specific, less time-consuming and cheaper method of predicting PPO that is easy to administer and can be used by athletes, coaches and practitioners.

There are limitations to this study that should be mentioned. Firstly, it is recommended that at least 50 participants are used when employing a multiple linear regression in comparison to the 20 used in this study (Green, 1991). In addition, the participants used in this experiment were generally a homogenous cohort. Despite this, a broad range of PPO and independent values were measured. This can exaggerate and bias the relationships to give the perception that there is a stronger association between the dependent and independent variables. Second, not all the major muscle groups were assessed. Two major lower body muscle groups, hip flexors and dorsiflexors, which have been shown to be maximally active during sprint cycling (Dorel *et al.*, 2012) were not assessed, and no upper body measurements, which have been shown to contribute to high intensity cycling even though it is sub-maximal (Grant *et al.*, 2015), were recorded.

6.5 Conclusion

In conclusion, of all the major lower body muscle groups, peak torque in the knee extensors from isometric dynamometry was the best predictor of peak power output in sprint cycling. Moreover, our data show that a stronger prediction of sprint cycling performance can be made from a measure of maximal torque that is performed in an isometric cycling-specific task to indirectly assess PPO. This provides a cheaper, easier and more applicable method for athletes, coaches and practitioners to monitor surrogate measurements of sprint cycling performance.

The work from this chapter helps address the aims of the thesis by identifying that the physiological factors affecting PPO are likely to be located in the thigh and, in particular, the knee extensors. Future work in this thesis will focus on measurements

based on examining the physiological properties of the thigh and, in particular, the quadricep femoris.

CHAPTER 7

PHYSIOLOGICAL DETERMINANTS OF PEAK POWER OUTPUT IN SPRINT CYCLING: A CROSS-SECTIONAL STUDY OF ELITE CYCLISTS

7.1 Introduction

One of the principle findings of the previous chapter was the significant relationships exhibited between PPO and maximum isometric strength of the knee extensors, knee flexors and hip extensors. Of those, only the knee extensors predicted PPO, suggesting the main underpinning fundamental physiological factors are located in the thigh and, in particular, the knee extensors. In track sprint cycling, PPO relative to body mass and frontal area has been strongly associated with both acceleration (Martin *et al.*, 2006, 2007) and maximum velocity (Dorel *et al.*, 2005). Despite these relationships being well established, the underlying physiological determinants of PPO in cycling are poorly researched and understood (refer to section 2.12). A better understanding of these factors will facilitate exercise prescription targeted more effectively to the key determinants of PPO and may help to maximise performance.

Theoretically, muscle size, specifically muscle volume, is a key predictor of neuromuscular power (Jones *et al.*, 2004) and there is evidence, that, for example, quadriceps femoris volume explains a high proportion of the variance in single joint knee extension (~80%) and squat jump (90%) power (O'Brien *et al.*, 2009). It has also been suggested that muscle volume is a major predictor of PPO in cycling (Martin *et al.*, 2007). However, previous work has examined relatively crude estimates of muscle mass/volume (e.g. based on tape measurements of superficial anthropometry) in relation to sprint cycling performance (Dorel *et al.*, 2005; Rønnestad *et al.*, 2010), and has had low participant numbers when evaluating trained/elite cyclists ($n < 15$). Of the lower limb muscle groups, the strength of the knee extensors appears to be the best predictor of cycling PPO and, thus, accurate assessment of quadriceps femoris muscle volume, e.g. with magnetic resonance imaging (MRI), the gold standard technique

(Engstrom *et al.*, 1991; Cruz-Jentoft *et al.*, 2010), might be expected to be a key determinant of PPO.

Another important component of skeletal muscle mechanics and function is muscle architecture, including the pennation angle and fascicle length, that can be assessed *in vivo* with ultrasound imaging. A greater pennation angle is thought to be associated with an improvement of the generation of force output for contractions against high loads by packing more sarcomeres in parallel (Aagaard *et al.*, 2001; Blazevich *et al.*, 2009), while fascicle length plays an important role in determining shortening velocity of a muscle (Lieber & Fridén, 2000).

Furthermore, the ability to develop contractile force, and thus power, rapidly is dependent on neuromuscular activation (Van Cutsem *et al.*, 1998; Aagaard *et al.*, 2002) and likely plays a role in cycling PPO. However, the relationship between PPO and neuromuscular activation in a large cohort of elite cyclists has not been investigated.

The primary aim of this study was to use the evidence from previous studies and foregoing chapter of this thesis to examine the relationship of a range of putative neuromuscular determinants rooted in the thigh (muscle volume, architecture and neuromuscular activation) with cycling PPO. This involved a large cohort of elite cyclists who were all familiar with performing maximum cycling efforts and who were drawn from different disciplines in order to ensure a wide range of PPO values. The secondary aim was to compare and characterise the sprint performance and physiological measurements of elite sprint and endurance cyclists.

7.2 Methodology

7.2.1 Participants

Thirty-five elite male cyclists volunteered to take part in the study (mean ± SD age, 22 ± 4 yr; stature, 179.1 ± 5.9 cm; mass, 77.4 ± 11.3 kg). The whole cohort was comprised of two different groups of cyclists: sprint (n = 17; age, 21 ± 3 yr; stature, 178 ± 4.0 cm; mass, 85.3 ± 9.2 kg) and endurance (n = 18; age, 22 ± 4 yr; stature, 179.1 ± 5.9 cm; mass, 69.1 ± 5.9 kg). Sprint covered disciplines that were 'all-out'/ maximal for ≤60 s i.e. BMX (n = 4) and track sprinters (n = 13). Endurance covered disciplines that were > 4 mins in duration and were not 'all-out', i.e. track endurance cyclists who rode team pursuit (n = 9), road endurance and/or road time trial (n = 7) and mountain bike (n = 2). Twenty-eight of the cyclists are currently competing internationally in their respective Union Cycliste Internationale disciplines/categories, as well as having trained on a full-time basis for at least the past two years. More specifically, their collective experience and success included: 2 Olympic medals, 8 Olympic games representations, 3 Paralympic medals, 3 Paralympic games representations (as pilot or stoker of tandem), 10 Senior World Championship medals, 37 Senior World Championships representations, 8 Senior Para-cycling World Championship golds and 6 Senior Para-cycling World Championship medals (as pilot or stoker of tandem). The remaining seven participants who were not competing internationally were competing in the 'Elite' category of national level road cycling events (n = 4) or had won national level medals on the track (n = 3). Ethical approval was attained from Northumbria University Research Ethics Committee. Following an explanation of the study design and protocol, the cyclists provided written informed consent prior to their participation in the study.

7.2.2 Study Overview

Before experimental sessions at the laboratory, the cyclists were instructed to avoid caffeine and food for 3 h prior to testing and to avoid strenuous exercise in the 24 h before each session. The cyclists made two identical cycling laboratory visits within 7 days at the same time of day (± 1 hour). Firstly, the cyclists assumed their race cycling-specific position on a custom-built ergometer that had the cast flywheel clamped to ensure the cranks were stationary. In this position, the architecture of the VL (i.e. the pennation angle [$P\theta_{VL}$] and fascicle length [Fl_{VL}]) were assessed at rest prior to exercise. Subsequently, the cyclists had surface EMG electrodes placed on three muscles of both legs (GM, BF, and VL) and mounted another custom-modified isovelocity ergometer (again, the position mirrored their racing position). A standardised warm-up of 10 mins at 80 – 90 RPM and 100 – 150 W followed by a maximal 2 s sprint at 125 RPM was completed by each cyclist. Once this was completed, a series of isovelocity sprints (4 s maximal sprints at each of five velocities: 60, 115, 125, 135 and 180 RPM). The intermediate cadences were altered from the previous data collections as the results from Chapter 4 had shown that PPO had occurred at ~125 RPM. Accordingly, the cadences were adjusted to give the best possible probability to capture the cadence where PPO occurred. Crank data, i.e. power, torque and cadence with surface EMG, were simultaneously recorded and synced off-line using custom-written scripts. On a third occasion, within 7 days of the cycling laboratory visits, MR imaging was used to assess the quadricep femoris and hamstring muscle volume of both legs of each cyclist.

7.2.3 Muscle Architecture

For the architecture measurements, a custom-built cycling ergometer (United Kingdom Sports Innovation) was set-up according to the individual cyclist's track or road bike set-up. BMX riders had their position fitted to a typical track cycling set-up (closed hip angle, flat back parallel with the floor and bent arms on the dropped handle bars). The ergometer was previously used and described in more detail in sections 3.3.4.3, 5.2.5 and 6.2.4. Before the cyclist mounted the ergometer, bib shorts were pulled up to expose their thighs in order to allow the mid-thigh to be measured and marked. When the cyclists first mounted the ergometer for the ultrasound imaging, the flywheel was clamped to ensure that the crank position was fixed with the drive-side (right) crank positioned at 90° from top dead centre (TDC). Once in this position, the cyclists were asked to take their racing position with their hands on the 'drops'.

An ultrasound (5-10 MHz scanning width 92 mm and depth 65 mm, EUP-L53L; Hitachi EUB-8500) linear array transducer was used to capture B-mode ultrasound images. Water-soluble transmission gel was used to coat the transducer, which was positioned with minimal pressure over the skin. Images were captured with the transducer placed on the medial longitudinal line of the muscle, being positioned on the skin over the VL at 50% of femur length (from the knee joint space to the greater trochanter) in order to correspond to the area of greatest anatomical CSA (Erskine *et al.*, 2009). The transducer was orientated perpendicular to the skin and parallel to the fascicular path. Parallel fascicle alignment was presumed when the transducer orientation produced an image whereby the aponeuroses and the fascicle perimysium trajectory were clearly identified, with no visible fascicle distortion at the image edges. Once the images were captured, the cyclists were instructed to switch lead legs and have the non-drive side (left) crank positioned at 90° from TDC and the process was

repeated with the left VL. Images were later imported into analysis software (ImageJ, v.1.46; National Institutes of Health, Bethesda, MD, USA) to measure Fl_{VL} and $P\theta_{VL}$. The Fl_{VL} was measured as the length of the fascicular path between the superficial and deep aponeurosis. The manual (fascicular line tracing) linear extrapolation approach was adopted when the full fascicle length could not be seen within the ultrasound image, as has previously been validated and used (Kawakami *et al.*, 1993). The $P\theta_{VL}$ was measured as the angle between the fascicular path and the insertion of fascicles into the deep aponeurosis. Three different ultrasound images of each leg were recorded and analysed during each visit before first averaging the measured values from each session, and then averaging across the two sessions. The intra-rater repeatability of the measurements of $P\theta_{VL}$ had CV of 4.1% and ICC of 0.86, Fl_{VL} had a CV of 1.9% and ICC of 0.98, the within-participant repeatability $P\theta_{VL}$ had CV of 2.9% and ICC of 0.91, and Fl_{VL} had a CV of 1.3% and ICC of 0.97.

7.2.4 Surface Electromyography

A wireless surface EMG system (Delsys Trigno® Wireless EMG systems, Boston, MA, USA) was used to ascertain muscle activation by measuring EMG amplitude. EMG electrodes were placed over both GM, BF and VL as described in section 3.3.8.

The results from Chapter 5 that investigated traditional and task specific isometric reference tasks compared to normalised sprint cycling tests highlighted concerns regarding the between-session reliability of using maximal isometric MVCs as reference tasks. However, it is still essential to normalise against a reference task to be able to compare muscle activation between participants and so an alternative method was explored. When performing the isovelocity sprint test battery, one of the

efforts requires the participants to maximally pedal at 60 RPM. This represents an effort that is relatively high in torque production, low in angular velocity (/cadence) and, due to its invariable cadence, is also constant, maximal and task specific to sprint cycling, making it a potentially suitable reference task when assessing sprint cycling and/or PPO. Peak muscle activation was measured and averaged for the first three consecutive revolutions commencing from when the highest mechanical power output was achieved (at 60 RPM). This was used as the reference value to normalise against. The data analysis was done identically to what is described in section 5.2.7. In brief, this meant that the peak rmsEMG values of said muscles (GM, VL, BF) were assessed at the highest rmsEMG during a 90º sector of crank displacement (i.e. ¼ of a revolution) during the revolution where PPO was achieved (measure from TDC to TDC). Therefore, the isovelocity sprint at a constant 60 RPM used a 250 ms epoch (as that is the time window equivalent to a 90º sector). This ensured that all EMG measurements during both tests were assessed over a consistent range of motion, despite different velocities.

The peak rmsEMG amplitude during the 60 RPM isovelocity sprint was used to normalise peak rmsEMG from the isovelocity sprint with the highest measured PPO (peak $rmsEMG_{PPO}$), i.e. peak $rmsEMG_{PPO}$/peak $rmsEMG_{60}$, and then used as a criterion value of activation of each muscle at PPO (GM_{ACT}, VL_{ACT}, BF_{ACT}). From this data collection, CV for between-session peak rmsEMG reliability during isovelocity cycling at 60 RPM as a reference task for GM, VL and BF was 9.9, 13.0 and 9.5%, respectively. With the graded system for CV presented in Chapter 5, these CV values rated better than both isometric tasks and have been used in the ensuing chapters.

7.2.5 Sprint Cycling Performance Test

Isovelocity sprint test methodology was used as per chapters 3.3.2.1, 4.2.3 and 6.2.5. The equipment used was identical to the aforementioned experimental chapters. Participants performed 4 s sprints at 60, 115, 125, 135 and 180 RPM. The order of cadences was selected at random and every cyclist performed the efforts in the following order: 115, 60, 135, 125 and 180 RPM.

The maximum power output over three consecutive revolutions (from TDC to TDC) at each cadence was used and then averaged over both sessions. From that, P-C and T-C relationships were established by fitting a quadratic and linear equation, respectively, by the least square method, as used previously (Arsac *et al.*, 1996; Dorel *et al.*, 2005; Gardner *et al.*, 2007). The apex of the P-C relationship was interpolated to derive PPO (as well as PPO: mass by dividing PPO by body mass [W/Kg]) and cadence at PPO (C_{OPT}). Individual T-C relationships, maximal torque and maximal cadence were extrapolated.

7.2.6 MR Imaging

On a separate occasion, within 7 days of the cycling laboratory visits, the muscle volume of both legs was measured via MR imaging as described in section 3.3.6. Muscle volume was measured by an experienced operator, who was blind to the participant's identity and performance data, using open source software (OsiriX Imaging Software™ version 5.5.1, Geneva, Switzerland). Volume was calculated by measuring anatomical (CSA) in the axial plane, by manual segmentation of the VL, vastus intermedius (VI), vastus medialis (VM) and rectus femoris (RF), as well as semitendinosus (ST) and semimembranosus (SM), long and short head BF. In each individual image, the 'closed polygon' tool was used. Manual outlining started with

the most distal slice above the knee, where the muscles were visible, and ended with the most proximal slice where the muscle was no longer visible. The total number of slices was noted and used to determine the length of the segment (length = n × 15 mm, where n is the number of slices, given that MR image slices were 5 mm in thickness). On average, thirty images were analysed per thigh. Muscle volume was then calculated by using the Cavalieri formula, which is shown in Equation 3 (Lund *et al.*, 2002):

$$\text{Muscle Volume} = \sum_n e_i \times \text{CSA}_i \quad \text{(equation 3)}$$

where n is the number of slices used, and e_i is the distance between the measured slices.

Knee extensor muscle volume (Q_{VOL}) was measured by summating the muscle volume of VL, VM, VI and RF of each leg. The hamstring muscle volume (HAM_{VOL}) was measured by summating the muscle volume of long and short head BF of each leg. Both Q_{VOL} and HAM_{VOL} were averaged over both legs.

7.2.7 Statistical Analysis

All data are presented as mean ± SD. A Shapiro-Wilk test of the measurements showed that the data were normally distributed and suitable for parametric testing. Data from all thirty-five cyclists were used to perform bivariate correlations and subsequent regression analysis with the physiological measurements. Initially, Pearson's product-moment correlations (r) were employed to examine the relationship between individual physiological variables and the criterion variable (PPO). The following criteria were adopted to interpret the magnitude of the relationship between test measurements: <0.1 trivial, 0.1 to 0.3 small, >0.3 to 0.5 moderate, >0.5 to 0.7

large, >0.7 to 0.9 very large, and >0.9 to 1.0 almost perfect (Hopkins, 2015). In addition, the overall coefficient of determination (R^2) for the set of physiological measurements with PPO was also calculated. All physiological variables that were significantly correlated with PPO were included in the step-wise regression analysis to predict PPO. With this set of predictors, our collinearity diagnostic exploration resulted in variance inflation factors of 2.0 - 5.0 and tolerance of 0.20 – 0.80, which indicated acceptable levels of multicollinearity (Hair *et al.*, 1995). The sprint and endurance groups within the whole cohort were compared using an independent-samples t-test for sprint performance measurements (i.e. PPO, PPO: mass, C_{OPT}, T_{MAX} and C_{MAX}) and physiological measurements (i.e. Q_{VOL}, HAM_{VOL}, $P\theta_{VL}$, Fl_{VL}, GM_{ACT}, VL_{ACT}, BF_{ACT}). All physiological measurements (mentioned above) were averaged over both limbs, and then both sessions (with the exception of MR imaging). The level of statistical significance was set at $p < 0.05$ for all tests. All statistics were calculated using SPSS (IBM Corp. Version 24.0. Armonk, USA).

7.3 Results

Collectively for all thirty-five riders, the average ± SD, range (i.e. maximum and minimum) and fold variability (multiple between maximum and minimum values) of the performance and physiological measurements are presented in Table 7-1. Very large, positive bivariate relationships were found between Q_{VOL} ($r = 0.87$; $p < 0.001$), HAM_{VOL} ($r = 0.71$; $p < 0.001$) and $P\theta_{VL}$ ($r = 0.81$; $p < 0.001$) with cycling PPO (Table 7-1; Figure 7-1). The remaining measurements (Fl_{VL}, VL_{ACT}, BF_{ACT} and GM_{ACT}) were unrelated to PPO. Subsequently, step-wise multiple regression analysis was done using the three significant predictor variables from the bivariate correlations (Q_{VOL}, HAM_{VOL}, $P\theta_{VL}$) to examine their combined relationship with PPO. The regression

analysis found 87% of the variability in PPO between cyclists ($F_{(2, 28)} = 72.83$, $p < 0.001$) was explained by two variables Q_{VOL} (76%) and $P\theta_{VL}$ (11%). When examining the relationships for the physiological measures with PPO with the sprint cyclists, a large relationship was seen with Q_{VOL} ($r = 0.51$; $p = 0.04$), moderate relationship with $P\theta_{VL}$ ($r = 0.37$; $p = 0.14$) and small was seen with HAM_{VOL} ($r = 0.26$; $p = 0.31$). A trivial relationship was seen for Fl_{VL}, VL_{ACT}, BF_{ACT} and GM_{ACT} (all $r < 0.01$)

Table 7-1: Sprint cycling performance and physiological measurements for thirty-five elite cyclists. Data are mean ± SD, range and fold variability for minimum to maximum values.: Peak power output (PPO), optimal cadence (C_{OPT}), maximum torque (T_{MAX}), maximal cadence (C_{MAX}), quadriceps muscle volume (Q_{VOL}), hamstring muscle volume (HAM_{VOL}), pennation angle of the vastus lateralis ($P\theta_{VL}$) and fascicle length of vastus lateralis (Fl_{VL}). In addition, relative maximum activation of gluteus maximus (GM_{ACT}), vastus lateralis (VL_{ACT}) and bicep femoris (BF_{ACT})

	Mean ± SD	**Range (max - min)**	**Fold variability**
PPO (W)	1240 ± 335	2025 - 775	×2.6
C_{OPT} (RPM)	131 ± 12	161 - 112	×1.3
T_{MAX} (N.m)	175 ± 37	236 - 117	×2.0
C_{MAX} (RPM)	267 ± 31	362 - 221	×1.6
Q_{VOL} (cm^3)	2268 ± 582	3343 - 1347	×2.5
HAM_{VOL} (cm^3)	804 ± 206	1263 - 348	×3.6
$P\theta_{VL}$ (^{o})	15.6 ± 2.0	18.8 - 11.7	×1.6
Fl_{VL} (cm)	7.6 ± 0.7	9.0 - 6.5	×1.4
GM_{ACT} (%)	102 ± 16	128 – 62	×2.1
VL_{ACT} (%)	97 ± 15	137 – 69	×2.0
BF_{ACT} (%)	95 ± 11	120 - 75	×1.6

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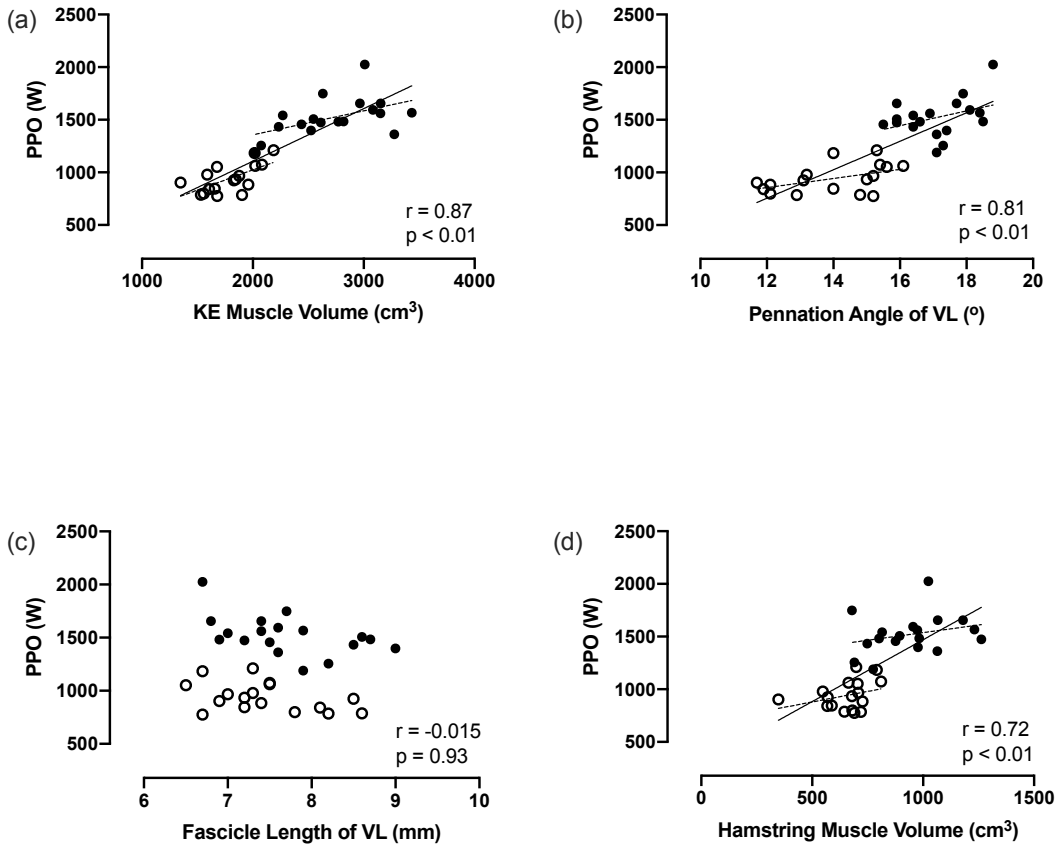
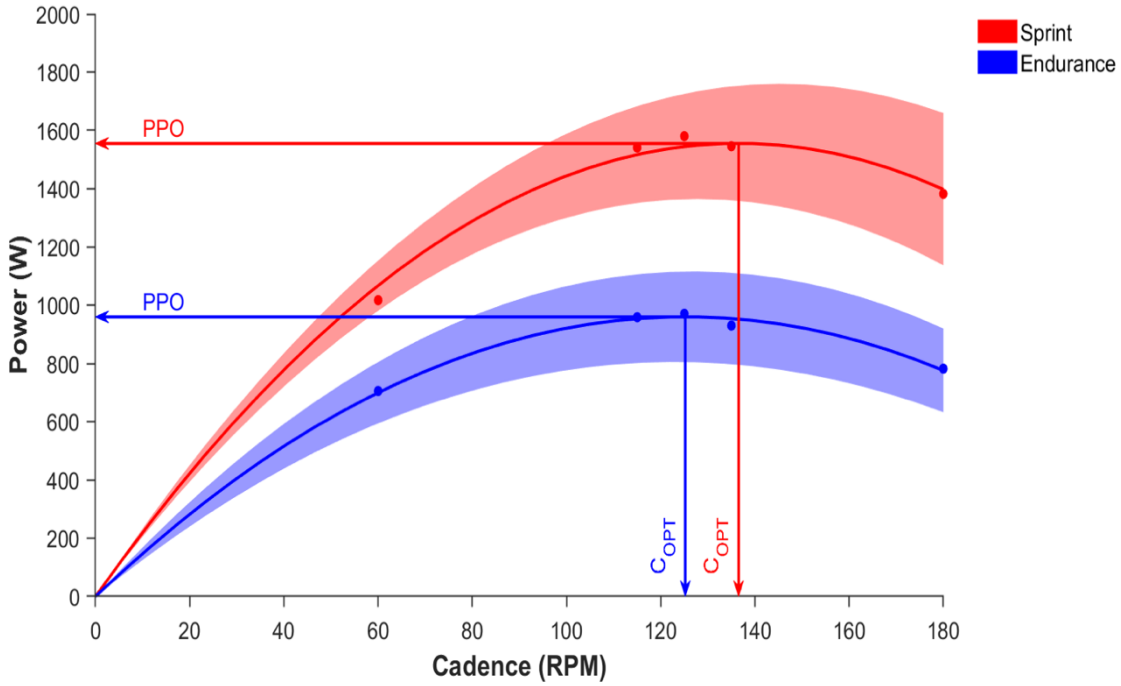


Figure 7-1: Scatter plots showing the overall relationships (solid line) between cycling peak power output (PPO) and different physiological measurements: (a) quadriceps muscle volume, (b) pennation angle of vastus lateralis (VL), (c) fascicle length of VL and (d) hamstrings muscle volume (n = 35). Filled circles represent sprint cyclists and open circles represents endurance cyclists. Pearson's correlation coefficient (r) and significance are for overall relationships.

The comparison of P-C and T-C relationships between the groups of sprint and endurance cyclists (Figure 7-2) showed that sprint cyclists had substantially higher PPO (~ +579 W; +47 %; $p < 0.001$), PPO: Mass (~ +4.3 W:Kg; +27 %; $p < 0.001$), C_{OPT} (~ +11 RPM; 8 %; $p < 0.05$), T_{MAX} (~ +62 N·m; +35 %; $p < 0.001$) and C_{MAX} (~ +31 RPM; +11 %; $p < 0.05$; Table 7-3). In terms of the physiological measurements, sprint cyclists had significantly higher Q_{VOL}, HAM_{VOL} and $P\theta_{VL}$ (all $p < 0.001$). No significant differences were seen between groups when Fl_{VL}, VL_{ACT}, and GM_{ACT} were examined, whilst the endurance cyclists exhibited higher BF_{ACT} ($p < 0.05$) during sprint cycling.

(a)



(b)

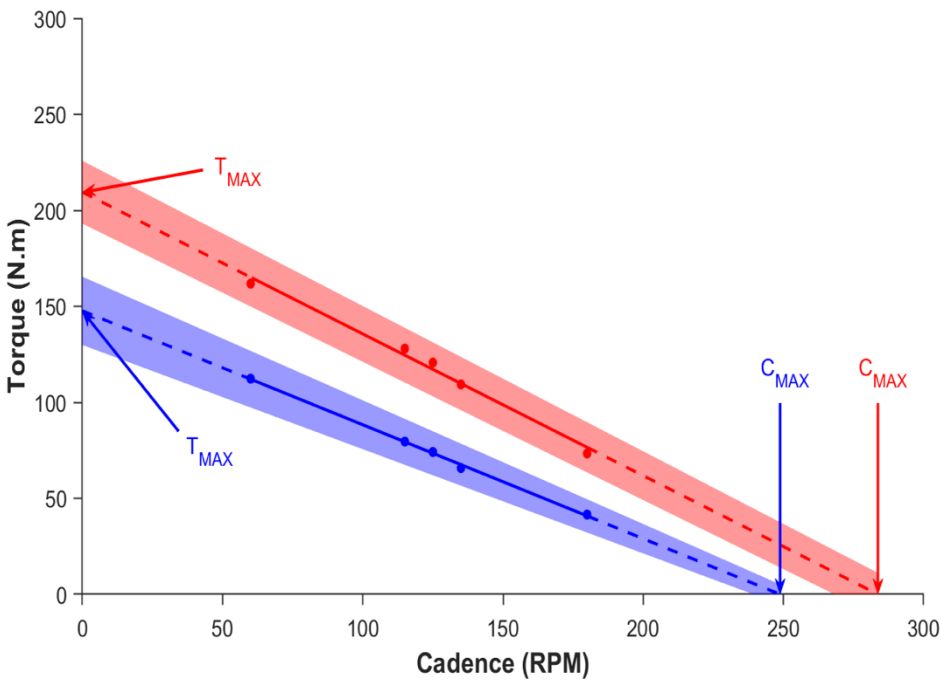


Figure 7-2: (a) Power-cadence relationships (b) Torque-cadence relationship of sprint (red) and endurance (blue) cyclists. Panel (a) peak power output (PPO) and optimal cadence (C_{OPT}) are highlighted. Significant differences were measured between PPO and C_{OPT} of both groups.

Panel (b): extrapolated maximum torque (T_{MAX}) and (C_{MAX}) are shown for both groups Significant differences were measured between T_{MAX} and C_{MAX} of both groups; solid lines represent the mean relationship of measured cadences and dotted line represents extrapolation; shaded areas represent standard deviation.

Table 7-2: Bivariate relationships (r) and associated coefficient of determination (R^2) for a range of physiological measurements and the criterion measure (peak power output) in elite cyclists (n = 35). Knee extensor muscle volume (Q_{VOL}); knee flexor muscle volume HAM_{VOL}); pennation angle ($P\theta_{VL}$); fascicle length (Fl); gluteus maximus (GM_{ACT}); vastus laterlais (VL_{ACT}) and bicep femoris (long head) (BF_{ACT}) muscle activation.

	r	R^2	Relationship	p
Q_{VOL}	0.87	76%	Very large	<0.001
HAM_{VOL}	0.71	50%	Very large	<0.001
$P\theta_{VL}$	0.81	66%	Very large	<0.001
Fl_{VL}	-0.15	2%	Small	0.933
GM_{ACT}	0.21	4%	Small	0.276
VL_{ACT}	-0.01	0%	Trivial	0.977
BF_{ACT}	-0.29	9%	Small	0.107

Table 7-3: Sprint cycling performance and physiological measurements of sprint and endurance cyclists. Performance measurements: peak power output (PPO), PPO normalised to body mass (PPO: Mass), optimal cadence (C_{OPT}), maximal torque (T_{MAX}) and maximal cadence (C_{MAX}). Physiological measurements: knee extensor muscle volume (Q_{VOL}); hamstring muscle volume (HAM_{VOL}); pennation angle ($P\theta_{VL}$); fascicle length of VL (Fl_{VL});

	Sprint (n = 18)	Endurance (n = 17)
PPO (W)	1521 ± 186 **	942 ± 136
PPO: Mass (W/kg)	17.9 ±1.9 **	13.6 ± 1.6
C_{OPT} (RPM)	136 ± 14 *	125 ± 7
T_{MAX} (N·m)	205 ± 18 **	143 ± 20
C_{MAX} (RPM)	282 ± 84 *	251 ± 18
Q_{VOL} (cm^3)	2723 ± 420**	1786 ± 229
HAM_{VOL} (cm^3)	994 ± 176**	655 ± 108
$P\theta_{VL}$ (^{o})	17.1 ± 1.0**	14.8 ± 1.5
Fl_{VL} (cm)	7.6 ± 0.6	7.5 ± 0.7
GM_{ACT} (%)	103 ± 16	101 ± 16
VL_{ACT} (%)	99 ± 18	96 ± 12
BF_{ACT} (%)	91 ± 9	98 ± 11†

*gluteus maximus (GM_{ACT}); vastus lateralis (VL_{ACT}) and bicep femoris (long head) (BF_{ACT}) muscle activation. * denotes significantly higher than endurance ($p < 0.05$); ** denotes significantly higher than endurance ($p < 0.001$); † denotes significantly higher than sprint ($p < 0.05$)*

7.4 Discussion

This is the first study to forensically investigate the physiological attributes that determine PPO in an elite highly-trained cycling cohort. The main finding of this study was the very large positive relationships between Q_{VOL}, HAM_{VOL} and $P\theta_{VL}$ with PPO, with multiple regression showing that, in combination, Q_{VOL} and $P\theta_{VL}$ explained 87% of the variability in PPO between cyclists. These findings appear to demonstrate the importance of muscle morphology for sprint cycling performance. In contrast, the remaining variables, particularly neuromuscular activation of three hip and knee joint muscles, showed no relationships with PPO. The secondary finding was that, as expected, elite sprint cyclists had substantially higher P-C and T-C relationships (i.e. PPO, PPO: mass, C_{OPT}, T_{MAX} and C_{MAX}) than endurance cyclists, and this was underpinned by greater Q_{VOL}(+52%), HAM_{VOL} (+52%) and $P\theta_{VL}$ (+20%).

The sprint performance measurements in the current study were similar to previous reports. For example, the sprint group recorded PPO of 1521 ± 186 W that was within 80 W of three previous studies using similar although somewhat smaller elite cohorts (Calbet *et al.*, 2003; Dorel *et al.*, 2005, 2012). The endurance group in the current study had PPO of 942 ± 136 W, similar to untrained cyclists (941 ± 124 W; (Leong *et al.*, 2014)) and somewhat lower than a previous elite endurance cohort (1122 ± 65 W) (Calbet *et al.*, 2003)). Of the physiological measurements, the endurance cyclists had muscle volume $P\theta_{VL}$ similar to the untrained groups (Massey *et al.*, 2018), whereas the endurance group had muscle volume similar to long-term resistance-trained participants (Massey *et al.*, 2018) and $P\theta_{VL}$ similar to sprint runners (Abe *et al.*, 2000).

Q_{VOL}, HAM_{VOL} and $P\theta_{VL}$ all showed very large positive bivariate relationships with PPO, and multiple regression analysis found Q_{VOL} and $P\theta_{VL}$ explained 87% of

the variance in PPO, whereas the neuromuscular activation measurements were unrelated to PPO. For the first time and in elite cyclists, this study suggests that PPO could potentially be determined by muscle morphology, particularly the size and pennation angle of the quadriceps, rather than the ability of the nervous system to activate the muscles.

Using MR imaging, a 'gold standard' method for determining muscle volume (Engstrom *et al.*, 1991; Cruz-Jentoft *et al.*, 2010), we found Q_{VOL}, i.e. the amount of skeletal muscle, alone explained 76% of the variance in PPO between cyclists, which makes this variable a desirable attribute for competitive (sprint) cyclists. Whilst no previous studies have carefully imaged the quadriceps and hamstring muscles in relation to sprint cycling performance, some crude estimates of lower body/thigh muscle mass have been found to be moderately/strongly related to cycling PPO (Dorel *et al.*, 2005; Leong *et al.*, 2014; Maciejczyk *et al.*, 2015). Our findings for the predominant influence of Q_{VOL} on PPO reinforce the importance of muscle size for neuromuscular power (9,10) ~~and confirm that cyclists and their coaches should be especially attentive to training and nutrition strategies to enhance Q_{VOL}. In particular, resistance training is well known to stimulate hypertrophy and increased muscle volume. In fact, it was surprising that the elite sprint cyclists in the current study had slightly smaller Q_{VOL} than a long-term (mean 4 years) resistance-trained, but not elite, cohort assessed with an almost identical MR protocol~~ (Massey *et al.*, 2018).

$P\theta_{VL}$ was a strong correlate of PPO in the current study (r = 0.81) and, given the relationship of muscle volume and PPO, this might have been expected as the pennation angle is known to be associated with muscle size indices (e.g. Fukunaga *et al.* (1997)). This was also the case in the current study (Q_{VOL} vs $P\theta_{VL}$ r = 0.78). However, what was perhaps more surprising was that $P\theta_{VL}$ was an independent

predictor of PPO, in addition to $Q_{VOL,}$ within the regression analysis, suggesting that a high $P\theta_{VL}$ is advantageous for neuromuscular power, even after muscle volume has been accounted for. This may reflect a net positive balance of advantages and disadvantages of increasing $P\theta_{VL}$ at the relatively low angles found in this study (< 20°). For PPO, theoretically greater $P\theta_{VL}$ has the advantage of greater physiological cross-sectional area (PCSA) and thus higher force production capacity, but the potential disadvantages of loss of force transmission to the tendon and/or reduction in fascicle length, and thus shortening velocity. In the current study, PPO was unrelated to FL, which is somewhat contrary to the findings of a positive association of FL with sprint running (100 m) performance (Abe *et al.*, 2000). Furthermore, Fl_{VL} was also unrelated to $P\theta_{VL}$ (r = -0.23), suggesting no negative consequence of increasing $P\theta_{VL}$ on Fl_{VL}

Data in this experiment indicated that peak muscle activation recorded with surface EMG exhibited no relationship to PPO, and thus was not a meaningful determinant of PPO in elite cyclists. Therefore, it is possible that more accurate and sensitive measurements of neuromuscular activation, perhaps including surface EMG from more muscles and multiple sites per muscle (Balshaw *et al.*, 2017), as well as alternative normalisation techniques (Lanza *et al.*, 2018), might reveal a greater role for activation in determining PPO. However, given that muscle morphology explained 87% of the variability in PPO, the unexplained variance was relatively small (13%) and the contribution of other independent factors, including neuromuscular activation, appears limited for this performance task.

Sprint cyclists were greater in every measure of the sprint cycling performance test (i.e. PPO +61 %, PPO: Mass +32 %, T_{MAX} +43 %, C_{OPT} +9 % and C_{MAX} +12 %) compared to endurance riders, which is likely to be the consequence of sprint riders

being stronger in all the physiological measurements that had a positive and significant relationship with PPO (i.e. Q_{VOL}, HAM_{VOL} and $P\theta_{VL}$). This perhaps gives further weight to the physiological mechanisms of PPO.

The greater PPO of sprint cyclists (+61 % vs endurance cyclists) appeared to be primarily due to their higher T_{MAX} (+43 %) as opposed to a smaller difference in C_{OPT} (+9 %). The greater T_{MAX} of the sprint cyclists was likely due to their greater Q_{VOL} and HAM_{VOL} as a greater muscle volume provides more sarcomeres in parallel that can exert a greater force/torque (the relationship between the sum of Q_{VOL} and HAM_{VOL} with PPO: $r = 0.81$; $p < 0.001$). No differences were seen for Fl_{VL} which further suggested that it may not be an important physiological determinant of sprint cycling ability.

The higher C_{OPT} and C_{MAX} in sprint cyclists could be attributed to the distribution and number of muscle fibre-types. A strong positive relationship ($r = 0.88$; $R^2 = 0.77$ %; $p < 0.001$) between the proportion and or number of fast-twitch fibres and C_{OPT} has been reported (Hautier *et al.*, 1996). Despite this study only using 10 participants in a correlation study, there is some evidence to suggest that the higher C_{OPT} and C_{MAX} might simply reflect a higher proportion and/or number of fast-twitch muscle fibres.

Although the data collection within the current study was extensive, there were a number of limitations associated with the methodology. Firstly, the selection of two different highly specialised and distinct groups of cyclists may have created coincidental or exaggerated relationships by having big differences between groups for a whole cluster of variables (both assessed variables, e.g. PPO and muscle volume, but also potentially unassessed variables, e.g. fibre type composition, tendon stiffness). Therefore, the strength of the relationships between predictor and outcome variables

in this study may actually be reflective of a range of predictor variables. Secondly, correlation does not demonstrate causality and, therefore, whilst there were very strong relationships between Q_{VOL} and $P\theta_{VL}$ with PPO, and these factors in combination explained 87% of the variation of PPO, the data cannot attribute a cause-effect relationship between changes in muscle volume equate to changes in PPO. On the basis of the interesting findings of the current work, it is recommended that future studies use a wider range of predictor variables (e.g. fibre type composition, surrogate measurements of contractile properties, or tendon stiffness) for cross-sectional analyses and, particularly, that intervention studies examine the effect of changing muscle morphology on cycling PPO.

The VL is a major muscle in PPO production (Akima *et al.*, 2005) and assessment of VL muscle architecture has been used extensively (Kwah *et al.*, 2013). However, these images only capture a superficial two-dimensional representation of the muscle, which may not be representative of the whole muscle or other groups of muscles. A future study could examine multiple muscles involved in cycling and a range of sites within each muscle in order to further investigate the relationship of muscle architecture and PPO.

7.5 Conclusion

In conclusion, these new data showed quadriceps femoris muscle volume and the pennation angle accounted for 76 and 11 % respectively of the variance of PPO in elite cyclists. These findings emphasise the importance of quadriceps muscle morphology for sprint cycling events and reinforce that cyclists and their coaches should be attentive to maximising these characteristics during their preparation and training. In addition, sprint cyclists achieved higher PPO than endurance cyclists, with

T_{MAX} appearing to be the primary explanation for their greater PPO, which was likely because of their greater muscle morphology (Q_{VOL}, HAM_{VOL} and $P\theta_{VL}$).

The work from this chapter starts to address the aims of this thesis and has identified that muscle volume in the thigh and, in particular, when considering the findings of the previous chapter, muscle volume of the quadriceps femoris largely predicts PPO. In addition, $P\theta_{VL}$ was also identified as a predictor, and the evidence from this research could be used to see whether the effects of particular types of training changes PPO in accordance with changes in the aforementioned predictors of PPO. The next chapter sets out to investigate this.

CHAPTER 8

ISOMETRIC VS. TRADITIONAL RESISTANCE TRAINING IN ELITE TRACK SPRINT CYCLISTS

8.1 Introduction

In the previous chapter, a range of established physiological estimates was taken from elite level cyclists from all disciplines ranging from endurance riders (e.g. road riders, time-trial specialists and mountain bikers) to sprint specialists (e.g. track sprint and BMX riders). A number of significant relationships were established and, in particular, muscle volume (of the quadricep femoris) and the pennation angle of the vastus lateralis ($P\theta_{VL}$) were found to be significant predictors of PPO. Whilst the findings from this data collection were beneficial to better understanding what determines PPO, it could be argued that the relationships and results from the previous chapter could have been somewhat exaggerated due to the broad range of ability, making the sample population relatively heterogeneous. Results from a more homogenous specialised group of elite track sprinters who are already highly experienced in resistance and track sprint training would provide a greater test of the theory (Calder *et al.*, 1981) and give insight to what physiologically determines PPO in highly trained sprint cyclists.

Longitudinal studies that have examined changes in sprint cycling ability in parallel with physiological measurements are relatively scarce (Rønnestad *et al.*, 2010, 2015; Koninckx *et al.*, 2010; Leong *et al.*, 2014). Of the studies that have been undertaken, Rønnestad and colleagues (Rønnestad *et al.*, 2010, 2015) examined the introduction of heavy resistance training and monitored the changes in strength and PPO in well-trained or elite endurance riders. The results of these experiments demonstrated improvements in anatomical cross-sectional area (Rønnestad *et al.*, 2010) and maximum strength (Rønnestad *et al.*, 2010, 2015; Koninckx *et al.*, 2010), accompanied with increases in PPO. Other modalities, such as chronic eccentric cycle training (Leong *et al.*, 2014) and maximal low-cadence high-torque concentric cycling

(Koninckx *et al.*, 2010), have also been investigated and revealed improvements in PPO in previously untrained participants. The improvements of PPO from Leong et al. (2014) were associated with an increase in $P\theta_{VL}$ and muscle thickness (a surrogate measure of muscle volume). Whilst these findings are pertinent to understanding the determinants of PPO, Leong et al. (2014) performed a training study that used participants that were previously untrained and did not contain a control group. Their results were somewhat mirrored in the previous chapter of this thesis as $P\theta_{VL}$ and muscle volume (of which muscle thickness is a surrogate measure) were suggested to be predictive of PPO. All of the studies that have previously been published and discussed here have either used untrained or endurance trained cyclists (i.e. no experience of strength training or sprinting) or when national or elite level sprint cyclists have been researched, used basic physiological measurements. The question still remains whether these findings will elicit similar changes in sprinting ability when investigating a well-trained or elite track sprint cycling population. This is particularly important as this population are highly-experienced in resistance training and track sprinting. Thus, the likelihood of markedly improving these physiological measurements is likely to be more difficult to augment (because they are closer to the 'training ceiling') in comparison to untrained individuals (Ahtiainen *et al.*, 2003).

All the aforementioned studies have examined maximum strength or muscle morphology estimates. None have tried to isolate and assess the relationships between neurophysiological factors and sprint cycling ability. One aspect of Chapter 7 was to examine the relationship between peak EMG amplitude of VL, GM and BF during sprint cycling with PPO. No relationships were found, which was thought to be, at least in part, due to the methodological limitations presented by surface EMG in such a ballistic and dynamic movement, as well as using only one EMG electrode per site.

Supramaximal stimulation of the femoral nerve can be used to quantify voluntary activation and cause muscle compound action potentials (M-wave), which can be used to normalise surface EMG signals, helping to reduce some of the aforementioned limitations with surface EMG. To date, no studies have examined the relationship between voluntary activation and sprinting ability in addition to quantifying the EMG amplitude relative to M-wave amplitude. Doing so will provide a better insight into any possible relationship between neurophysiological factors and sprint cycling ability, and potentially provide more focused training methods.

Resistance training, aiming to improve maximum strength, is a foundation of an elite track sprint cyclists training programme. The most effective way to improve maximal strength is still relatively unknown. However, traditional gym-based exercises that are most commonly used to improve strength are dynamic in nature and exercises are usually made up of eccentric and concentric contractions. Of the three main muscle contraction types (eccentric, isometric and concentric), it is well-established that concentric muscle contractions produce lower forces and do not provide the most optimal training stimulus to improve maximum force (Gordon *et al.*, 1966). As such, traditional training exercises are usually 'concentric limiting', meaning that because there is a concentric component, the maximum loads/forces produced are limited to what can be produced concentrically and are likely not to be as high as the forces that could be produced isometric and/or eccentrically. Maximal isometric strength training has been previously investigated and reported to stimulate large and rapid improvements in maximal strength, but it is highly angle-joint specific (Young *et al.*, 1985; Thépaut-Mathieu *et al.*, 1988). In contrast, dynamic contractions that involve a range of muscle lengths, and hence joint angles, have shown more modest improvements throughout the whole range of motion/joint-angles (Graves *et*

al., 1989). Previous work has shown that maximal isometric training of the adductor pollicis leads to significant improvements in maximal power (of the power-velocity relationship). This was achieved by increasing the speed of movement against high mechanical resistance, consequently improving maximal extrapolated force in the underpinning force-velocity relationship (Duchateau & Hainaut, 1984). Chapter 5 of this thesis demonstrated that maximal torque production during an isometric cycling task exhibited a very large relationship to PPO and was a better predictor of PPO compared to maximal torque production of other single joint muscle groups. A next logical step would be to examine whether a cycling-specific isometric task can be adapted to be used as a novel cycling-specific training tool; one similar to Duchateau and Hainaut (1984) which helped modulate improvements in PPO by improving T_{MAX} of the T-C relationship.

As such, the aim of this study was to use a pool of elite and/or highly-trained track sprint cyclists to i) investigate and compare the changes of P-C and T-C relationships, along with selected neuromuscular measurements, in traditional resistance training and an isometric maximum strength cycling protocol, prescribed alongside a track sprinter's habitual training; and ii) whether any changes in the physiological measurements can predict changes in sprinting ability (i.e. PPO).

8.2 Methodology

8.2.1 Sprint Cyclists

In total, twenty-four (seventeen men) track sprint cyclists (age, 23 ± 3 yr; mass 80.8 ± 10.9 kg and stature 172.0 ± 9.4 cm) participated in this study. The 200 m personal best time for the male sprinters was between 9.6 to 10.8 s (within 1 – 12% of sea-level World Record) and 10.9 to 12.0 s (within 3 – 11% of sea-level World Record) for the female sprinters. Two men's and one woman's tandem also participated in this

study. The able-bodied pilots also competed individually on their solo bikes; the stokers were visually impaired but otherwise able-bodied. The male tandems had personal best 200 m times of 9.6 (current World Record) and 9.9 s, whilst the women tandem had a best 200 m time of 10.6 s (current World Record). Of the sprinters, four had participated in two Olympic games, winning three Olympic Gold, one Silver, and one Bronze medal. Thirteen had competed in senior World Championships winning four silver medals. The tandem pilots and stokers had participated in three Paralympic games, winning two Gold, one Silver, and one Bronze medal, as well as having participated in nine World Championships, winning a total of twenty-one medals. The remaining were either competing internationally at UCI Class one or two track competitions, World Cups, senior or under-23 level or had won a National medal in a track sprint event.

8.2.2 Study Design

All the sprinters who participated in this study did so after one or two weeks off from any structured training followed by a two-week 're-introduction' period during which the athletes slowly and progressively resumed their normal full training schedule. The testing battery was completed after the riders had 36 hours of rest and were then split into two groups: an AM and PM session. In the AM session, each sprinter had a body composition assessment using a DXA scan. For the PM session, they individually reported to the lab and completed a neuromuscular assessment followed by a sprint cycling performance test. The neuromuscular assessment involved them having the muscle architecture of both VL muscles captured using B-mode ultrasound. Then, a series of isometric maximal voluntary contractions (MVCs) were performed with supramaximal stimulation of the femoral nerve, delivered during and 2 s post, to determine voluntary activation. Subsequently, explosive voluntary

isometric contractions. The process was then repeated for the contralateral leg. After a short rest period (~5 mins), MVCs were performed during isometric cycling (ISO-CYC) before a sprint cycling test was performed to measure P-C and T-C relationships. All participants performed the full battery of physiological tests and the sprint cycling lab test before, and after, a 6-week training period.

Prior to completing the first physiological assessment and sprint cycling test and consulting with the various coaches, the sprinters were divided into two groups: "current best practice" controls (CON; n = 11), largely comprised of 'podium-level' international sprinters, and intervention (INT; n = 13), mainly composed of current international under-23 programme, national level and 'podium-level' riders. The CON group performed their habitual training routines whilst the INT group performed an identical programme in terms of structure and sessions but used ISO-CYC MVCs in place of their gym session.

8.2.3 Body Composition Assessment

In the morning of both pre- and post-assessments, cyclists reported for body composition assessment in a 10 h fasted state. They were asked to wear appropriate clothing (i.e. loose-fitting gym attire), which would allow proper scanning of the entire body. Dual energy X-ray absorptiometry (DXA; Lunar iDXA, GE Healthcare, Madison, WI) used a narrow fan beam to assess body composition. TLBM and LBLM were recorded as both have been shown to have significant relationships with PPO (Perez-Gomez *et al.*, 2008). Once the cyclists had completed their DXA scan, they reported to the lab in the PM, approximately 2 - 3 h after they had consumed their main meal.

8.2.4 Laboratory Assessment

8.2.4.1 Isometric Dynamometer

A custom-made dynamometer was used to measure voluntary and evoked forces. Refer to section 3.3.4.2 for more specific details of the methodology. The session on the isometric dynamometer set-up is shown in Figure 8-1; all the sprinters started the PM session on the isometric dynamometer.

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Figure 8-1: Set up of custom-built dynamometer, modified cycling ergometer with surface electromyography and constant-current stimulator.

8.2.4.2 Muscle Morphology Assessment

Once the sprinters were appropriately positioned and secured on the dynamometer, assessment of the VL muscle architecture commenced (see section 3.3.5 for further details). Images were imported into analysis software (ImageJ, v.1.46; National Institutes of Health, Bethesda, MD, USA) to measure muscle thickness (MT_{VL}) and $P\theta_{VL}$. The $P\theta_{VL}$ was measured as the angle between the fascicular path

and the insertion of fascicles into the deep aponeurosis and MT_{VL} is described as the distance between the superficial and deep aponeurosis.

8.2.4.3 Surface Electromyography

Once the sprinters had had their muscle architecture assessed, wireless surface EMG electrodes were attached on the skin of the muscle belly of each superficial quadricep femoris muscle, as described in section 3.3.8.

8.2.4.4 Evoked Twitch Force

Once the surface EMG electrodes were placed, the sprinters were 'connected' to the constant-current stimulator, as outlined in section 3.3.9.

8.2.4.5 Knee Extension Maximum Voluntary Contractions

Three isometric sub-maximal contractions that were 5 s in length were performed at 50, 75 and 90% of perceived maximum; each was separated by 60 s of passive rest. Once the warm-up contractions were complete, single stimuli were delivered to the relaxed muscle beginning at 50 mA and increasing by 25 mA until a plateau occurred in both twitch and M-wave amplitude. Supramaximal stimulation was delivered by increasing the final stimulator output by 30 % (mean intensity 355 ± 32 mA). Subsequently, the cyclists were asked to perform maximal 4 s isometric MVCs. Participants were informed that once a plateau in the maximal force trace was observed (visually relayed to the sprinters and investigators on two different monitors), a single supramaximal stimulation would be delivered, and they were instructed to 'keep pushing as hard as possible through the stimulus'. After each MVC, the force trace was allowed to return to baseline for 2 s before another single supramaximal

stimulation was delivered. A total of 3 MVCs were performed with 60 s rest between efforts. Vigorous verbal encouragement was given for the duration of each effort.

8.2.4.6 Knee Extension Explosive Voluntary Contractions

Once the MVCs (with femoral twitch) were complete, the cyclists had 5 mins of passive rest until they started their explosive voluntary contractions as described in section 3.3.4.2. Ten explosive voluntary contractions, the neuromuscular function protocol was repeated for the contralateral limb.

8.2.4.7 Isometric Cycling

After another 5 min period of passive rest, the cyclists then mounted a custom-built ergometer which could be made isometric to measure their maximum cycling-specific torque production. Before the ergometer was made isometric, the ergometer was adjusted to match the cyclists track bike position, and the cyclists were allowed a 3 min warm-up during which they pedalled at between 80 – 90 RPM and 100 – 150 W. Once this was done, maximum cycling-specific torque production (ISO-CYC) protocol commenced as described in section 3.3.4.3 and Figure 8-2.

Figure 8-2: Participants performing the isometric cycling task (ISO-CYC) with real-time feedback of torque production from the cranks being provided on the monitor

8.2.4.8 Sprint Cycling Test

The concluding segment of the lab visits was an isovelocity sprint cycling performance test as described in section 3.3.2.1 and identical to 7.2.5. The maximal isovelocity efforts were used to evaluate PPO, P-C and T-C relationships. All efforts were performed in the saddle, with each cyclist using the 'drop' handlebars (Figure 8-3).

Figure 8-3: An elite sprint cyclist performing an isovelocity effort

8.2.4.9 Training

After the initial assessment, sprinters were split into two groups for the course of 6 weeks: intervention (INT) and control (CON). The training was individual; however, all had similar content and general structure. Two track cycling sessions per week were undertaken, which were split into "high torque" efforts, such as stationary or slow-moving (starting maximal efforts that were between 3 – 12 reps and ranged between 6 – 20 s) and "high power" efforts (between 3 – 5 reps of 10 – 35 s), where the efforts were started from higher cadences/velocities. Gym sessions alternated during the intervening two weeks between sessions one and two and two and three, road rides. The road rides were prescribed to be within 60 - 90 mins in duration and to be between 2 – 4 out of 10 on an RPE scale (Borg, 1982). The intervention and control

groups had identical weekly track cycling sessions, gym sessions and scheduled road rides. The only major divergence from INT and CON was the gym content. The CON group had their habitual gym sessions that were structured in a similar fashion but was tailored to the individual. After warming-up, the gym sessions started with a bilateral compound multi-joint exercise. This was usually either back squat, front squat or deadlift, which ranged between ~85 – 98% of their predicted 1 RM, low repetition (i.e. < 5) and between 3 – 5 sets. This was usually followed by another multi-joint exercise with similar intensities such as cleans or barbell, dumbbell lunges or single or double leg-press. After the two main exercises, uni-lateral exercises were completed but were higher in volume (6 – 12 repetitions) and lower in load (~70 – 90% of predicted 1 RM), such as leg-press or single-leg Romanian deadlift. This was followed by auxiliary exercises, such as knee extensions, hamstring curls and calf raises. Lastly, accessory exercises which were focused on the conditioning the trunk, such as plank and side plank exercises, were done.

The INT group had their gym sessions altered to have their main exercise and focus as a progressive maximal isometric cycling protocol (ISO-CYC) instead of their traditional exercise. The progression (Figure 8-4) refers to the reps and sets performed in 3 separate positions for each lead leg: 45°, 90° and 135° from top dead centre. All efforts were maximal and 3 s in length. Between each rep, 60 s of passive rest was given. Between each set (and crank position change) 3 min of passive rest was given. For all efforts, the cyclists had real-time feedback on the torque produced through the crank arms via custom-made software (CrankCam, Sports Engineering Department, Sheffield Hallam University, UK). As part of the arrangement with the coaches of the sprinters in the INT group for them to participate in this study, it was agreed that the INT sprint cyclists would perform 3 sets of 5 reps of the sprinters preferred compound

exercise at ~70 - 75% of predicted 1RM after the ISO-CYC protocol. This was to ensure that, should the intervention not augment any positive improvements in PPO and sprint performance, the sprinters would then have attenuated any regression in their habitual gym training. Both CON and INT had similar accessory exercises that ended each gym session, such as core stability work.

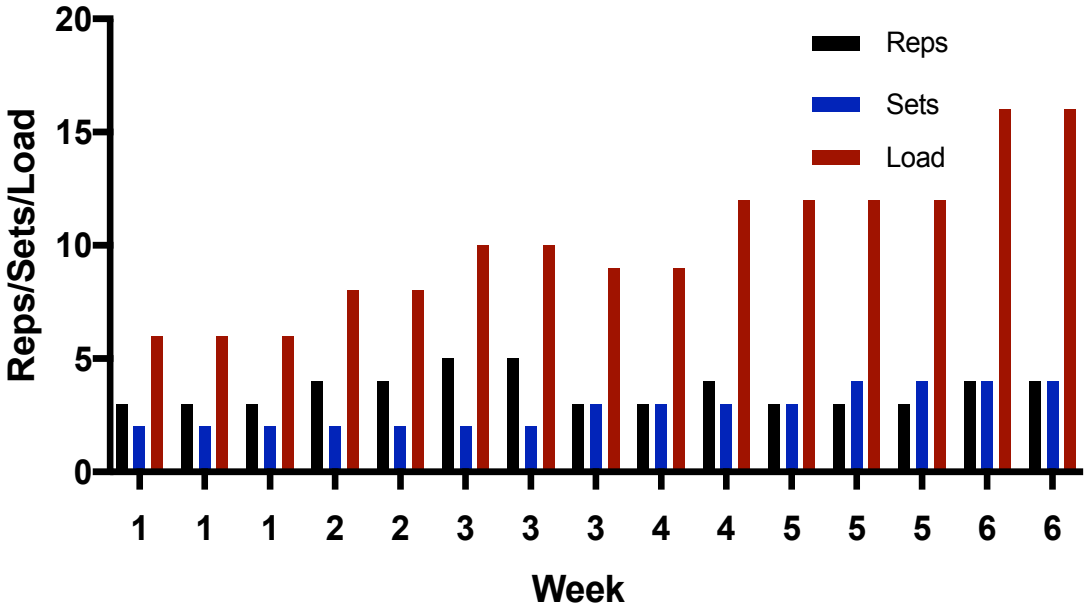

*Figure 8-4: Schematic of the isometric cycling ergometer sessions over a 6-week training period. Repetition (reps; black), sets (blue), load (reps * sets; red) of each individual session within the weeks.*

Figure 8-5: Participants simultaneously performing maximal cycling-specific isometric training as part of the intervention group (top); side-on picture of participants performing isometric cycling, with real-time feedback being provided by computer monitor (bottom).

8.2.5 Data Analysis

Three different ultrasound images were used for each leg on each visit to measure the muscle architecture of VL. The MT_{VL} and $P\theta_{VL}$ were measured three separate times on different fascicles per image, and the average of all the measurements on right and left VL was accepted as the architecture measurement for each visit. When analysing the voluntary contractions of the three efforts, the effort with the highest maximum torque produced was taken as the MVC, taken as the peak torque trace prior to the evoked femoral twitch. The level of knee extensor voluntary activation was calculated, as outlined in section 3.3.9. Of the 10 explosive voluntary contractions, the highest 3 torque measurements at 50, 100, 150 and 200 ms for each leg were used and averaged (Maffiuletti *et al.*, 2016). During ISO-CYC, the highest peak torque measured for each individual crank arm for all six efforts was used and averaged, as previously described in section 5.2.7.

The highest torque (and therefore, greatest power) output averaged over a revolution (top dead centre to top dead centre) during each isovelocity effort was used for analysis to plot P-C and T-C relationships. The P-C and T-C relationships were established and PPO calculated, by fitting a quadratic and linear equation respectively, by the least square method, as previously described in section 7.2.5. The apex of the P-C relationship was interpolated and PPO and cadence at PPO (C_{OPT}) were established. With respect to the T-C relationships, maximal torque (T_{MAX}) and maximal cadence (C_{MAX}), these were extrapolated as has been done throughout this thesis. In addition, power and torque measurements were also normalised to body mass. Though PPO from P-C and T-C relationships are formulated from absolute values. However, their translation to track speed and/or performance is also influenced by body mass (Martin *et al.*, 2006; Driss & Vandewalle, 2013*b*), particularly as the

ratio of power (and/or torque) to body mass is a determinant of performance in track sprint cycling performance, as outlined earlier in section 2.5. Consequently, power in the P-C relationship (and therefore, PPO) and torque in the T-C relationship (and therefore, T_{MAX}) are presented and analysed in both absolute values as well as being normalised to body mass.

8.2.6 Statistical Analysis

All results were reported as mean ± SD. Absolute changes and percentages were also reported for measurements for both training groups pre- and post-intervention. Absolute changes in all of the measurements were used to assess any pre-/post-training differences by using a mixed-factorial, two-way repeated-measures ANOVA by time (i.e. pre- and post-) and group (CON and INT). Subsequently, relative (%) changes in the independent physiological variables were plotted against relative (%) changes in PPO to form Pearson's product-moment correlations (r), the significance of the relationship, as well as corresponding coefficient of determination (R^2). Any significant relationships were then put into a step-wise regression to assess which measurements significantly predicted PPO.

8.3 Results

The absolute and normalised pre- and post-P-C and T-C relationships of both INT and CON are presented in Figure 8-6 (a) and (b), respectively. Significant main effects differences were seen for within-participants (i.e. between pre- and post-testing) for T_{MAX} ($F_{(1,22)} = 6.291$; $p = 0.02$); $Torque_{200}$ ($F_{(1,22)} = 6.189$; $p = 0.021$) and $P\theta_{VL}$ ($F_{(1,22)} = 24.518$; $p < 0.01$). Of all the performance measures of the P-C and T-C relationships, significant interaction between group (i.e. CON and INT) and time (i.e.

pre- and post-testing) were seen between PPO:BM ($F_{(1, 22)} = 3.27$; $p = 0.085$); T_{MAX}:BM ($F_{(1,22)} = 4.39$; $p = 0.048$). Of the physiological measures, only ISOCYC ($F_{(1,22)} = 12.075$; $p = 0.002$) showed significant interaction between group and time. Post-hoc Bonferroni pairwise tests showed that the INT group significantly increased in PPO:BM ($p = 0.004$), T_{MAX}:BM ($p = 0.003$) and ISOCYC ($p = 0.001$). No significant changes were seen in the post-hoc analysis of the CON group between pre- and post-tests of the aforementioned measures. All other changes in absolute and normalised P-C and T-C relationships did not reach statistical significance. The results are summarised in Table 8-1 and 8-2.

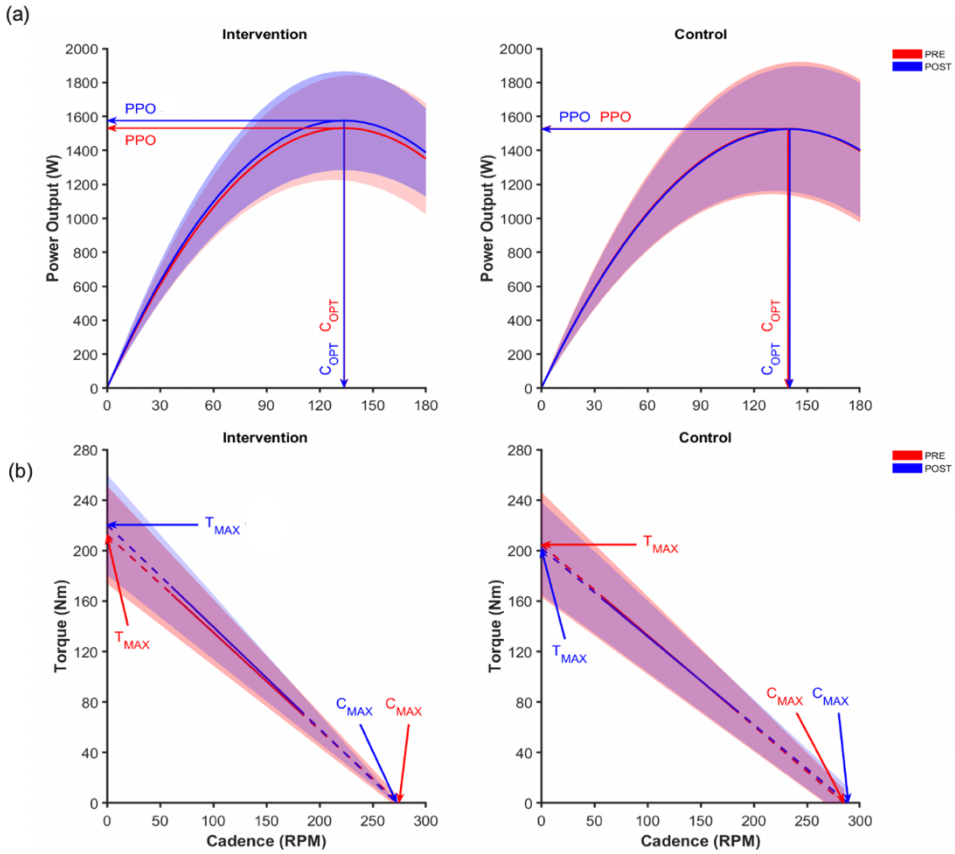

Figure 8-6: Absolute (a) power-cadence and (b) torque-cadence relationships of intervention (n = 13) and 'best-practice' control groups (n = 11). Mechanical peak power output (PPO) and optimal cadence (C_{OPT}) pre- and post-intervention are annotated on the power-cadence relationship. Maximum extrapolated torque (T_{MAX}) and maximum extrapolated cadence (C_{MAX}) pre- and post-internvetion are also highlighted for both groups. Shaded areas represent the standard deviation around the respective means which are represented by solid lines (measured values) and dotted lines (extrapolated values).

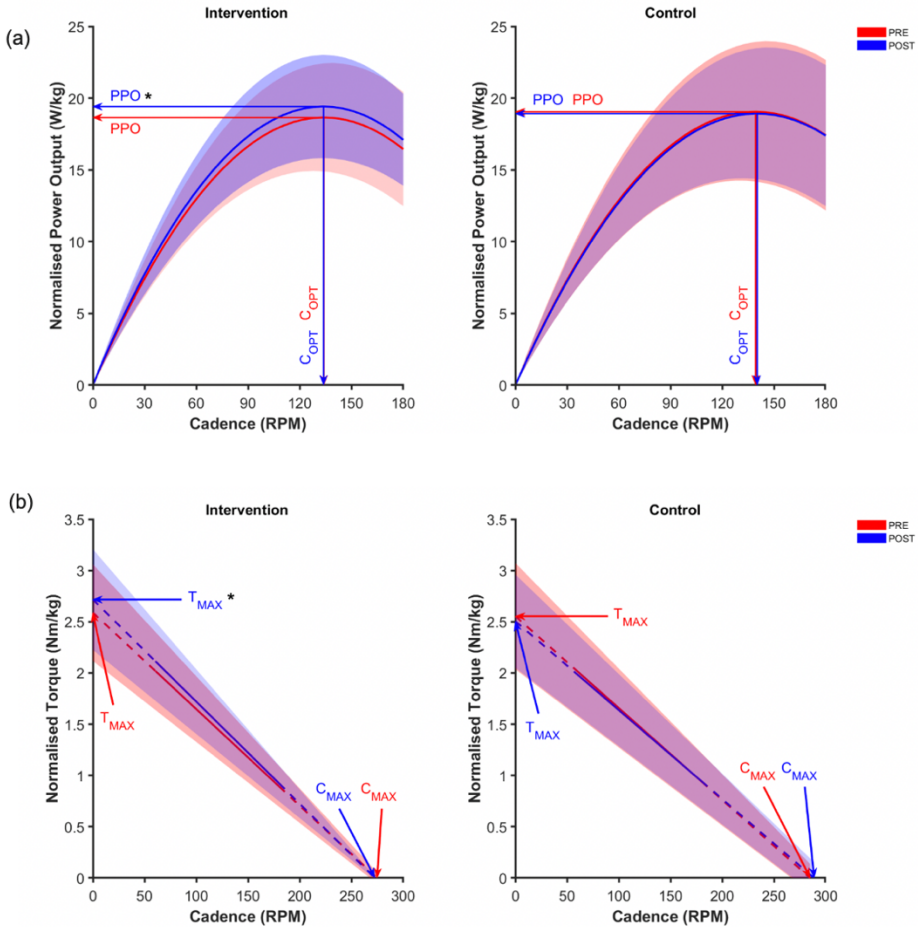

*Figure 8-7: (a) power-cadence and (b) torque-cadence relationships that are normalised to body mass of the intervention group (n = 13) and 'best-practice' control groups (n = 11). Mechanical peak power output (PPO) and optimal cadence (C_{OPT}) pre- and post-intervention are annotated on the power-cadence relationship. Maximum extrapolated torque (T_{MAX}) and maximum extrapolated cadence (C_{MAX}) pre- and post-internvetion are also highlighted for both groups. Shaded areas represent the standard deviation around the respective means which are represented by solid lines (measured values) and dotted lines (extrapolated values). * denotes significant increase from baseline measures.*

*Table 8-1: Pre- and Post-intervention assessments of intervention group (INT) and control (CON) of peak power output (PPO), PPO normalised to body mass (PPO:BM), optimal cadence (C_{OPT}), maximum torque (T_{MAX}), T_{MAX} normalised to body mass (T_{MAX}:BM) and maximal cadence (C_{MAX}); * denotes significant main effect change; # denotes significant change from pre-measure ($p < 0.05$).*

	INT				**CON**			
	Pre-	**Post-**	**Difference**	**% Change**	**Pre-**	**Post-**	**Difference**	**% Change**
Body Mass (kg)	82.1 ± 13.1	81.1 ± 12.0	−1.0	−1.2	80.2 ± 8.3	80.6 ± 8.0	0.4	0.5
PPO (W)	1537 ± 307	1581 ± 287	44.0	2.9	1541 ± 389	1536 ± 366	−5.0	−0.3
PPO:BM (W/kg)	18.7 ± 2.5	19.5 ± 2.3	0.8*	4.3	19.0 ± 3.5	18.9 ± 3.1	−0.1	−0.5
C_{OPT} (RPM)	138 ± 9	138 ± 9	0.0	0.0	144 ± 13	142 ± 12	−2.0	−1.4
T_{MAX} (N.m)*	207 ± 32	214 ± 32	7.1	4.2	194 ± 34	196 ± 34	2.4	1.0
T_{MAX}:BM (N.m/kg)	2.5 ± 0.2	2.6 ± 0.3	0.1*	4.0	2.6 ± 0.5	2.6 ± 0.5	0.0	0.0
C_{MAX} (RPM)	276 ± 18	277 ± 19	1.0	0.4	289 ± 12	284 ± 24	−5.0	−1.7

Table 8-2: Pre-, Post-, absolute difference and percentage (%) change of measured physiological dependent variables for both intervention group (INT) and 'best-practice' controls (CON) for lean body mass, lean lower body mass, pennation angle of the vastus lateralis ($P\theta_{VL}$), muscle thickness of the vastus lateralis (MT_{VL}), peak torque through maximum voluntary contraction of the knee extensors (MVC), torque at 50ms ($Torque_{50}$), 100ms ($Torque_{100}$), 150ms ($Torque_{150}$) and 200ms ($Torque_{200}$), peak torque of isometric cycling (Iso-Cyc), muscle activation level of the knee extensors, peak muscle activation of vastus lateralis (VL), vastus medialis (VM) and rectus femoris (RF) during PPO normalised to peak-to-peak M-Wave and peak-to-peak M-wave amplitude of VL, VM and RF; * denotes significant main effect between pre- and post-testing ($p < 0.05$); # denotes significant increase between pre- and post-testing ($p < 0.05$).

	INT				CON			
	PRE-	POST-	Difference	% Change	PRE	POST	Difference	% Change
Total Lean Body Mass (kg)	63.8 ± 10.9	63.9 ± 10.4	0.1	0.2	63.3 ± 9.6	63.5 ± 9.7	0.2	0.3
Lean Lower Body Mass (kg)	23.2 ± 4.0	23.1 ± 3.8	−0.1	−0.4	22.6 ± 3.4	22.7 ± 3.5	0.1	0.4
$P\theta_{VL}$ (°)*	17.1 ± 2.0	18.0 ± 1.7	0.9	5.2	17.1 ± 2.8	18.2 ± 2.4	1.1	6.4
MT_{VL} (mm)	22.4 ± 2.6	23.0 ± 3.0	0.6	2.6	21.9 ± 3.5	23.3 ± 3.9	1.4	6.3
MVC (N·m)	309 ± 75	323 ± 65	14	4.5	296 ± 44	296 ± 44	0	0
$Torque_{50}$ (N·m)	115 ± 33	118 ± 23	3	2.6	114 ± 28	109 ± 30	−5	−4.4
$Torque_{100}$ (N·m)	189 ± 45	196 ± 28	7	3.7	184 ± 36	183 ± 40	−1	−0.5
$Torque_{150}$ (N·m)	227 ± 53	240 ± 37	13	5.7	226 ± 40	227 ± 43	1	0.4
$Torque_{200}$ (N·m)*	241 ± 59	260 ± 43	19	7.9	242 ± 39	244 ± 37	2	0.8
Iso-Cyc (N·m)	400 ± 78	450 ± 113#	50	12.5	383 ± 98	367 ± 82*	−16	−4.2
Activation Level (%)	97.1 ± 2.0	97.3 ± 2.4	0.2	0.2	97.6 ± 2.5	97.5 ± 2.2	−0.1	−0.1
Peak Muscle Activation during PPO (%)								
VL	8.64 ± 2.63	9.73 ± 3.86	1.09	12.6	7.45 ± 3.34	6.86 ± 2.79	−0.59	−7.9
VM	7.87 ± 3.62	8.95 ± 3.62	1.08	13.7	8.34 ± 3.50	7.90 ± 3.32	−0.44	−5.3
RF	8.04 ± 4.46	7.11 ± 4.07	−0.93	−11.5	7.75 ± 3.19	6.34 ± 2.61	−1.41	−18.2
M-Wave amplitude (mV)								
VL	5.52 ± 2.92	5.86 ± 3.07	0.34	6.2	5.56 ± 2.95	7.23 ± 0.90	1.67	30.0
VM	5.53 ± 3.40	6.66 ± 3.04	1.13	2.0	5.53 ± 3.27	6.17 ± 3.30	0.64	11.6
RF	5.30 ± 1.90	6.10 ± 2.78	0.8	15.1	4.31 ± 2.13	4.23 ± 2.93	−0.08	−1.9

Once all pre- and post-changes of PPO and predictive measurements were converted to percentage changes, the difference between testing sessions was calculated and Pearson's correlation coefficient (r), the significance of the relationship and variance (R^2) were formed with the individual independent variables with PPO (Table 8-4). Of these relationships, only $Torque_{150}$ and $Torque_{200}$ exhibited significant relationships (Figure 8-8), were put into a step-wise regression model and significantly predicted PPO $F_{(1, 22)} = 6.21$; $p = 0.014$; $R^2 = 22$ %. However, of the two independent variables that were used for the step-wise regression, only $Torque_{200}$ contributed significantly to the prediction ($p = 0.014$). $Torque_{150}$ did not contribute to the model ($p = 0.972$). Changes in PPO were equal to $0.524 + 0.236*(Torque_{200})$ where $Torque_{200}$ is measured in N.m at 200 ms.

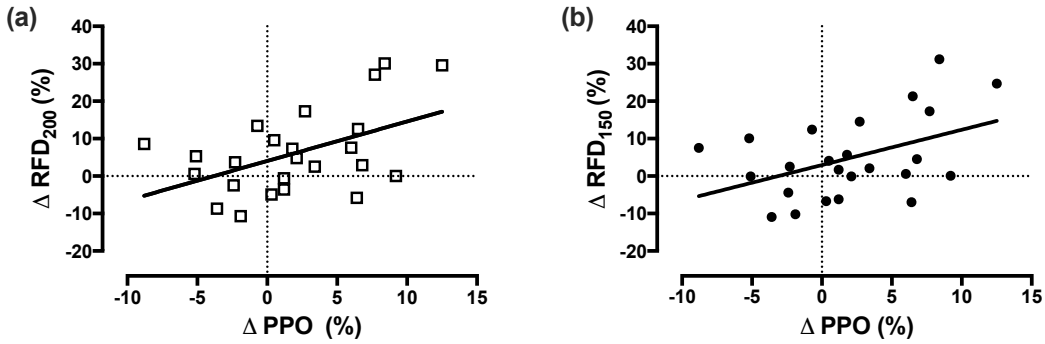

Figure 8-8: Relative (percentage) changes in peak power output (PPO) in relation to relative (percentage) changes in (a) torque at 200 ms ($Torque_{200}$); and (b) torque at 150 ms ($Torque_{150}$). The relationship exhibited with changes with PPO and $Torque_{200}$ was $y = 1.05x + 4.04$ and the relationship exhibited with changes with PPO and $Torque_{150}$ was $y = 0.94x + 2.95$

*Table 8-3: Pearson's correlation coefficient (r) of the individual physiological predictors with PPO, the significance of the relationship (p-value) and coefficient of variation (R^2). The individual physiological predictors are lean body mass (LBM); lower body lean mass (LBLM); Isometric Cycling (ISO-CYC); Maximum voluntary contraction of knee extensors (MVC); rate of force development at 50ms ($Torque_{50}$), 100ms ($Torque_{100}$), 150ms ($Torque_{150}$) and 200ms ($Torque_{200}$); pennation angle of the vastus lateralis ($P\theta_{VL}$); muscle thickness of vastus lateralis (MT_{VL}); Voluntary muscle activation of knee extensors (Vol Muscle Act); * denotes $p < 0.05$.*

	r	**p-value**	**R^2**
LBM	0.30	0.15	0.09
LBLM	0.20	0.35	0.04
ISO-CYC	0.22	0.30	0.05
MVC	0.36	0.08	0.17
$Torque_{50}$	0.26	0.22	0.07
$Torque_{100}$	0.33	0.12	0.11
$Torque_{150}$	0.42	0.04*	0.18
$Torque_{200}$	0.47	0.02*	0.22
$P\theta_{VL}$	0.20	0.35	0.04
MT_{VL}	0.26	0.22	0.07
Vol Muscle Act	0.07	0.75	< 0.01

8.4 Discussion

To the best of the author's knowledge, this is the first study to forensically investigate changes in a range of putative physiological measurements with corresponding changes in PPO, P-C and T-C relationships using a highly-trained, elite track sprint cycling sub-population. As such, the principle findings of this experiment were: 1) sprint cycling training increases T_{MAX}, $P\theta_{VL}$, and $Torque_{200}$; 2) replacing maximal strength training in the gym for maximum isometric cycling augments PPO:BM, T_{MAX}:BM and ISOCYC over a 6-week period; 3) changes in explosive strength measured at 200 ms ($Torque_{200}$) was shown to be the only significant off-bike predictor with changes in PPO.

The significant differences for the main effects suggested sprint cycling training increases T_{MAX}, $P\theta_{VL}$, and $Torque_{200}$. These findings could suggest that, at least in the first instance, sprint cycling training (for the elite population) improves T_{MAX} in the T-C relationship before significantly affecting the P-C relations and consequently, PPO. Furthermore, the physiological mechanisms underpinning the increase in T_{MAX} could be due to increases in $P\theta_{VL}$, and $Torque_{200}$. The increase in $Torque_{200}$ rather than $Torque_{50}$, $Torque_{100}$ and $Torque_{150}$ suggests that the physiological or neuromuscular improvements are more morphological or within the tendons rather than neural. This adds more weight that the increase in $P\theta_{VL}$ is likely to a key physiological determinant that is associated with changes in T-C relationship. The increases in $P\theta_{VL}$ suggests an increase in sarcomeres in parallel resulting in a greater PCSA causing an increase in force production and transfer through the connecting tendons. Leong et al. (2014) showed that the increases in $P\theta_{VL}$ were associated with increases in PPO in untrained participants. The only plausible reason why there was no change in PPO or P-C relationships, despite an increase in $P\theta_{VL}$ in this data collection, which is eluded to in

Leong et al. (2014), would be because highly-trained elite sprint cyclists might need a longer time period to express these changes on the sprint cycling test.

The only difference between the training CON and INT intervention groups was that INT sprinters replaced their traditional resistance gym training sessions with a progressive maximal isometric cycling-specific strength protocol. The INT group exhibited improvements in PPO:BM and $T_{MAX:}$BM increased. The findings from this intervention mirrors previous work, but from a mutli-joint sprint cycling perspective (Duchateau & Hainaut, 1984). They suggested the plausability that training at maximal isometric force (F_{MAX}) coincided with "increases in the speed of movement against high mechanical resistances". Consequently, muscle maximum power improved by improving F_{MAX} in the underpinning force-velocity relationship (Duchateau & Hainaut, 1984). The sprint cycling equivalent is demonstrated in this experiment where maximum ISO-CYC training concided with increases in the speed of movement against high mechanical resistances, consequently improving PPO:BM by increasing T_{MAX}:BM (cycling equivalent of $F_{MAX;}$ refer to section 2.6 for further explanation) of the T-C relationship and, therefore, PPO (Duchateau & Hainaut, 1984). This could be useful for sprint cyclists as an increase in PPO:BM can improve standing start performance as well as accelerations from low moving velocities where rolling resisitance and body mass are the largest contributors to resistive forces (as explained in section 2.5 . Furthermore, the INT group exhibited a significant improvement of ISO-CYC, a cycling specific measure of strength by 12.5%. This is somewhat expected as the training intervetion was focused around using ISO-CYC.

Conversely, no changes were seen in absolute or normalised PPO, P-C and T-C relationships for the CON sprinters. This could be due to the lack of specificity of the gym-based resistance training programme of the CON sprinters. Despite their gym

programmes progressing in repetitions, sets and load of their exercises, suggesting that there is a strong likihood that improvements in strength occurred, the CON sprinters did not exhibit any improvement in any of the pre- and post-strength tests (i.e. maximal voluntary strength, voluntary explosive strength and ISO-CYC). As such, there may be a certain delay or minimum time-frame where strength and sprint cycling ability would be expressed, as has been previously demonstrated (Leong et al., 2014).

Other than the muscle architecture of the VL, no other physiological changes were seen in either group. Chapter 7 of this thesis, along with a number of other studies, suggests that muscle mass is strongly associated with sprint cycling ability. The lack of association between changes in PPO and changes in any of the physiological measurements (e.g. DXA to measure muscle mass) suggests that perhaps the instruments used in this study are not sensitive enough to reflect the changes in PPO, particularly considering the duration of the time-frame.

Maximal strength has been reported in this thesis (see Chapter 6) and other studies in the literature to either predict and/or be significantly related to sprint cycling ability (Driss *et al.*, 2002; Stone *et al.*, 2004; Koninckx *et al.*, 2010; Kordi *et al.*, 2017). To date, no experiment has examined whether changes in off-bike measurements predict changes in sprint cycling ability (e.g. PPO). The results showed that only changes in explosive strength at 150 ms ($Torque_{150}$) and 200 ms ($Torque_{200}$) are related to changes in PPO and of those, only $Torque_{200}$ was shown to be a predictor of PPO. Whilst there have been conflicting reports on whether explosive strength is associated with sprint cycling ability in previous cross-sectional studies (Driss *et al.*, 2002; Stone *et al.*, 2004), this is the first finding that significantly predicts a change in an off-bike measurement with a change in sprint cycling ability. Potentially, athletes, coaches and

practitioners can measure and monitor changes in explosive strength ($Torque_{200}$) to examine how their training is affecting their sprinting ability/PPO.

The physiological variables that influence explosive strength are summarised in Figure 8-9. In this data collection, no relationship with PPO was observed with any of the shorter explosive torque time windows (i.e. at 50 and 100 ms) where the neural factors are most prominent (i.e. < 100 ms; Aagaard et al., 2002; de Ruiter et al., 2012). This, as already mentioned, is likely to eliminate neural factors (that influence explosive strength) as likely factors that affect PPO. Physiological factors that determine explosive strength over longer durations (e.g. 200 ms) are likely to be more influenced by speed-related and maximal voluntary force-related properties of the muscle (Andersen & Aagaard, 2006; Folland *et al.*, 2014) and, as such, most likely to influence PPO. Shifts in muscle fibre-type properties are also unlikely as they largely influence the early time-phase in explosive strength measurements (Häkkinen *et al.*, 1985; Andersen & Aagaard, 2006; Folland *et al.*, 2014). Hence, by process of elimination, the likely cause of the change in explosive strength which predicts the change in PPO may be rooted in changes to the muscle architecture of muscle-tendon unit/stiffness. This could be a potential mechanism to investigate in future experiments.

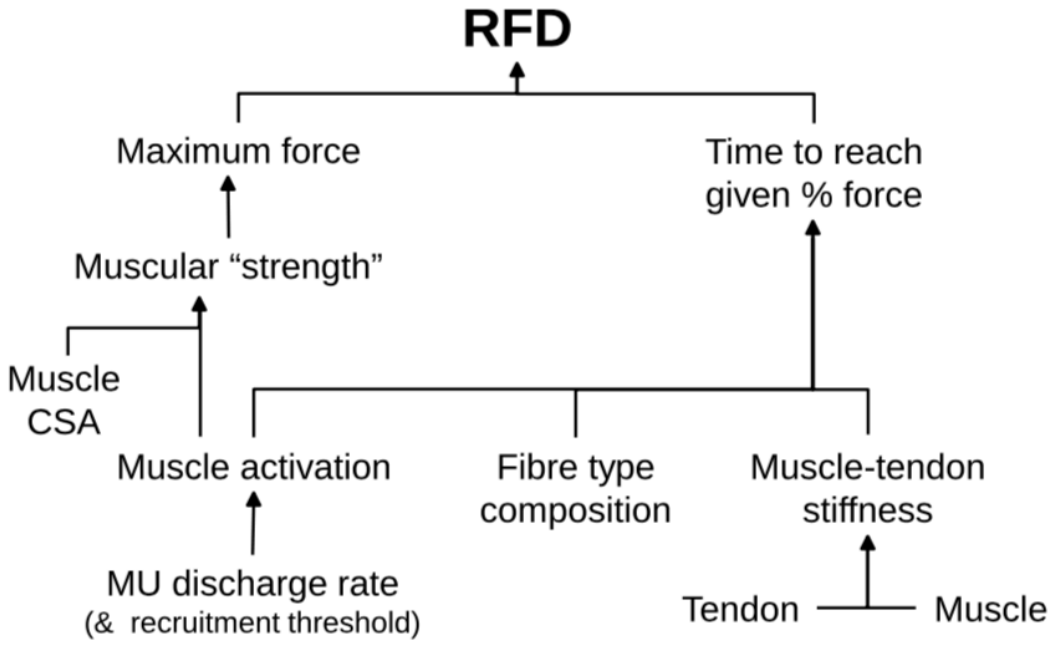

Figure 8-9: Summary of the numerous physiological factors that determine explosive strength (RFD). Taken from Maffiuletti et al. (2016).

This study was not without its limitations. Firstly, due to the constraints of the experiment and agreements with coaches to include the 'podium' level sprint cyclist, there was lack of randomisation between the two groups (i.e. CON and INT). The CON group had more 'senior' level/ 'established' riders than the INT group which was compromised of younger, less 'senior'/ 'established' riders. The concept of randomisation is to eliminate or at least, minimise any potential bias that may arise. Secondly, the instruments used to quantify many of the physiological measures may not have been distinguish any changes (should they have occurred). For example, muscle mass was measured using surrogate measurements (DXA and ultrasound). Using the 'gold' standard MR imaging might have given a more detailed insight of changes in muscle mass and have been more likely to detect changes in specific muscle groups. Thirdly, the time scale of the intervention could have been longer in duration and spread across a year or season, which would have given a better indication of the changes in the P-C and T-C relationships, changes in the physiological estimates, and

the efficacy of the different training modalities. Lastly, there were twenty-four track sprinters that participated in the study and a larger cohort might have helped increase the rigor of the research. Although, this study used 89% of the elite sprint cyclists in the UK, so getting additional cyclist would have been near impossible to achieve. Whilst this represents the majority of the available elite UK track sprinters, more participants would have added more weight to the findings.

8.5 Conclusion

In conclusion, the main findings of this experiment were three-fold. First, sprint cycling training initially improves T_{MAX} which is associated with increases in pennation angle of the VL and explosive strength measured at 200 ms. Second, isometric cycling can be used as a training modality to improve PPO-to-mass by increasing T_{MAX}-to-mass ratio in elite track sprinters. Third, changes in explosive strength at 200 ms of the knee extensors is an off-bike measurement that significantly predicts change in PPO in elite track sprint cyclists, but the exact physiological reason as to why remains unclear.

The findings from this chapter address the aims of this thesis by identifying a novel method of improving PPO in elite and national level track sprint cyclists. Changes in explosive strength rather than changes in muscle mass and the pennation angle show significant changes with PPO for reasons that are hitherto unknown. However, this development still provides a worthwhile and beneficial training modality to improve sprint cycling ability in elite level sprint cyclists.

CHAPTER 9

GENERAL DISCUSSION

9.1 Experimental Chapter Synopsis

The overarching aim of the thesis was to understand the physiological determinants of PPO in sprint cycling. The first experimental chapter (Chapter 4) was designed to ascertain between-session reliability and compare P-C and T-C relationships from isovelocity and isoinertial sprint cycling tests. The results showed that PPO, and all aspects of the P-C and T-C relationships, were reliable (i.e. < 5%) and each measure showed large to almost perfect relationships between tests. However, each measure exhibited significant differences between tests. This information suggests that both isovelocity and isoinertial sprint cycling tests have good and similar levels of between-session reliability, but the tests (and measurements) are not interchangeable.

The findings of the second experimental chapter (Chapter 5) suggested that surface EMG reliability for both maximal isometric normalising tasks and sprint cycling tests are poor and that absolute surface EMG values may be as reliable to monitor longitudinally. More pertinently, the data from this chapter and the previous one suggest that isovelocity sprint testing may be the more suitable test to adopt moving forward for this thesis as it exhibits similar reliability to the isoinertial sprint test in the performance measurements but generally scores between-session reliability when using peak surface EMG values.

The third experimental chapter (Chapter 6) aimed to achieve a better understanding of the maximum voluntary strength of lower body muscle groups, and if this was associated with, and could predict, PPO. No study had completed a comprehensive examination of maximal strength in all major lower body single-joint muscle groups and their relationship to PPO and/or sprint ability, and whether they could be used to predict PPO. The results displayed positive and significant

relationships with maximal strength of knee extensors, knee flexors and hip extensors with PPO. Of those, only knee extensors were shown to be able to predict PPO. Subsequently, the relationship of maximal strength of the knee extensors was put in a step-wise regression with maximal strength from isometric cycling. Isometric cycling was shown to be the only predictor of PPO. These findings suggest that of all the single joint muscle groups, the maximal strength of the knee extensors best predicts PPO, meaning that the main physiological determinants of PPO are likely to be found in the knee extensors.

The fourth experimental chapter (Chapter 7) was designed to establish the physiological determinants of sprint cycling using a broad range of elite level cyclists ranging from road riders to track sprinters and BMXers using a range of putative neuromuscular determinants within the thigh (muscle volume, architecture and neuromuscular activation) with PPO. The findings exhibited significant positive relationships with quadricep muscle volume, hamstring muscle volume and the pennation angle of the vastus lateralis. When put into a step-wise regression, quadricep muscle volume and pennation angle accounted for 76 and 11% of the variability of PPO, respectively. In addition, the sprint cyclists measured higher PPO and all measurements of the P-C and T-C relationships when compared to the endurance cyclists. In addition, of all the physiological measurements, quadricep muscle volume, hamstring muscle volume and the pennation angle of the vastus lateralis all measured higher for the sprint cyclists when compared to the endurance cyclists. The findings of this experiment emphasise the importance of quadricep muscle morphology for sprint cycling ability, in particular muscle volume and pennation angle (of the VL).

The final experimental chapter (Chapter 8) had two groups of elite or national level track cycling sprinters perform 6-weeks of habitual training compared to a group

that performed similar training but using an isometric maximum strength cycling protocol rather than traditional resistance training. Changes in PPO, P-C and T-C relationships and a range of putative neuromuscular measurements of both groups were monitored, which were additional to what was used previously in this thesis, such as explosive strength. Whilst using a broad heterogeneous group of elite cyclists to establish the predictors in the previous study, using a more homogenous sub-group of elite or national level sprint cyclists gives more strength to any results that arose from the previous chapters. The results suggested that in general, sprint cycling training increases T_{MAX} in parallel with pennation angle of the VL and explosive strength at 200 ms. For the specific groups, increases in normalised PPO and T_{MAX} for the intervention group. Collectively, changes in explosive strength at 150 and 200 ms were the only two physiological predictors that resulted in significant changes in PPO, with a change in explosive strength at 200 ms being the only significant predictor when trying to establish changes in PPO. This study concluded that a maximum strength specific protocol improved PPO, which was evidenced by improving T_{MAX} in the underpinning T-C relationship which could at least, in part, be explained by improvement in the pennation angle of the vastus lateralis. Of the off-bike measurements, changes in explosive strength at 200 ms predicted changes in PPO, but the exact reasons are not clear.

9.2 Main Findings

The overall aim of this thesis was to investigate the physiological determinants of peak power output in sprint cycling. A number of relevant issues have been discussed in each of the experimental chapters; however, the following sections

discuss the main findings of this thesis in the context of existing literature, the limitations of the work and potential future areas of investigation.

9.3 Maximal Strength

The initial aim of this thesis was to identify the physiological measurements that underpin PPO. Data from Chapter 4 corroborates the proposition that maximal strength of knee extensors, knee flexors and hip extensors exhibit positive and significant relationships with PPO. Of those, only the maximum strength of the knee extensors was able to predict PPO. The same experiment also showed a very large relationship with ISO-CYC and PPO and further analysis showed the findings agreed with previous research that specific maximum strength measurements, such as isometric single-joint dynamometry of the knee extensors (Driss et al., 2002) or more general strength measurements such as isometric mid-thigh pull (Stone *et al.*, 2004), are related and can predict PPO. It can be reasoned that the relationship between maximum strength and maximum power is somewhat predictable and intuitive as (maximum) force/torque accounts for half of the (maximal) power production relationship. Thus, stronger cyclists can generally produce more absolute power. This is exemplified in Chapter 7, where the larger PPO measured in the sprint cycling group was attributed to the larger T_{MAX} values in the underlying T-C relationship, averaging +35% higher in sprinters. However, despite maximal strength being identified as a predictor of PPO in the cross-sectional experiments, Chapter 8 examined relative changes in physiological measurements, including maximum strength (of knee extensors and ISO-CYC) with relative changes in PPO. No significant relationships were established, which is contrary to what would have been hypothesised. There is no obvious reason to explain the lack of relationship other than speculating about a potential 'expression' time window that goes from change in physiological measurements to change in PPO/T_{MAX}

on the bike, as has previously been discussed by other research groups (Leong *et al.*, 2014). Also, maximum strength measures *per se* are very specific to the mode they are measured in and it could be that an increase in strength is seen in the gym exercises specifically rather than the test rig used for testing. This has been somewhat evidenced in Chapter 6 and further in Chapter 8 by the significant increases in the ISO-CYC measure from the INT group was probably because their strength training specifically focused on performing MVCs using the ISO-CYC rig in identical joint-angles they performed during sprint cycling itself. This gives further weight that strength has a specific skill element when expressing force/torque in maximal sprint cycling.

9.4 Muscle Morphology and Architecture

Q_{VOL} and HAM_{VOL} were both quantified in Chapter 7 and both exhibited significant and very large relationships with PPO. When entered into regression analysis, Q_{VOL} predicted 76% of the variance in PPO. Previous studies have used more basic surrogate predictors of muscle volume or mass and shown similar levels of association with sprint cycling ability, for example the truncated cone method to make lean leg volume estimates (Martin *et al.*, 1997; Driss *et al.*, 2002; Dorel *et al.*, 2005). The findings in Chapter 7 should be used with caution and not be taken as a 'cause-and-effect' relationship, particularly as the Pearson's r relationship between Q_{VOL} and PPO was reduced to 0.51 when solely examining the sprint cyclist cohort. This suggests that the muscle volume of the knee extensors is not as strong as when the population becomes more homogenous. Chapter 8 used DXA to measure changes in TBLM and LBLM. No significant changes were measured over the 6-week period in either group and no relationships were found between relative changes of TBLM and/or LBLM with changes in PPO. However, the ability of DXA to detect small changes in body

composition, particularly in athletic populations, may be poor (Santos *et al.*, 2010). In any case, one of the principle findings of this thesis is that muscle size in the thigh and, in particular, the quadriceps is an important physiological factor in PPO but there is limited evidence as to what degree.

The results in Chapter 7 also suggested that $P\theta_{VL}$ exhibited a significant and large relationship with PPO, and also predicted 11% of the variance in PPO. However, no relationship was seen with Fl_{VL} and PPO. Chapter 8 also showed that an increase in $P\theta_{VL}$ is associated with increases in T_{MAX} which could be a precursor to improving PPO (see section 2.6). A greater pennation angle of a muscle allows more sarcomeres to be packed in parallel per area of tendon, which increases the physiological cross-sectional area and consequently increasing the muscles ability to produce more maximal force (Bamman *et al.*, 2000; Blazevich *et al.*, 2009), which has been shown to predict PPO. The final experimental chapter demonstrated that increases in $P\theta_{VL}$ were associated with increases in T_{MAX}. Despite this, the findings from this thesis do suggest that muscle volume is an important factor in maximum strength, PPO and sprinting ability, but there is not enough evidence for it to be concluded that there is established cause-effect relationship with $P\theta_{VL}$ and sprinting ability i.e. PPO.

9.5 Explosive Strength

Due to methodological limitations, explosive strength measures eres only introduced in the final experimental chapter in this thesis. There is no established or approved method to measure explosive strength as different studies have opted for different assessments (Maffiuletti *et al.*, 2016). As such, torque at 50, 100, 150 and 200 ms were measured to ensure all aspects of explosive strength were captured. The final experimental chapter of this thesis focussed on whether changes in putative

predictors of PPO are associated with or can predict changes in PPO. Of all the predictors measured, changes in explosive strength at 150 and 200 ms were only significant relationships with changes in PPO, and only changes in explosive strength at 200 ms predicted changes in PPO. With no relationship being established between changes in the early phase of explosive strength expression (i.e. at 50 and 100 ms) and changes in PPO, this suggests that it is unlikely that neural factors are the underpinning mechanism that influences PPO (Aagaard *et al.*, 2002; de Ruiter *et al.*, 2004; Del Balso & Cafarelli, 2007). More likely, it could be properties of the muscle and maximal force production (Andersen & Aagaard, 2006; Folland *et al.*, 2014), but the measurements from the same data collection present conflict, making the precise mechanism(s) unknown. It must also be noted that whilst no muscle-tendon unit/stiffness measurements were taken, this cannot be ruled out in potentially underpinning, at least in part, some aspect of PPO (Maffiuletti *et al.*, 2016).

Previous cross-sectional studies have had conflicting results when examining associations of explosive strength with sprinting ability. Driss et al. suggested strong correlations of explosive strength of the knee extensors with PPO (Driss *et al.*, 2002), whilst Stone and colleagues did not find any significant relationship between explosive strength and sprinting ability and performance when using the isometric mid-thigh pull (Stone *et al.*, 2004). However, the findings from the final experimental chapter of this thesis gives at least some weight for coaches, practitioners and cyclists to use explosive strength measures of the knee extensors as an off-bike measure of changes in sprint cycling ability.

9.6 Limitations of Findings

A number of limitations exist in the interpretation of the results and findings in the experimental chapters of this thesis which have all been discussed in each respective chapter. The following over-arching limitations are potential issues and criticisms of the work. First, the sensitivity of some instruments used to quantify some of the physiological measurements is questionable. For example, in this thesis (as well as in the literature), it has been demonstrated that surface EMG has poor between-session reliability, making it hard to identify any changes or differences, in particular, any longitudinal changes, between- or within-participants. Furthermore, other measurements, such as DXA (Santos *et al.*, 2010; Maden-Wilkinson *et al.*, 2013) and M-wave amplitude (Halaki & Gi, 2012), have had their reliability and sensitivity also questioned. Second, the availability and number of elite or well-trained track sprint cyclists restricts sample size. Despite the sprint cycling disciplines offering the most medal opportunities (six for track sprint cycling, eight including BMX) at the Olympics, greater than any other variant (i.e. track endurance, road, mountain bike and freestyle), it is still a relatively niche discipline and the number of well-trained or elite track sprint riders are much fewer than in other disciplines. This thesis succeeded in recruiting almost 90% of the top 30 ranked track sprint cyclists available in the country to participate. However, the numbers are still relatively small for establishing relationships. Third, though every effort was made to standardise training, due to the individual nature of elite/competitive track sprint cycling, not all training (and nutrition) and current training status could be standardised. The ability to monitor training in more detail was not a viable option as it is difficult to quantify all modalities of training without constant access to power cranks for both road and track bikes as well as force platforms during gym sessions.

Fourth, for Chapters 4, 6, 7 and 8, there was a large range of performance values (e.g. PPO) which could have exaggerated relationships between measures compared to what would have been seen in a smaller, more elite cohort of sprint cyclists. Chapter 4 and 6 tried to recruit similar standard amateur riders but still brought about a broad range of performance values (e.g. PPO). Whilst 35 elite level cyclists over a range of different disciplines participated in Chapter 7 also gave rise to a broad range of performance and physiological values. Chapter 8 did use elite track cyclists. However, it could also be argued that the inclusion of women sprinters would have brought a broader range and again, possibly exaggerating the relationships. All these factors, naturally, would have some effect on the results but it is hard to define for each effect. In addition, the two different groups were not completely randomised. Because of different training schedules, racing calendars and agreements made with coaches for riders to be part of the final experimental chapter, more of the 'senior' riders were in the 'best practice' control group. This lack of randomisation could potentially have biased the results as highly trained athletes exhibit smaller relative changes compared to lesser trained athletes, as previously discussed in the final two experimental chapters.

9.7 Practical Implications

The practical implications of the ISO-CYC protocol is something that can be implemented in an elite sprint cycling training programme. However, at least for now, it is recommended to introduce this novel stimulus to riders that are highly strength trained and either a) have reached a physiological 'ceiling' in their strength

training or b) have compromised strength training due to injury such as back injuries that limit them from lifting near their maximums in compound movements such as back squat. It could also be periodised as a 'bridging' tool in an annual training programme after a general strength training phase and prior to a racing phase to ensure that all training is maximal but still task specific. Doing it in conjunction with a full-strength training programme and track cycling efforts could result in too many maximal efforts in a meso- and/or macro-cycling of training.

9.8 Future Research Directions

The aims of this thesis have been addressed in the five experimental chapters and, more importantly, have contributed to the existing literature. The data from this thesis has provided an initial insight into the physiological determinants of sprint cycling ability. Consequently, a number of potential avenues for future research have been identified.

Measurements of the P-C and T-C relationships, as well as other accompanying physiological measurements, could be measured systematically over a season (rather than six weeks) to get more data regarding the changes in physiological estimates and performance. This would give more detailed information concerning training relative to performance. In particular, using MR imaging (and perhaps $P\theta_{VL}$) to ascertain the changes in muscle volume of specific muscle groups would help better understand changes in muscle volume with training/sprinting ability, along with muscle architecture and strength measurements.

More invasive neuromuscular measurements and their relationship with PPO or sprinting ability could also be investigated, such as transcranial magnetic stimulation, and the contribution of neural and contractile determinates of rate of force

development with PPO could be investigated using force responses to evoked twitch and octet contractions.

Future experiments could also focus around understanding more about the use of ISO-CYC. In particular, its position in an annual training programme or whether it replaces an aspect of or acts as an adjunct in a training programme. In addition, investigating whether there an optimum time-window of using ISO-CYC until a 'ceiling' is reached and the effects of load and volume on sprinting ability over time would be of value when trying to improve sprint cycling performance.

In conclusion, the series of investigations in this thesis has provided the first evidence of detailed physiological measurements and their effect on PPO, P-C and T-C relationships in elite cyclists. These findings are of importance as they highlight the potential importance of muscle volume of the thigh, pennation angle of vastus lateralis and maximal torque produced at 200 ms in increasing sprint cycling ability. The thesis also focuses on off-bike assessments that could direct coaches, practitioners and athletes to monitor and predict PPO. Also, this thesis has introduced an alternative training modality other than traditional resistance training for the improvement of PPO, which could be beneficial for riders who are not experienced in multi-joint, high load resistance training or are limited to what exercises they can do because of injury.

CHAPTER 10

REFERENCE LIST

Aagaard P, Andersen JL, Dyhre-Poulsen P, Leffers AM, Wagner A, Magnusson SP, Halkjaer-Kristensen J & Simonsen EB (2001). A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *J Physiol* **534,** 613–623.

Aagaard P, Simonsen EB, Andersen JL, Magnusson P & Dyhre-Poulsen P (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol Bethesda Md 1985* **93,** 1318–1326.

Abe T, Kawakami Y, Suzuki Y, Gunji A & Fukunaga T (1997). Effects of 20 days bed rest on muscle morphology. *J Gravitational Physiol J Int Soc Gravitational Physiol* **4,** S10-14.

Abe T, Kumagai K & Brechue WF (2000). Fascicle length of leg muscles is greater in sprinters than distance runners. *Med Sci Sports Exerc* **32,** 1125–1129.

Ahtiainen JP, Pakarinen A, Alen M, Kraemer WJ & H□kkinen K (2003). Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. *Eur J Appl Physiol* **89,** 555–563.

Akima H, Kinugasa R & Kuno S (2005). Recruitment of the thigh muscles during sprint cycling by muscle functional magnetic resonance imaging. *Int J Sports Med* **26,** 245–252.

Albertus-Kajee Y, Tucker R, Derman W & Lambert M (2010). Alternative methods of normalising EMG during cycling. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* **20,** 1036–1043.

Alegre LM, Ferri-Morales A, Rodriguez-Casares R & Aguado X (2014). Effects of isometric training on the knee extensor moment-angle relationship and vastus lateralis muscle architecture. *Eur J Appl Physiol* **114,** 2437–2446.

Andersen LL & Aagaard P (2006). Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *Eur J Appl Physiol* **96,** 46–52.

Ando R, Taniguchi K, Saito A, Fujimiya M, Katayose M & Akima H (2014). Validity of fascicle length estimation in the vastus lateralis and vastus intermedius using ultrasonography. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* **24,** 214–220.

Arsac LM, Belli A & Lacour JR (1996). Muscle function during brief maximal exercise: accurate measurements on a friction-loaded cycle ergometer. *Eur J Appl Physiol* **74,** 100–106.

Ball N & Scurr J (2010). An assessment of the reliability and standardisation of tests used to elicit reference muscular actions for electromyographical normalisation. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* **20,** 81–88.

Balshaw TG, Fry A, Maden-Wilkinson TM, Kong PW & Folland JP (2017). Reliability of quadriceps surface electromyography measurements is improved by two vs. single site recordings. *Eur J Appl Physiol* **117,** 1085–1094.

Balshaw TG, Massey GJ, Maden-Wilkinson TM, Lanza MB & Folland JP (2018). Neural adaptations after 4 years vs 12 weeks of resistance training vs untrained. *Scand J Med Sci Sports*; DOI: 10.1111/sms.13331.

Bamman M, Ingram S, Caruso J & Greenisen M (1997). Evaluation of Surface Electromyography During Maximal Voluntary Contraction. *J Strength Cond Res* **11,** 68–72.

Bamman MM, Newcomer BR, Larson-Meyer DE, Weinsier RL & Hunter GR (2000). Evaluation of the strength-size relationship in vivo using various muscle size indices. *Med Sci Sports Exerc* **32,** 1307–1313.

Baron R, Bachl N, Petschnig R, Tschan H, Smekal G & Pokan R (1999). Measurement of maximal power output in isokinetic and non-isokinetic cycling. A comparison of two methods. *Int J Sports Med* **20,** 532–537.

Basmajian J & De Luca CJ (1985). *Muscles Alive : their functions revealed by electromyography*, 5th edn. Williams & Wilkins, Baltimore.

Beelen A & Sargeant AJ (1991). Effect of fatigue on maximal power output at different contraction velocities in humans. *J Appl Physiol Bethesda Md 1985* **71,** 2332–2337.

Bernús G, González de Suso JM, Alonso J, Martin PA, Prat JA & Arús C (1993). 31P-MRS of quadriceps reveals quantitative differences between sprinters and long-distance runners. *Med Sci Sports Exerc* **25,** 479–484.

Bertucci W, Taiar R & Grappe F (2005). Differences between sprint tests under laboratory and actual cycling conditions. *J Sports Med Phys Fitness* **45,** 277–283.

Blazevich AJ, Coleman DR, Horne S & Cannavan D (2009). Anatomical predictors of maximum isometric and concentric knee extensor moment. *Eur J Appl Physiol* **105,** 869–878.

Bobbert MF (2012). Why is the force-velocity relationship in leg press tasks quasi-linear rather than hyperbolic? *J Appl Physiol* **112,** 1975–1983.

Borg GA (1982). Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* **14,** 377–381.

Brand PW, Beach RB & Thompson DE (1981). Relative tension and potential excursion of muscles in the forearm and hand. *J Hand Surg* **6,** 209–219.

Buchheit M, Lefebvre B, Laursen PB & Ahmaidi S (2011). Reliability, Usefulness, and Validity of the 30–15 Intermittent Ice Test in Young Elite Ice Hockey Players: *J Strength Cond Res* **25,** 1457–1464.

Buchheit M, Mendez-Villanueva A, Simpson BM & Bourdon PC (2010). Match running performance and fitness in youth soccer. *Int J Sports Med* **31,** 818–825.

Buckthorpe MW, Hannah R, Pain TG & Folland JP (2012). Reliability of neuromuscular measurements during explosive isometric contractions, with special reference to electromyography normalization techniques. *Muscle Nerve* **46,** 566–576.

Bundle MW & Weyand PG (2012). Sprint exercise performance: does metabolic power matter? *Exerc Sport Sci Rev* **40,** 174–182.

Burden A (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* **20,** 1023–1035.

Burke D (2002). Effects of activity on axonal excitability: implications for motor control studies. *Adv Exp Med Biol* **508,** 33–37.

Buttelli O, Seck D, Vandewalle H, Jouanin JC & Monod H (1996). Effect of fatigue on maximal velocity and maximal torque during short exhausting cycling. *Eur J Appl Physiol* **73,** 175–179.

Buttelli O, Vandewalle H, Jouanin JC, Seck D & Monod H (1997). Effects of aerobic exercise on the torque-velocity relationship in cycling. *Eur J Appl Physiol* **75,** 499–503.

Calbet JAL, De Paz JA, Garatachea N, Cabeza de Vaca S & Chavarren J (2003). Anaerobic energy provision does not limit Wingate exercise performance in endurance-trained cyclists. *J Appl Physiol* **94,** 668–676.

Calder BJ, Phillips LW & Tybout AM (1981). Designing Research for Application. *J Consum Res* **8,** 197.

Cormie P, McGuigan MR & Newton RU (2011). Developing maximal neuromuscular power: Part 1--biological basis of maximal power production. *Sports Med Auckl NZ* **41,** 17–38.

Cruz-Jentoft AJ, Baeyens JP, Bauer JM, Boirie Y, Cederholm T, Landi F, Martin FC, Michel J-P, Rolland Y, Schneider SM, Topinková E, Vandewoude M, Zamboni M & European Working Group on Sarcopenia in Older People (2010). Sarcopenia: European consensus on definition and diagnosis: Report of the European Working Group on Sarcopenia in Older People. *Age Ageing* **39,** 412–423.

Dawson B, Fitzsimons M, Green S, Goodman C, Carey M & Cole K (1998). Changes in performance, muscle metabolites, enzymes and fibre types after short sprint training. *Eur J Appl Physiol* **78,** 163–169.

Del Balso C & Cafarelli E (2007). Adaptations in the activation of human skeletal muscle induced by short-term isometric resistance training. *J Appl Physiol Bethesda Md 1985* **103,** 402–411.

Del Vecchio A, Bazzucchi I & Felici F (2018). Variability of estimates of muscle fiber conduction velocity and surface EMG amplitude across subjects and processing intervals. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* **40,** 102–109.

Del Vecchio A, Negro F, Felici F & Farina D (2017). Associations between motor unit action potential parameters and surface EMG features. *J Appl Physiol Bethesda Md 1985* **123,** 835–843.

Delmonico MJ, Kostek MC, Johns J, Hurley BF & Conway JM (2008). Can dual energy X-ray absorptiometry provide a valid assessment of changes in thigh muscle mass with strength training in older adults? *Eur J Clin Nutr* **62,** 1372–1378.

Dorel S, Couturier A, Lacour J-R, Vandewalle H, Hautier C & Hug F (2010). Force-velocity relationship in cycling revisited: benefit of two-dimensional pedal forces analysis. *Med Sci Sports Exerc* **42,** 1174–1183.

Dorel S, Guilhem G, Couturier A & Hug F (2012). Adjustment of muscle coordination during an all-out sprint cycling task. *Med Sci Sports Exerc* **44,** 2154–2164.

Dorel S, Hautier CA, Rambaud O, Rouffet D, Van Praagh E, Lacour J-R & Bourdin M (2005). Torque and power-velocity relationships in cycling: relevance to track sprint performance in world-class cyclists. *Int J Sports Med* **26,** 739–746.

Driss T & Vandewalle H (2013*a*). The measurement of maximal (anaerobic) power output on a cycle ergometer: a critical review. *BioMed Res Int* **2013,** 589361.

Driss T & Vandewalle H (2013*b*). The measurement of maximal (anaerobic) power output on a cycle ergometer: a critical review. *BioMed Res Int* **2013,** 589361.

Driss T, Vandewalle H, Le Chevalier J-M & Monod H (2002). Force-velocity relationship on a cycle ergometer and knee-extensor strength indices. *Can J Appl Physiol Rev Can Physiol Appl* **27,** 250–262.

Duchateau J & Hainaut K (1984). Isometric or dynamic training: differential effects on mechanical properties of a human muscle. *J Appl Physiol* **56,** 296–301.

Duché P, Ducher G, Lazzer S, Doré E, Tailhardat M & Bedu M (2002). Peak power in obese and nonobese adolescents: effects of gender and braking force. *Med Sci Sports Exerc* **34,** 2072–2078.

Dwyer DB (2014). The effect of environmental conditions on performance in timed cycling events. *J Sci Cycl* **3,** 17–22.

Edman KA (1979). The velocity of unloaded shortening and its relation to sarcomere length and isometric force in vertebrate muscle fibres. *J Physiol* **291,** 143–159.

Elmer SJ, Barratt PR, Korff T & Martin JC (2011). Joint-specific power production during submaximal and maximal cycling. *Med Sci Sports Exerc* **43,** 1940–1947.

Ema R, Wakahara T, Mogi Y, Miyamoto N, Komatsu T, Kanehisa H & Kawakami Y (2013). In vivo measurement of human rectus femoris architecture by ultrasonography: validity and applicability. *Clin Physiol Funct Imaging* **33,** 267–273.

Ema R, Wakahara T, Yanaka T, Kanehisa H & Kawakami Y (2016). Unique muscularity in cyclists' thigh and trunk: A cross-sectional and longitudinal study: Muscle-specific adaptation to cycling. *Scand J Med Sci Sports* **26,** 782–793.

Engstrom CM, Loeb GE, Reid JG, Forrest WJ & Avruch L (1991). Morphometry of the human thigh muscles. A comparison between anatomical sections and computer tomographic and magnetic resonance images. *J Anat* **176,** 139–156.

Ericson M (1986). On the biomechanics of cycling. A study of joint and muscle load during exercise on the bicycle ergometer. *Scand J Rehabil Med Suppl* **16,** 1–43.

Erskine RM, Jones DA, Maganaris CN & Degens H (2009). In vivo specific tension of the human quadriceps femoris muscle. *Eur J Appl Physiol* **106,** 827–838.

Farina D, Merletti R & Enoka RM (2014). The extraction of neural strategies from the surface EMG: an update. *J Appl Physiol Bethesda Md 1985* **117,** 1215–1230.

Ferretti G, Narici MV, Binzoni T, Gariod L, Le Bas JF, Reutenauer H & Cerretelli P (1994). Determinants of peak muscle power: effects of age and physical conditioning. *Eur J Appl Physiol* **68,** 111–115.

Folland JP, Buckthorpe MW & Hannah R (2014). Human capacity for explosive force production: neural and contractile determinants. *Scand J Med Sci Sports* **24,** 894–906.

Folland JP & Williams AG (2007). The adaptations to strength training : morphological and neurological contributions to increased strength. *Sports Med Auckl NZ* **37,** 145–168.

Franchi MV, Longo S, Mallinson J, Quinlan JI, Taylor T, Greenhaff PL & Narici MV (2018*a*). Muscle thickness correlates to muscle cross-sectional area in the assessment of strength training-induced hypertrophy. *Scand J Med Sci Sports* **28,** 846–853.

Franchi MV, Raiteri BJ, Longo S, Sinha S, Narici MV & Csapo R (2018*b*). Muscle Architecture Assessment: Strengths, Shortcomings and New Frontiers of in Vivo Imaging Techniques. *Ultrasound Med Biol* **44,** 2492–2504.

Freda PU, Shen W, Reyes-Vidal CM, Geer EB, Arias-Mendoza F, Gallagher D & Heymsfield SB (2009). Skeletal muscle mass in acromegaly assessed by

magnetic resonance imaging and dual-photon x-ray absorptiometry. *J Clin Endocrinol Metab* **94,** 2880–2886.

Fukunaga T, Kawakami Y, Kuno S, Funato K & Fukashiro S (1997). Muscle architecture and function in humans. *J Biomech* **30,** 457–463.

Fukunaga T, Miyatani M, Tachi M, Kouzaki M, Kawakami Y & Kanehisa H (2001). Muscle volume is a major determinant of joint torque in humans. *Acta Physiol Scand* **172,** 249–255.

Fuller NJ, Hardingham CR, Graves M, Screaton N, Dixon AK, Ward LC & Elia M (1999). Assessment of limb muscle and adipose tissue by dual-energy X-ray absorptiometry using magnetic resonance imaging for comparison. *Int J Obes Relat Metab Disord J Int Assoc Study Obes* **23,** 1295–1302.

Gandevia SC & Taylor JL (2006). Supraspinal fatigue: the effects of caffeine on human muscle performance. *J Appl Physiol Bethesda Md 1985* **100,** 1749–1750.

Gans C & de Vree F (1987). Functional bases of fiber length and angulation in muscle. *J Morphol* **192,** 63–85.

Gardner AS, Martin DT, Jenkins DG, Dyer I, Van Eiden J, Barras M & Martin JC (2009). Velocity-specific fatigue: quantifying fatigue during variable velocity cycling. *Med Sci Sports Exerc* **41,** 904–911.

Gardner AS, Martin JC, Martin DT, Barras M & Jenkins DG (2007). Maximal torque- and power-pedaling rate relationships for elite sprint cyclists in laboratory and field tests. *Eur J Appl Physiol* **101,** 287–292.

Gardner SA, Martin TD, Barras M, Jenkins GD & Hahn GA (2005). Power output demands of elite track sprint cycling. *Int J Perform Anal Sport* **5,** 149–154.

Gastin PB (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Med Auckl NZ* **31,** 725–741.

Gordon AM, Huxley AF & Julian FJ (1966). The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *J Physiol* **184,** 170–192.

Grant MC, Watson H & Baker JS (2015). Assessment of the upper body contribution to multiple-sprint cycling in men and women. *Clin Physiol Funct Imaging* **35,** 258–266.

Grassi B, Cerretelli P, Narici MV & Marconi C (1991). Peak anaerobic power in master athletes. *Eur J Appl Physiol* **62,** 394–399.

Graves JE, Pollock ML, Jones AE, Colvin AB & Leggett SH (1989). Specificity of limited range of motion variable resistance training. *Med Sci Sports Exerc* **21,** 84–89.

Green SB (1991). How Many Subjects Does It Take To Do A Regression Analysis. *Multivar Behav Res* **26,** 499–510.

Haderslev KV, Haderslev PH & Staun M (2005). Accuracy of body composition measurements by dual energy x-ray absorptiometry in underweight patients with chronic intestinal disease and in lean subjects. *Dyn Med DM* **4,** 1.

Hair JFJr, R. E. Anderson, R. L. Tatham & Black WC (1995). *Multivariate Data Analysis*, 3rd edn. New York: Macmillan.

Häkkinen K, Komi PV & Alén M (1985). Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiol Scand* **125,** 587–600.

Halaki M & Gi K (2012). Normalization of EMG Signals: To Normalize or Not to Normalize and What to Normalize to? In *Computational Intelligence in Electromyography Analysis - A Perspective on Current Applications and Future Challenges*, ed. Naik GR. InTech. Available at: http://www.intechopen.com/books/computational-intelligence-in-electromyography-analysis-a-perspective-on-current-applications-and-future-challenges/normalization-of-emg-signals-to-normalize-or-not-to-normalize-and-what-to-normalize-to- [Accessed April 1, 2019].

Hanson J & Huxley HE (1953). Structural basis of the cross-striations in muscle. *Nature* **172,** 530–532.

Hautier CA, Linossier MT, Belli A, Lacour JR & Arsac LM (1996). Optimal velocity for maximal power production in non-isokinetic cycling is related to muscle fibre type composition. *Eur J Appl Physiol* **74,** 114–118.

Heinonen A, Sievänen H, Viitasalo J, Pasanen M, Oja P & Vuori I (1994). Reproducibility of computer measurement of maximal isometric strength and electromyography in sedentary middle-aged women. *Eur J Appl Physiol* **68,** 310–314.

Henriksson-Larsen K, Wretling M-L, Lorentzon R & □berg L (1992). Do muscle fibre size and fibre angulation correlate in pennated human muscles? *Eur J Appl Physiol* **64,** 68–72.

Hermansen L (1981). Muscular Fatigue During Maximal Exercise of Short Duration. In *Medicine and Sport Science*, ed. di Prampero PE & Poortmans J, pp. 45–52. S. Karger AG. Available at: https://www.karger.com/Article/FullText/397192 [Accessed January 1, 2019].

Hermens HJ, Freriks B, Disselhorst-Klug C & Rau G (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* **10,** 361–374.

Hill AV (1938). The Heat of Shortening and the Dynamic Constants of Muscle. *Proc R Soc B Biol Sci* **126,** 136–195.

Hintzy F, Belli A, Grappe F & Rouillon J-D (1999). Optimal pedalling velocity characteristics during maximal and submaximal cycling in humans. *Eur J Appl Physiol* **79,** 426–432.

Hodges PW, Pengel LHM, Herbert RD & Gandevia SC (2003). Measurement of muscle contraction with ultrasound imaging. *Muscle Nerve* **27,** 682–692.

Hopkins WG (2015). Spreadsheets for analysis of validity and reliability. *Sportscience* **19,** 36–42.

Hopkins WG, Marshall SW, Batterham AM & Hanin J (2009). Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* **41,** 3–13.

Hughes C (2003). Skeletal Muscle Structure, Function, and Plasticity: The Physiological Basis of Rehabilitation, 2nd Edition: *Med Sci Sports Exerc*710.

Huxley AF & Niedergerke R (1954). Structural changes in muscle during contraction; interference microscopy of living muscle fibres. *Nature* **173,** 971–973.

Ingham SA, Whyte GP, Jones K & Nevill AM (2002). Determinants of 2,000 m rowing ergometer performance in elite rowers. *Eur J Appl Physiol* **88,** 243–246.

Jaafar H, Attiogbé E, Rouis M, Vandewalle H & Driss T (2015). Reliability of Force-Velocity Tests in Cycling and Cranking Exercises in Men and Women. *BioMed Res Int* **2015,** 1–12.

Jeukendrup AE, Craig NP & Hawley JA (2000). The bioenergetics of World Class Cycling. *J Sci Med Sport* **3,** 414–433.

Jones D, Round JM & Haan A de (2004). *Skeletal muscle from molecules to movement: a textbook of muscle physiology for sport, exercise, physiotherapy and medicine*. Churchill Livingstone, Edinburgh.

Jones PR & Pearson J (1969). Anthropometric determination of leg fat and muscle plus bone volumes in young male and female adults. *J Physiol* **204,** 63P-66P.

Kashiwagi K, Tanaka M, Kawazoe T, Furuichi K & Takada H (1995). Effect of amplitude normalization on surface EMG linear envelopes of masticatory muscles during gum chewing. *J Osaka Dent Univ* **29,** 19–28.

Kawakami Y, Abe T & Fukunaga T (1993). Muscle-fiber pennation angles are greater in hypertrophied than in normal muscles. *J Appl Physiol Bethesda Md 1985* **74,** 2740–2744.

Knutson LM, Soderberg GL, Ballantyne BT & Clarke WR (1994). A study of various normalization procedures for within day electromyographic data. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* **4,** 47–59.

Koninckx E, Van Leemputte M & Hespel P (2010). Effect of isokinetic cycling versus weight training on maximal power output and endurance performance in cycling. *Eur J Appl Physiol* **109,** 699–708.

Kordi M, Goodall S, Barratt P, Rowley N, Leeder J & Howatson G (2017). Relation between Peak Power Output in Sprint Cycling and Maximum Voluntary Isometric Torque Production. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* **35,** 95–99.

Kumagai K, Abe T, Brechue WF, Ryushi T, Takano S & Mizuno M (2000). Sprint performance is related to muscle fascicle length in male 100-m sprinters. *J Appl Physiol Bethesda Md 1985* **88,** 811–816.

Kwah LK, Pinto RZ, Diong J & Herbert RD (2013). Reliability and validity of ultrasound measurements of muscle fascicle length and pennation in humans: a systematic review. *J Appl Physiol Bethesda Md 1985* **114,** 761–769.

Lanza MB, Balshaw TG, Massey GJ & Folland JP (2018). Does normalization of voluntary EMG amplitude to M_{MAX} account for the influence of electrode location and adiposity? *Scand J Med Sci Sports*; DOI: 10.1111/sms.13270.

Lehman GJ (2002). Clinical considerations in the use of surface electromyography: Three experimental studies. *J Manipulative Physiol Ther* **25,** 293–299.

Leong CH, McDermott WJ, Elmer SJ & Martin JC (2014). Chronic eccentric cycling improves quadriceps muscle structure and maximum cycling power. *Int J Sports Med* **35,** 559–565.

Lieber RL & Baskin RJ (1981). Direct memory access of diffraction patterns from striated muscle--a software view. *Comput Programs Biomed* **13,** 27–31.

Lieber RL & Fridén J (2000). Functional and clinical significance of skeletal muscle architecture. *Muscle Nerve* **23,** 1647–1666.

Lippold OCJ (1952). The relation between integrated action potentials in a human muscle and its isometric tension. *J Physiol* **117,** 492–499.

Loeb GE, Pratt CA, Chanaud CM & Richmond FJ (1987). Distribution and innervation of short, interdigitated muscle fibers in parallel-fibered muscles of the cat hindlimb. *J Morphol* **191,** 1–15.

Low J & Reed A (2000). *Electrotherapy explained : principles and practice*, 3rd edn. Butterworth-Heinemann, Boston MA.

Lund H, Christensen L, Savnik A, Boesen J, Danneskiold-Samsøe B & Bliddal H (2002). Volume estimation of extensor muscles of the lower leg based on MR imaging. *Eur Radiol* **12,** 2982–2987.

MacDougall JD, Ward GR, Sale DG & Sutton JR (1977). Biochemical adaptation of human skeletal muscle to heavy resistance training and immobilization. *J Appl Physiol* **43,** 700–703.

Maciejczyk M, Wiecek M, Szymura J, Szygula Z & Brown LE (2015). Influence of increased body mass and body composition on cycling anaerobic power. *J Strength Cond Res* **29,** 58–65.

Maden-Wilkinson TM, Degens H, Jones DA & McPhee JS (2013). Comparison of MRI and DXA to measure muscle size and age-related atrophy in thigh muscles. *J Musculoskelet Neuronal Interact* **13,** 320–328.

Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N & Duchateau J (2016). Rate of force development: physiological and methodological considerations. *Eur J Appl Physiol* **116,** 1091–1116.

Martin JC, Davidson CJ & Pardyjak ER (2007). Understanding sprint-cycling performance: the integration of muscle power, resistance, and modeling. *Int J Sports Physiol Perform* **2,** 5–21.

Martin JC, Diedrich D & Coyle EF (2000). Time Course of Learning to Produce Maximum Cycling Power. *Int J Sports Med* **21,** 485–487.

Martin JC, Gardner AS, Barras M & Martin DT (2006). Modeling sprint cycling using field-derived parameters and forward integration. *Med Sci Sports Exerc* **38,** 592–597.

Martin JC, Wagner BM & Coyle EF (1997). Inertial-load method determines maximal cycling power in a single exercise bout. *Med Sci Sports Exerc* **29,** 1505–1512.

Massey GJ, Balshaw TG, Maden-Wilkinson TM & Folland JP (2018). Tendinous tissue properties after short- and long-term functional overload: Differences between controls, 12 weeks and 4 years of resistance training. *Acta Physiol Oxf Engl* **222,** e13019.

Maughan RJ, Watson JS & Weir J (1984). Muscle strength and cross-sectional area in man: a comparison of strength-trained and untrained subjects. *Br J Sports Med* **18,** 149–157.

McArdle WD, Katch FI & Katch VL (2010). *Exercise physiology : nutrition, energy, and human performance*, 7th edn. Wolters Kluwer Health/Lippincott Williams & Wilkins, Philadelphia, PA.

McDaniel J, Behjani NS, Elmer SJ, Brown NA & Martin JC (2014). Joint-specific power-pedaling rate relationships during maximal cycling. *J Appl Biomech* **30,** 423–430.

Mcphedran AM, Wuerker RB & Henneman E (1965). PROPERTIES OF MOTOR UNITS IN A HOMOGENEOUS RED MUSCLE (SOLEUS) OF THE CAT. *J Neurophysiol* **28,** 71–84.

Mendez-Villanueva A, Bishop D & Hamer P (2007). Reproducibility of a 6-s maximal cycling sprint test. *J Sci Med Sport Sports Med Aust* **10,** 323–326.

Merton PA (1954). Voluntary strength and fatigue. *J Physiol* **123,** 553–564.

Miaki H, Someya F & Tachino K (1999). A comparison of electrical activity in the triceps surae at maximum isometric contraction with the knee and ankle at various angles. *Eur J Appl Physiol* **80,** 185–191.

Miyatani M, Kanehisa H, Kuno S, Nishijima T & Fukunaga T (2002). Validity of ultrasonograph muscle thickness measurements for estimating muscle volume of knee extensors in humans. *Eur J Appl Physiol* **86,** 203–208.

Moritani T & deVries HA (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. *Am J Phys Med* **58,** 115–130.

Munro LA, Stannard SR, Fink PW & Foskett A (2017). Potentiation of sprint cycling performance: the effects of a high-inertia ergometer warm-up. *J Sports Sci* **35,** 1442–1450.

Murphy AJ, Wilson GJ & Pryor JF (1994). Use of the iso-inertial force mass relationship in the prediction of dynamic human performance. *Eur J Appl Physiol* **69,** 250–257.

Narici MV, Binzoni T, Hiltbrand E, Fasel J, Terrier F & Cerretelli P (1996*a*). In vivo human gastrocnemius architecture with changing joint angle at rest and during graded isometric contraction. *J Physiol* **496 (Pt 1),** 287–297.

Narici MV, Hoppeler H, Kayser B, Landoni L, Claassen H, Gavardi C, Conti M & Cerretelli P (1996*b*). Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiol Scand* **157,** 175–186.

Narici MV, Landoni L & Minetti AE (1992). Assessment of human knee extensor muscles stress from in vivo physiological cross-sectional area and strength measurements. *Eur J Appl Physiol* **65,** 438–444.

O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA & Maganaris CN (2009). Strong relationships exist between muscle volume, joint power and whole-body external mechanical power in adults and children: Development of joint and external mechanical power with adolescence. *Exp Physiol* **94,** 731–738.

Perez-Gomez J, Rodriguez GV, Ara I, Olmedillas H, Chavarren J, González-Henriquez JJ, Dorado C & Calbet JAL (2008). Role of muscle mass on sprint performance: gender differences? *Eur J Appl Physiol* **102,** 685–694.

Raasch CC, Zajac FE, Ma B & Levine WS (1997). Muscle coordination of maximum-speed pedaling. *J Biomech* **30,** 595–602.

Rønnestad BR, Hansen EA & Raastad T (2010). Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *Eur J Appl Physiol* **108,** 965–975.

Rønnestad BR, Hansen J, Hollan I & Ellefsen S (2015). Strength training improves performance and pedaling characteristics in elite cyclists: Strength training in elite cyclists. *Scand J Med Sci Sports* **25,** e89–e98.

Rouffet DM & Hautier CA (2008). EMG normalization to study muscle activation in cycling. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* **18,** 866–878.

de Ruiter CJ, Hutter V, Icke C, Groen B, Gemmink A, Smilde H & de Haan A (2012). The effects of imagery training on fast isometric knee extensor torque development. *J Sports Sci* **30,** 166–174.

de Ruiter CJ, Kooistra RD, Paalman MI & de Haan A (2004). Initial phase of maximal voluntary and electrically stimulated knee extension torque development at different knee angles. *J Appl Physiol Bethesda Md 1985* **97,** 1693–1701.

Rutherford OM & Jones DA (1992). Measurement of fibre pennation using ultrasound in the human quadriceps in vivo. *Eur J Appl Physiol* **65,** 433–437.

Sale DG (1988). Neural adaptation to resistance training. *Med Sci Sports Exerc* **20,** S135-145.

Sale DG, MacDougall JD, Alway SE & Sutton JR (1987). Voluntary strength and muscle characteristics in untrained men and women and male bodybuilders. *J Appl Physiol Bethesda Md 1985* **62,** 1786–1793.

Samozino P, Horvais N & Hintzy F (2007). Why does power output decrease at high pedaling rates during sprint cycling? *Med Sci Sports Exerc* **39,** 680–687.

Santos DA, Silva AM, Matias CN, Fields DA, Heymsfield SB & Sardinha LB (2010). Accuracy of DXA in estimating body composition changes in elite athletes using a four compartment model as the reference method. *Nutr Metab* **7,** 22.

Sargeant AJ, Hoinville E & Young A (1981). Maximum leg force and power output during short-term dynamic exercise. *J Appl Physiol* **51,** 1175–1182.

Seck D, Vandewalle H, Decrops N & Monod H (1995). Maximal power and torque-velocity relationship on a cycle ergometer during the acceleration phase of a single all-out exercise. *Eur J Appl Physiol* **70,** 161–168.

Sidhu SK, Bentley DJ & Carroll TJ (2009). Cortical voluntary activation of the human knee extensors can be reliably estimated using transcranial magnetic stimulation. *Muscle Nerve* **39,** 186–196.

Stewart D, Farina D, Shen C & Macaluso A (2011). Muscle fibre conduction velocity during a 30-s Wingate anaerobic test. *J Electromyogr Kinesiol* **21,** 418–422.

Stone MH, Sands WA, Carlock J, Callan S, Dickie D, Daigle K, Cotton J, Smith SL & Hartman M (2004). The Importance of Isometric Maximum Strength and Peak Rate-of-Force Development in Sprint Cycling. *J Strength Cond Res* **18,** 878.

Strojnik V & Komi PV (1998). Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *J Appl Physiol Bethesda Md 1985* **84,** 344–350.

Takai Y, Ohta M, Akagi R, Kato E, Wakahara T, Kawakami Y, Fukunaga T & Kanehisa H (2014). Applicability of ultrasound muscle thickness

measurements for predicting fat-free mass in elderly population. *J Nutr Health Aging* **18,** 579–585.

Tavoian D, Ampomah K, Amano S, Law TD & Clark BC (2019). Changes in DXA-derived lean mass and MRI-derived cross-sectional area of the thigh are modestly associated. *Sci Rep* **9,** 10028.

Taylor A (1990). Energy metabolism and fatigue. In *Biochemistry of exercise VII: international series on sport sciences*, pp. 73–92. Human Kinetics, Champaign (IL).

Thépaut-Mathieu C, Van Hoecke J & Maton B (1988). Myoelectrical and mechanical changes linked to length specificity during isometric training. *J Appl Physiol Bethesda Md 1985* **64,** 1500–1505.

Thorstensson A, Grimby G & Karlsson J (1976). Force-velocity relations and fiber composition in human knee extensor muscles. *J Appl Physiol* **40,** 12–16.

Tomas A, Ross EZ & Martin JC (2010). Fatigue during maximal sprint cycling: unique role of cumulative contraction cycles. *Med Sci Sports Exerc* **42,** 1364–1369.

Van Cutsem M, Duchateau J & Hainaut K (1998). Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *J Physiol* **513 (Pt 1),** 295–305.

Vera-Garcia FJ, Moreside JM & McGill SM (2010). MVC techniques to normalize trunk muscle EMG in healthy women. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* **20,** 10–16.

Westerblad H, Allen DG & Lännergren J (2002). Muscle fatigue: lactic acid or inorganic phosphate the major cause? *News Physiol Sci Int J Physiol Prod Jointly Int Union Physiol Sci Am Physiol Soc* **17,** 17–21.

Weyand PG, Lin JE & Bundle MW (2006). Sprint performance-duration relationships are set by the fractional duration of external force application. *Am J Physiol-Regul Integr Comp Physiol* **290,** R758–R765.

Wilson GJ & Murphy AJ (1996). The use of isometric tests of muscular function in athletic assessment. *Sports Med Auckl NZ* **22,** 19–37.

Yang JF & Winter DA (1983). Electromyography reliability in maximal and submaximal isometric contractions. *Arch Phys Med Rehabil* **64,** 417–420.

Young K, McDonagh MJ & Davies CT (1985). The effects of two forms of isometric training on the mechanical properties of the triceps surae in man. *Pflugers Arch* **405,** 384–388.

CHAPTER 11:

APPENDICES

11.1 Appendix 1: Example of Informed Consent Document

Project Title:

Participant ID:

Principal Investigator: Mehdi Kordi

Investigator contact details: mehdi.kordi@eis2win.co.uk

please tick where applicable	
I have carefully read and understood the Participant Information Sheet.	☐
I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers.	☐
I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice.	☐
I agree to take part in this study.	☐
I would like to receive feedback on the overall results of the study at the email address given below. Email address……	☐

Signature of participant..... Date.....…….. (NAME IN BLOCK LETTERS).....……
Signature of Parent / Guardian in the case of a minor .....
Signature of researcher..... Date.....…….. (NAME IN BLOCK LETTERS).....……

11.2 Appendix 2: Example of Participant Health Questionnaire

northumbria UNIVERSITY

PHYSIOLOGY LAB

Health Questionnaire

ENGLISH INSTITUTE OF SPORT

Name: Date of Birth:

1. Do you wheeze or feel tightness in your chest during or following exercise or any other time **AND/OR** have you ever been diagnosed with asthma? Yes ☐ No ☐

2. Do you ever experience chest pain, heart palpitations, unexplained shortness of breath, or passing out/feeling like you are going to pass out, **AND/OR** have you ever been diagnosed with a heart condition? Yes ☐ No ☐

3. Have any immediate family members been diagnosed with heart disease before the age of 50? Yes ☐ No ☐

4. Do you currently have any form of muscle or joint injury that may be made worse by performing a maximal exercise test? Yes ☐ No ☐

5. Have you suspended your normal training, for any reason, in the two weeks prior to this test? Yes ☐ No ☐

6. Is there anything to your knowledge that may prevent you from successfully completing the tests that have been outlined to you?

   If yes, please give details: Yes ☐ No ☐

7. Are you currently taking any medication or supplements?

   If yes, please list: Yes ☐ No ☐

8. Do you have any implants, pacemaker or prosthetic devices? Yes ☐ No ☐

9. It may be advisable to share any medical information disclosed during this testing session with other members of staff. Please tick the boxes next to those staff members who you do NOT wish to be have this information. You may withdraw your consent at any time.

   ☐ Doctor ☐ Physiotherapist ☐ Coach
   ☐ Performance Director ☐ Team Manager ☐ Masseur

Signature:
Date:

11.3 Appendix 3: Example of MRI Safety Screening Questionnaire

MRI, unlike other methods of imaging the body, does not use radiation but rather uses magnetism and radio waves. Extensive evaluation has shown no long term adverse side effects related to MR imaging. However, the magnetic field can cause problems for patients with metallic implants and can damage certain items, such as watches, hearing aids, electronic pagers and credit cards. If in doubt, please ask.

You cannot have a scan if you have:

- A cardiac (heart) pacemaker
- Certain clips in your skull from brain operations e.g. aneurysm clips
- A cochlea (ear) implant
- A neuro-stimulator
- A metallic foreign body in your eye
- A programmable shunt for hydrocephalus (fluid on the brain)

Surname: ..... Forenames: .....

Weight: ..... Height: .....

Please answer the following questions, which relate to metallic objects that may be present in the body

1. Do you have a cardiac (heart) pacemaker? YES / NO
2. Have you ever had any other surgery to your heart? YES / NO
3. Have you **EVER** had any metal fragments in your eyes? YES / NO
   If Yes, did you see a doctor or get medical advice? YES / NO
   If Yes, did a doctor tell you everything had been completely removed? YES / NO
4. Do you have a programmable hydrocephalus shunt? YES / NO
5. Do you have a cochlear (ear) implant? YES / NO
6. Have you had any operations on your head? YES / NO
5. Have you had any operations on your spine (neck or back)? YES / NO
8. Have you ever had any shrapnel (metal) injuries to the body? YES / NO
9. Have you had any operations involving metal clips, pins, plates or implants? YES / NO
10. Have you had any operations in the last three months? YES / NO
11. Do you suffer from epilepsy or have you ever had a fit/blackout? YES / NO
12. Do you wear a medicine patch? (e.g. Nicotine patch, etc.)? YES / NO
13. Do you have any tattoos, permanent cosmetics or piercings? YES / NO
14. Do you suffer from claustrophobia? YES / NO

If you have answered "YES" to any of the questions above, please inform the study investigators as soon as possible.
By signing below, you acknowledge that you have had the procedure explained to you by the study investigator and you have answered the above listed questions.

Participant's Signature: ..... Date: .....

Investigator's Signature: ..... Date: .....