THE NEUROMUSCULAR RESPONSES TO ECCENTRIC CYCLING AND THE IMPLICATIONS FOR ATHLETIC DEVELOPMENT

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THE NEUROMUSCULAR RESPONSES TO ECCENTRIC CYCLING AND THE IMPLICATIONS FOR ATHLETIC DEVELOPMENT

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ABSTRACT

Eccentric cycling is an emerging exercise modality in which an individual resists pedals being driven towards them on a motorised recumbent cycle ergometer. The attractiveness of eccentric cycling as a training modality stems, at least in part, from its propensity to elicit greater levels of mechanical tension for a lower metabolic cost compared to predominantly concentric or isometric training modalities. The aim of this thesis was to systematically investigate the neuromuscular responses and application to athletic performance of a bespoke eccentric cycling instrument. Study 1 assessed the reproducibility of torque, power, and muscle activation during maximal eccentric cycling over a range of cadences. This study demonstrated that at least one familiarisation session should be employed to account for the initial learning effect, although, generally poor between-session reliability was observed. A cadence of 60 rpm displayed the greatest reliability thus highlighting it as a preferential choice for use in future work. Study 2 compared the mechanical stress of, and muscle activation responses to, maximal eccentric and concentric cycling over a range of cadences. Eccentric cycling elicited up to 2.1 times greater torque and power compared to concentric cycling. Additionally, markers of technique e.g. pedal angle of peak muscle activation, and peak torque, also varied between modalities. Study 3 compared the immediate and delayed (up to 72 h post) responses to work-matched interval and continuous eccentric cycling. Decrements in muscle function (31% vs. 18%), and recovery time (48 vs. 24 hrs) were greater after the interval session; a finding attributed to greater peak mechanical tension. This greater mechanical potency of interval eccentric cycling provided rationale for its use over a longer period of training. In study 4 (a pilot study) the effects of an 8-week interval eccentric cycling intervention was examined in well trained distance runners. There was a limited effect on running economy, stretch shortening cycle function, and strength, however, data indicated a possible effect on eccentric strength and jump performance which warrants further investigation. Eccentric cycling does not appear to impact upon well trained athletes to the extent previously observed in untrained or physically impaired populations. Although, there is evidence in this thesis to support the potency of eccentric cycling as a mechanical training stimulus, the consequences of different session structures, and the ease at which it can be added to the training program of well-trained runners.

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A PhD is not just about the physical outcomes; the publications, the presentations, and the p-values. A PhD teaches you how to approach problems with an open mind. A PhD teaches you how to solve problems creatively. A PhD teaches you how to evaluate work without bias. In the past five years I have been fortunate to have my way of thinking probed, prodded, and challenged by several talented scientists. Their attention to detail and constant drive for improvement has not only shaped this thesis but also my way of thinking. Skills I have developed during these past five years will impact the way I work throughout my career and I am grateful to following individuals for their support throughout.

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LIST OF SYMBOLS AND ABBREVIATIONS

ACL	Anterior cruciate ligament
AEL	Accentuated eccentric loading
ATP	Adenosine tri phosphate
BF	Biceps femoris
CK	Creatine kinase
CMJ	Countermovement jump
CSA	Cross-sectional area
DJ	Depth jump
DOMS	Delayed onset muscle soreness
EEG	Electroencephalography
EIMD	Exercise induce muscle damage
HR	Heart rate
H-reflex	Hoffman reflex
MAP	Maximal aerobic power
MEP	Motor evoked potential
MG	Medial gastrocnemius
M_{max}	Maximal M-wave
MRFD	Maximum rate of force development
MRR	Maximum rate of relaxation
MVC	Maximum voluntary contraction
M-wave	Compound muscle action potential
PO	Power output
$Q_{tw,pot}$	Potentiated quadriceps twitch force
RBE	Repeated bout effect
RFE	Residual force enhancement
RPE	Rate of perceived exertion
RPM	Revolutions per minute
$RT_{0.5}$	One half relaxation time
SD	Standard deviation
sEMG	Surface electromyography
SIT	Super imposed twitch
SJ	Squat jump
SSC	Stretch shortening cycle
TMS	Transcranial magnetic stimulation
VAS	Visual analogue scale
VL	Vastus lateralis
$\dot{V}O_2$	Oxygen uptake

PUBLICATIONS AND CONFERENCE PRESENTATIONS ARISING FROM THE THESIS

Green, D.J., Thomas, K., Ross, E., Pringle, J., Howatson, G., 2017. Familiarisation to maximal recumbent eccentric cycling. *Isokinetics and Exercise Science*. 25, 17–24. doi:10.3233/IES-160640

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Green, D.J., Thomas, K., Ross, E., Howatson, G. Greater neuromuscular fatigue following work-matched interval compared to continuous eccentric cycling (Oral presentation). British Association of Sport and Exercise Science Student Conference 2018. Northumbria University, Newcastle.

DECLERATION

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Any ethical clearance for the research presented In this thesis has been approved. Approval has been sought and granted by the Faculty of Health and Life Sciences Ethics committee for each study.

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CHAPTER 1

INTRODUCTION

Success in competitive sport is heavily determined by the ability of the muscle tendon unit to produce, transmit, or absorb large forces. For example, in sprint cycling quadriceps force production and thigh volume are key determinants of performance (Kordi *et al.*, 2018), in 100 m sprinting, mechanical power output and the ability to produce force at fast contraction velocities delineates fast from slow athletes (Bourdin *et al.*, 2012), and in distance running, the ability to store and return elastic energy is critical to performance (Fletcher and MacIntosh, 2017). A key means of inducing adaptation within the muscle tendon complex is resistance training (Folland and Williams, 2007). Consequently, research examining the effectiveness of resistance training practices, and novel methods to provoke desired adaptation, is highly sought by athletes, coaches, and researchers.

Resistance training involves at least one of three types of muscular contraction; concentric, isometric, or eccentric. Respectively, these three contraction types occur when the muscle shortens, remains equal in length (at least not translating to changes in joint angle), and lengthens during muscle activation. Typically, concentric contractions are considered more sport-specific due to their predominance in many sporting movements. Consequently, resistance training programmes have traditionally comprised of predominantly concentric exercises that are often prescribed based upon one repetition maximum (Kraemer and Duncan, 1998). The evidence for positive muscle tendon complex adaptation after a period of concentric resistance training is irrefutable (Folland and Williams, 2007). However, the notion that specificity of training should be prioritised above all else has been challenged (Hawley, 2008). Cardiovascular training research has shown that short duration high intensity intervals might confer similar adaptations compared to more traditional endurance training (Burgomaster *et al.*, 2008). Furthermore, in resistance training, there is good evidence indicating that eccentric training might elicit greater increases in strength, muscle size, and stretch shortening cycle (SSC) function compared to traditional concentric training (Elmer *et al.*, 2012; Hortobagyi *et al.*, 1996; Hortobágyi *et al.*, 1996; Roig *et al.*, 2009). More specifically, eccentric training has increased in popularity due to its ability to generate much greater levels of absolute tension in the muscle tendon unit compared to concentric resistance training

(Aagaard *et al*., 2000; Borges *et al*., 2003; Ghena *et al*., 1991; Kramer *et al*., 1993; Westing *et al*., 1991).

Early research examining the effect of eccentric resistance training typically used single limb models and isokinetic dynamometry (Hortobagyi *et al*., 1996; Hortobágyi *et al*., 1996). Eccentric contractions require an external force to facilitate muscle lengthening and an isokinetic dynamometer can provide this whilst simultaneously removing the need for isometric or concentric actions, thus making them an ideal tool to isolate eccentric muscle contractions for research purposes. However, due to their single limb setup, isokinetic dynamometers do not allow for the investigation of multi-joint eccentric training, which is arguably of higher ecological validity. Recently, many novel training modalities that do facilitate multi-joint eccentric exercise have been developed. Examples include flywheel resistance machines, weight releaser hooks, motorised leg presses, and eccentric cycling ergometers (Elmer et al., 2012; Franchi et al., 2014; Harden *et al*., 2018). In particular, eccentric cycling ergometers can induce a large volume of eccentric contractions whilst closely controlling the speed of movement, thus making them well suited for research purposes. During eccentric cycling an individual resists the pedals that are driven towards them by a motor; normally on a recumbent ergometer (Elmer *et al*., 2012; Gross *et al*., 2010; Leong *et al*., 2013).

Eccentric cycle training for 7 - 8 weeks has been shown to increase jump power, concentric cycling power, pennation angle, muscle thickness, and leg stiffness in healthy, un-trained participants (Elmer *et al*., 2012; Leong *et al*., 2013). Given the importance of a stiff muscle tendon unit to sporting movements underpinned by SSC function, an eccentric cycling induced increase in leg stiffness could be beneficial across a range of sporting disciplines (Elmer *et al*., 2012). Despite this, the suggestion that eccentric cycling can improve performance in elite athletes has only been tested once, in alpine skiers, with positive effects on jump height (Gross *et al*., 2010). There is currently very little data regarding the most effective protocol for prescribing eccentric cycle training, with the majority of eccentric cycling prescribed sub-maximally at ~60rpm (Elmer *et al*., 2012; Gross *et al*., 2010; Lastayo *et al*., 2000; Leong *et al*., 2013; Peñailillo *et al*., 2015, 2014). Data from upright eccentric cycling does demonstrate that a large mechanical stimulus is possible over a range of cadences (Brughelli and Van Leemputte, 2013), although this has not been documented on the more common recumbent -style ergometer. There is also little research examining the fatigue induced by eccentric cycling. Evidence of a decrement in muscle function and a subsequent repeated bout effect have been reported following eccentric cycling (Peñailillo *et al.*, 2013). Although again, no research has investigated this beyond cadences of 60 rpm or with a specific focus on the type of fatigue i.e. peripheral or central. For eccentric cycling to advance as a training modality for athletes across a range of sports it is critical that the fundamental aspects of this novel exercise modality, and how they can inform practice with elite athletes, are understood more clearly. Therefore, the aim of this thesis was to systematically investigate the neuromuscular responses and application to performance of a bespoke eccentric cycling ergometer.

Specifically, the aim of each experimental chapter was to:

1) Characterise the familiarisation process to eccentric cycling and thus determine a reliable method of assessing the mechanical stimulus afforded by eccentric cycling (Chapter 4).

2) Investigate the stimulus provided by eccentric cycling over a range of cadences (Chapter 5).

3) Examine the effect of session structure, i.e. intervals or a continuous bout of eccentric cycling, on the metabolic and mechanical strain during exercise and the fatigue and muscle damage response post exercise (Chapter 6).

4) Examine the efficacy of eccentric cycling as a method to improvement the determinants of performance in trained athletes (Chapter 7).

CHAPTER 2

LITERATURE REVIEW

This review of the literature contains two broad sections. The first section will introduce the various terminologies used with regards to eccentric muscle actions, the fundamental differences between eccentric and concentric muscle actions, and the unique defining characteristics of eccentric muscle actions. The second section will discuss the practicalities of employing eccentric muscle actions as a training modality and will focus on the acute and chronic responses to eccentric exercise with a particular emphasis on improving the limits of human performance.

2.1 Eccentric muscle actions

An eccentric contraction occurs when an active muscle lengthens whilst under tension. However, technically speaking the term eccentric contraction is a misnomer on two fronts. Firstly, in the context of muscle actions, the noun contraction is defined as "the process in which a muscle becomes or is made shorter and tighter" (Oxford English Dictionary). Such a definition is the antithesis of the lengthening action that actually occurs within the muscle during eccentric contractions. In reality the word contraction, when used after eccentric, refers only to the active state of the muscle rather than its direction of movement. Whilst technically incorrect, this terminology has become the commonly used terms in the scientific literature and wider community. Secondly, the definition of the adjective eccentric is "not placed centrally or not having its axis or other part placed centrally" or alternatively, and more widely used, "(of a person or their behaviour) unconventional and slightly strange" (Oxford English Dictionary), neither of which accurately describe the events of a muscle actively lengthening whilst under tension. The latter definition often leads to confusion amongst wider audiences not familiar with muscle physiology. Used literally the term eccentric (and concentric) contraction can refer to the three dimensional contractions of the heart which can be on-centre or off-centre in nature, although the cardiac muscle itself is still shortening in both instances. The use of the term eccentric with regards to muscle actions is thought to have been first used by Asmussen in 1953 (Asmussen, 1953) and was spelt excentric, with reference to ex- (and ec-) being the latin prefixs meaning "out of/from" and centric meaning "pertaining to the centre". It's origin is from the Greek word ekkentros meaning "out of centre"; from ek- "out of" and kentron "centre" (Oxford English Dictionary). Such provenance helps explain its almost universal adoption when referring to lengthening muscle actions despite its technical short-comings in the English language. Over the years numerous efforts have been made to instigate a more technically accurate convention for the description of muscles actively lengthening whilst under tension (or indeed shortening and remaining equal in length), however, they have generally lacked uptake in the scientific community. For example, pliometric and miocentric have been proposed as more appropriate terms for eccentric and concentric contractions respectively (Hubbard and Stetson, 1938). Plio from the Greek plio meaning “longer”, mio meaning “shorter” in Greek, and metric from the Greek metron meaning “pertaining to measurement” (Faulkner, 2003). However, such attempts have failed and eccentric and concentric contractions remain imbedded in the world of muscle physiology. Within the following thesis the situation in which a muscle lengthens whilst under tension will be referred to as an eccentric contraction or described in literal terms as a muscle lengthening whilst under tension. The author deems that despite any technical shortcomings in such phrases they have become so widely adopted that resistance to such terminology is only likely to increase confusion in what is already a grammatically challenging area of muscle physiology. Given that the Oxford English Dictionary updates the meanings of hundreds of words every year perhaps muscle physiologists would be wise to petition for an updated version of eccentric, concentric and contraction when pertaining to muscle actions to align with the already widespread use of these terms.

Human muscles can produce force via one of three different methods; whilst shortening (concentric), remaining equal in length (isometric), or lengthening (eccentric). All three types of contraction use the same muscle-tendon structures but their unique defining characteristics are determined by how these structures interact. This section will briefly summarise the classical theories of muscle contraction before providing a detailed review into the unique characteristics of eccentric muscle contractions. Although this section will focus on the muscle-tendon complex and its role in muscular contractions it is important to acknowledge the important role of processes that occur upstream from the muscle-tendon complex and their contribution to force production in skeletal muscle.

Voluntary muscle activation originates in the premotor cortex of the brain (Miller and Cohen, 2001), subsequent to which an action potential is generated in the primary motor cortex (M1) (Rizzolatti and Luppino, 2001). The action potential propagates along spinal motor neurons in the form of a localised membrane depolarisation (Sasaki *et al*., 2011). At the neuromuscular junction the action potential releases the neurotransmitter acetylcholine, which initiates an action potential in the sarcolemma (Hughes *et al*., 2006). This action potential propagates along the sarcolemma and down t-tubules to the sarcoplasmic reticulum where it initiates calcium release into the muscle (Lanner *et al*., 2010). The basic structure of muscle tissue can be seen in Figure 2.1. When calcium concentration increases within the sarcomere the actin and myosin filaments slide past each other causing the sarcomere to shorten and generate mechanical force. This mechanism of force production was first published in 1954 (Andersen, 2004; Hanson and Huxley, 1953; Huxley and Niedergerke, 1954; Huxley, 2004) and is called sliding filament theory. An important aspect of sliding filament theory is cross bridge cycling, the mechanism by which the actin and myosin filaments slide past each other in the presence of increased calcium concentration.

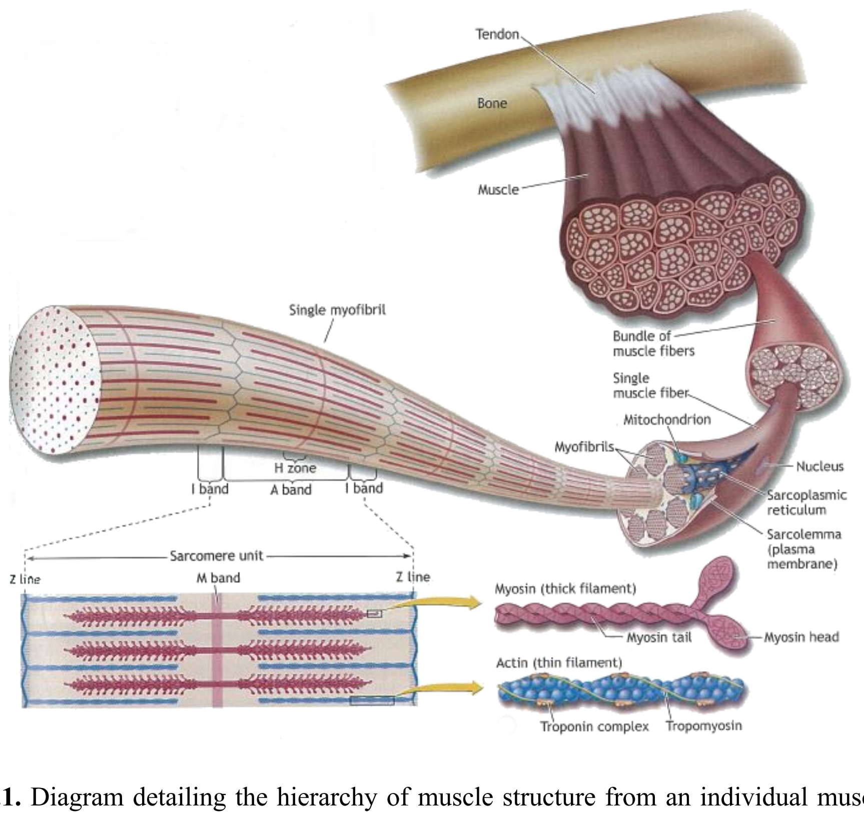


Figure 2.1. Diagram detailing the hierarchy of muscle structure from an individual muscle down to single actin and myosin filaments (McArdle *et al*., 2001).

Cross bridge cycling is described in Figure 2.2. Briefly, in the presence of calcium tropomyosin reveals binding sites on the actin thin filament. Myosin heads form cross bridges with these actin binding sites and via the hydrolysis of ATP perform a power stroke of the myosin heads which creates mechanical movement. Muscle relaxation occurs when calcium is actively taken back up by the sarcoplasmic reticulum and tropomyosin re-blocks the active sites on the actin filament. Sliding filament theory dictates that muscle force peaks when the overlap of actin and myosin is greatest, and the highest number of cross bridges can be formed. Although, typically visualised as a two-dimensional concept (i.e. Figure 2.2) cross bridge cycling is actually a complex three-dimensional process (Schoenberg, 1980). The radial distance between myosin and actin filaments, termed lattice spacing, plays a role in force production at any given sarcomere length (Williams *et al*., 2013). Greater lattice spacing, i.e. an increase in radial distance between filaments, reduces force production for a given sarcomere length (Williams *et al*., 2013). This modulation of force production via changes in lattice spacing occurs as a result of altered myosin kinetics (David Williams *et al*., 2010; Schoenberg, 1980).

Under concentric conditions the force produced by the sarcomeres exceeds the external force on the muscle and thus the muscle shortens. During isometric contractions sarcomere force and external force are equal, and therefore the muscle doesn’t change length. During eccentric contractions external force exceeds sarcomere force and thus the muscle lengthens whilst generating tension. Sliding filament theory adequately explains the experimental observations of concentric and isometric contractions, however there are several observations during eccentric contractions that cannot be explained by this mechanism. The next section will discuss these observations and how they have challenged the traditional sliding filament theory of muscle contraction.

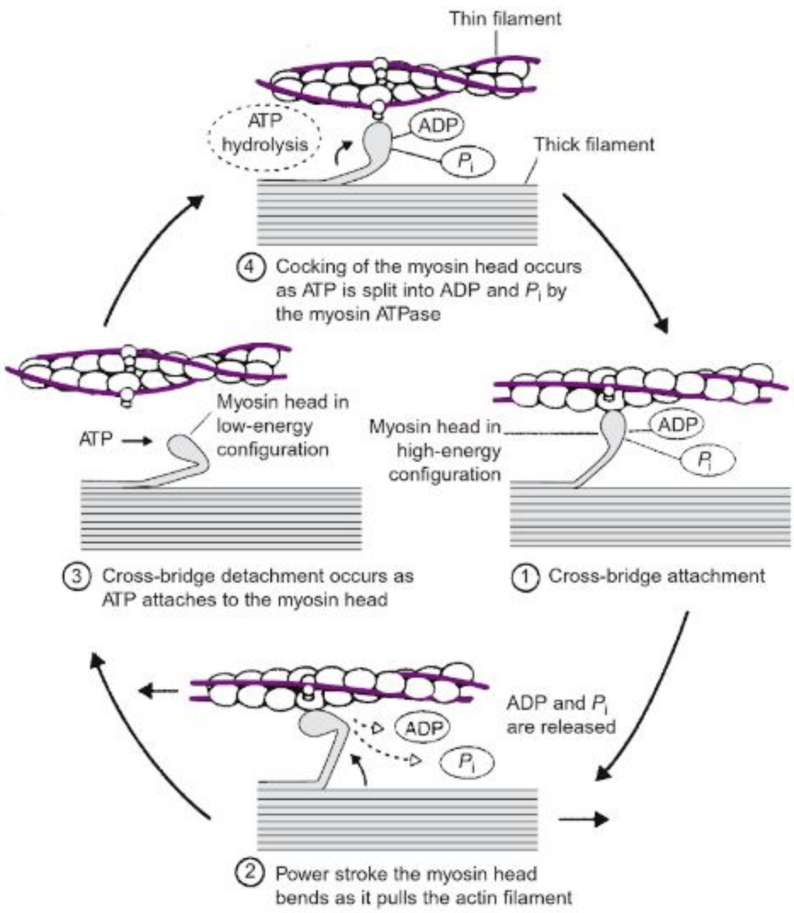


Figure 2.2. Sequence of events in cross bridge cycling (Maughan and Gleeson, 2010).

2.1.1 Force production

A defining characteristic of eccentric contractions is the ability to produce greater force compared to a concentric contraction of equivalent velocity (Aagaard *et al.*, 2000; Borges *et al.*, 2003; Edman, 1988; Ghena *et al.*, 1991; Katz, 1939; Kramer *et al.*, 1993; Westing *et al.*, 1991). This discrepancy in force production is greater at faster contraction velocities (Aagaard *et al.*, 2000; Kramer *et al.*, 1993; Westing *et al.*, 1991). For example, above 180 $deg \cdot s^{-1}$ eccentric knee extensor torque can reach up to 178% of the equivalent concentric torque, however, below 90 $deg \cdot s^{-1}$ this difference reduces to between 104% - 127% (Aagaard *et al.*, 2000; Kramer *et al.*, 1993; Westing *et al.*, 1991). This can be attributed to the different force-velocity relationships between eccentric and concentric contractions (Figure 2.3). When contracting concentrically an *in-vitro* muscle fibre produces less force as contraction velocity increases (Edman, 1988; Hill, 1938; Katz, 1939). This relationship is hyperbolic in nature and is consistent across numerous single joint movements (Wickiewicz *et al.*, 1984; Wilkie, 1950). In contrast, an eccentrically contracting muscle fibre (*in-vitro*) increases force concomitantly with contraction velocity (Edman, 1988; Hill, 1938; Katz, 1939). Although in single joint eccentric actions this rise in force with increasing velocity is not as great as that observed in single muscle fibre preparations (Carney *et al*., 2012; Chapman *et al*., 2005; Ghena *et al*., 1991; Kramer *et al*., 1993; Westing *et al*., 1988).

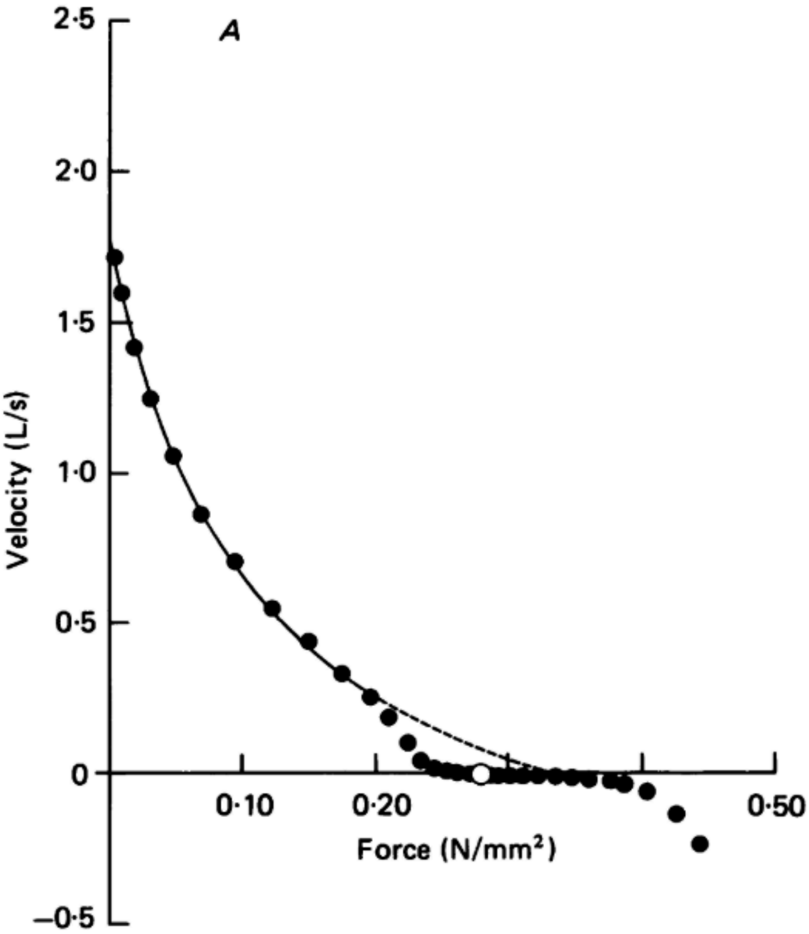


Figure 2.3. Force-velocity relationship in a single frog muscle fibre including data at loads greater than isometric force, P_0 (O) (Edman, 1988).

Not only can eccentric contractions produce greater force than an equivalent concentric contraction but they can also enhance force production in a subsequent isometric contraction (Pinniger and Cresswell, 2007; Shim and Garner, 2012). This ability to facilitate an increase in isometric force production beyond that observed during a stand-alone contraction is termed residual force enhancement (RFE). Residual force enhancement has been well documented *in-vitro* (Edman *et al*., 1982;

Joumaa *et al*., 2008; Peterson *et al*., 2004; Rassier *et al*., 2003; Sugi and Tsuchiya, 1988), and *in-vivo* with electrically stimulated (Cook and McDonagh, 1995; Lee and Herzog, 2002; Pinniger and Cresswell, 2007; Ruiter *et al*., 2000) and voluntary activated (Lee and Herzog, 2002; Pinniger and Cresswell, 2007; Shim and Garner, 2012) muscles. Sliding filament theory fails to explain this difference in isometric force production between two isometric contractions at identical muscle lengths. In theory, at identical muscle lengths an equal number of cross bridges should be formed and force production should be equal. However, residual force enhancement provides conclusive evidence that force production is dependent on the contraction history of the muscle. There are three main models that expand on sliding filament theory in an attempt to explain the unique observation of RFE (for a detailed review see 13).

(1) Increased active force of cross bridges

Within the constraints of sliding filament theory the greater force production during, and following, eccentric contractions could be explained by enhanced cross-bridge force transmission (Mehta and Herzog, 2008). A stretch-induced increase in the number of cross bridge attachments and/or a greater force per cross bridge would achieve this (Mehta and Herzog, 2008). However, when stretched, the duty cycle of cross bridge formation is unchanged thus making it unlikely that increased cross bridge numbers are responsible for force enhancement (Mehta and Herzog, 2008). Furthermore, if greater numbers of cross bridges were formed under stretch conditions an increase in stiffness would be expected, which has not been observed (Sugi and Tsuchiya, 1988). However, there is experimental evidence for an increase in average cross bridge force following an induced stretch (Mehta and Herzog, 2008). Although, it is unlikely that a) this effect lasts the duration of the longest observed RFE, ~ 1 min (Leonard *et al*., 2010), or that b) cross bridges can sufficiently elongate to generate the required force (Herzog, 2014). Perhaps most interestingly though is the observation that when single myofibrils are actively stretched to the degree that actin and myosin filaments no longer overlap, force production was still greater than passively stretched myofibrils (Leonard and Herzog, 2010); thus, indicating the involvement of a cross bridge-independent mechanism of stretch induced force enhancement.

(2) Sarcomere-length non-uniformity theory

This theory postulates that during eccentric contractions individual sarcomeres do not lengthen homogenously on the descending limb of the length-tension curve. Relative to their length during an isometric contraction some sarcomeres remain shorter whilst others increase in length. Shorter sarcomeres have greater filament overlap and therefore an increased force production whilst lengthened sarcomeres have reduced filament overlap and therefore a reduced force production. The sarcomere-length non-uniformity theory suggests that longer sarcomeres compensate for a loss of force production by engaging passive structures and that in combination with the increased force production of shorter sarcomeres generate greater overall force. It is also suggested that this sarcomere non-uniformity is evident post-contraction and is the mechanism of RFE. However, this theory dictates that RFE is not seen on the ascending limb of the length-tension curve and that RFE can never exceed optimal length isometric force; both of which have been proved experimentally untrue (Abbott and Louvain, 1951; Bullimore et al., 2007; Morgan et al., 2000; Peterson et al., 2004) and Lee and Herzog, 2008; Morgan et al., 2000; Peterson et al., 2004; Schachar et al., 2004, respectively).

(3) Engagement of passive structures

This final hypothesis is not based on the traditional cross bridge theory of muscle contraction, but instead proposes that the structural protein titin mediates changes in passive stiffness which contributes to enhanced force production during eccentric contractions (Herzog, 2014). Titin supports the sarcomere by connecting the Z-line to the M-line and acts like a molecular spring. Experimental evidence has shown that removing titin from sarcomeres eliminates passive force enhancement (Leonard and Herzog, 2010), which suggests a causative role. A ‘three filament model’ (Herzog, 2014) and a ‘winding filament theory’ (Nishikawa *et al*., 2012), both incorporating titin, have been proposed to explain the unique force characteristics of eccentric contractions. The essence of both theories is that, in the presence of calcium (i.e. during muscle activation), the free spring length of titin is reduced due to an interaction with the adjacent actin (Herzog, 2014; Nishikawa *et al*., 2012). This smaller free spring length would increase passive force production for any given degree of stretch. The winding filament theory suggests that active cross bridge cycling causes titin to wind around a rotating actin filament, thus shortening it (Nishikawa *et al*., 2012). In contrast, the three filament theory suggests that upon muscle activation titin binds directly to actin to reduce the free spring length (Figure 2.3) (Herzog, 2014). Furthermore, the 3-filament model also proposes that calcium binds directly with titin to increase the stiffness of the remaining free spring (Herzog, 2014). In summary, the engagement of passive structures theory has less contradictory evidence when compared to the increased active cross bridge force and sarcomere non-uniformity theories and therefore, at the present time, best explains force production during eccentric contractions. Although, it is equivocal as to which titin based model is most accurate.

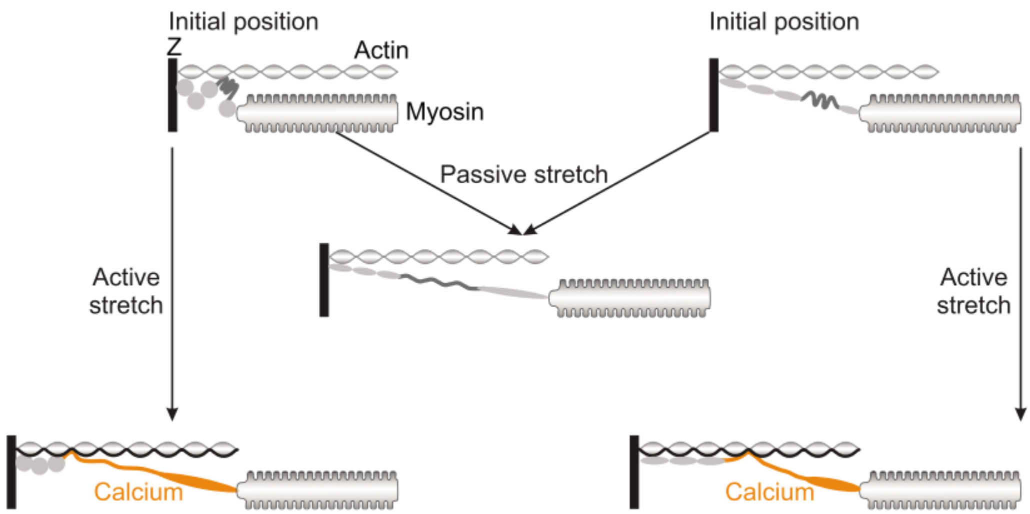


Figure 2.4. Sequence of events in which the free spring length of titin can shorten by binding with actin during an active stretch of the muscle (Herzog, 2013).

2.1.3 Neural control of eccentric contractions

As previously described, eccentric contractions can generate greater peak force compared to their concentric counterparts (Edman, 1988; Katz, 1939). A phenomenon that occurs to a greater extent *in-vitro* compared to *in-vivo*, for example, eccentric force can exceed concentric force by up to 80% in electrically stimulated muscle fibres (Edman, 1988; Katz, 1939; Morgan *et al*., 2000), whereas in human subjects peak eccentric knee extensor force is typically 10 – 35% greater than during the equivalent concentric action (Aagaard *et al*., 2000; Babault *et al*., 2001; Beltman *et al*., 2004; Seger and Thorstensson, 2000; Westing *et al*., 1991). Though, this discrepancy can be muscle specific as eccentric-concentric peak force ratios of up to 50% have been observed in the ankle dorsiflexors (Pasquet *et al*., 2000). It has been suggested that force production during *in-vivo* eccentric contractions is limited by a reduction in neural drive, which is absent when the muscle is electrically stimulated *in-vitro* (Duchateau and Enoka, 2016). Such evidence suggests that neural drive during *in-vivo* lengthening contractions might not be capable of eliciting maximum muscle force. Evidence of reduced EMG (Aagaard *et al*., 2000; Amiridis *et al*., 1996; Kellis and Baltzopoulos, 1998; Westing *et al*., 1991), reduced motor unit firing rates (Del Valle and Thomas, 2005), and reduced voluntary activation (Amiridis *et al*., 1996; Beltman *et al*., 2004) during eccentric contractions compared to concentric contractions support this theory. Reductions in neural drive are greater in eccentric naïve individuals but can be reduced with task specific habituation (Aagaard *et al*., 2000). It has been suggested that reduced voluntary drive during maximal eccentric contractions is a mechanism designed to protect the muscle tendon unit from extreme forces (Del Valle and Thomas, 2005; Seger and Thorstensson, 2000; Westing *et al*., 1991). However, sub-maximal eccentric force is also greater when the muscle is electrically stimulated rather than voluntarily activated to the same degree, as determined by root mean squared EMG signal (Pinniger *et al*., 2000). Therefore, protection against high forces is at the very least not the only factor influencing the neural control of eccentric contractions. These findings at sub-maximal intensities have led to the suggestion that eccentric actions have a unique neural activation strategy that is independent of force production (Duchateau and Enoka, 2016).

Using transcranial magnetic stimulation (TMS) it has been shown that intracortical facilitation and cortical responsiveness is greater during eccentric (compared to concentric) contractions (Duclay *et al*., 2014, 2011; Howatson *et al*., 2011). Furthermore, using electroencephalography (EEG), it has been observed that eccentric contractions activate a larger area of the brain compared to concentric contractions (Fang *et al*., 2004, 2001). However, despite this greater brain activity and cortical facilitation, eccentric contractions exhibit reduced neural drive at the muscle. Evidence suggests this is due to greater spinal/supra spinal inhibition during eccentric contractions. When TMS is used during eccentric contractions, motor evoked potentials (MEP) (Abbruzzese *et al*., 1994; Gruber *et al*., 2009) and H-reflex responses (Abbruzzese *et al*., 1994; Nordlund *et al*., 2002; Romano and Schieppati, 1987; Sekiguchi *et al*., 2003) are reduced compared to concentric contractions. These findings indicate greater spinal and/or supra spinal inhibition of motor signals and reduced spinal excitability via a reduction in motor unit responsiveness to type 1a afferent nerve excitation. Further work has suggested that spinal inhibition is greater than cortico-spinal inhibition during eccentric contractions. Evidence for this comes from a greater decrement in H-reflex (vs MEP) during electrical stimulation of the soleus during eccentric, compared to concentric contractions (the later not involving the cortico-spinal tract) (Duclay *et al*., 2014).

Historically, there has been a belief that eccentric exercise may selectively recruit type II motor units (Enoka, 1996; Nardone *et al*., 1989), especially at higher contraction velocities (Kulig *et al*., 2001; Nardone and Schieppati, 1988). However, in more recent times this view has been gradually dismissed (Duchateau and Enoka, 2016). The majority of research has observed no difference in motor unit recruitment between eccentric and concentric contractions of the same relative and absolute intensity (Altenburg *et al*., 2009; Garland *et al*., 1996; Laidlaw *et al*., 2000; Pasquet *et al*., 2006; Sogaard *et al*., 1996; Stotz and Bawa, 2001). Additionally, when switching between concentric and eccentric contractions of the same absolute load the motor units recruited last during the concentric contraction (higher threshold motor units) are de-recruited first during the eccentric contraction (Pasquet *et al*., 2006). This de-recruitment is to be expected as eccentric contractions generate more force per motor unit and therefore require less motor units for a given force. Motor unit recruitment during eccentric contractions appear to follow Henneman's size principle (Henneman, 1957).

2.1.4 Metabolic demand

As early as 1896, Chauveau (1896) observed that the eccentric dominant action of walking backwards downstairs was metabolically less demanding than the concentric dominant activity of walking forwards upstairs. The first researchers to examine this phenomenon in a cycling model were Abbott, Bigland and Ritchie in 1953 (Abbott *et al*., 1952). By using back to back bicycles directly connected by a chain one cyclist could pedal forwards in a conventional concentric manner whist the second cyclist resisted the backwards movement of the pedals in a predominantly eccentric manner (Figure 2.4).

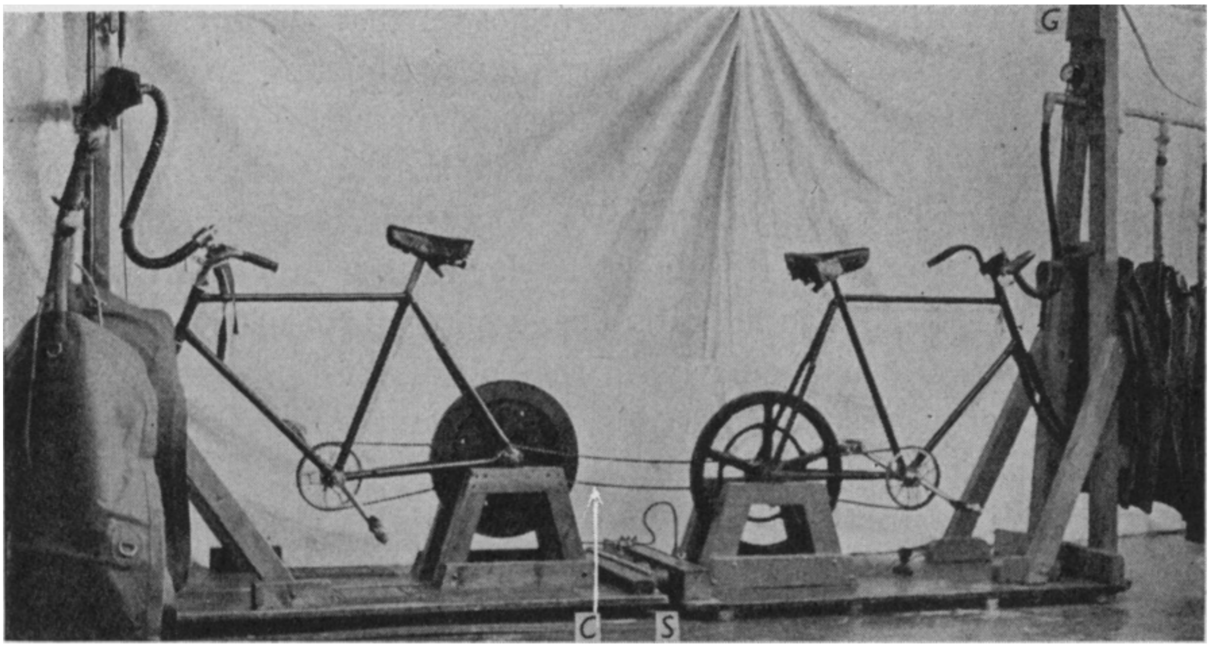


Figure 2.5. Two bicycle ergometers coupled together in opposition and separated by a flexible water-filled buffer system S connected to the gauge G. One bicycle is mounted on rollers resting on a smooth metal sheet (Abbott *et al*., 1952).

Despite the equivalent power outputs the individuals performing eccentric cycling displayed a much lower metabolic cost compared to those who were cycling concentrically. More recently, the advent of motorised eccentric cycle ergometers (discussed later) has allowed for greater experimental control (Elmer *et al*., 2010a). The reduced metabolic stress of eccentric cycling has been replicated many times over; eccentric cycling can be up to five times less metabolically demanding than an equivalent concentric power output (Dufour et al., 2004; Knuttgen et al., 1982; Lechauve et al., 2014; Peñailillo et al., 2017a, 2013; Perrey et al., 2001). In addition to a reduced oxygen uptake ($\dot{V}O_2$), eccentric cycling elicits lower levels of blood lactate (Peñailillo *et al*., 2013), rate of perceived exertion (Peñailillo *et al*., 2013), ventilation (Lechauve *et al*., 2014), and cardiac output (Dufour *et al*., 2004), and greater tissue oxygenation (Peñailillo et al., 2017a) compared to concentric cycling at a similar mechanical power output. This uniquely low metabolic stress makes eccentric cycling an attractive exercise modality for individuals with existing cardiorespiratory limitations such as coronary heart disease (Gremeaux *et al*., 2010; Meyer *et al*., 2010; Steiner *et al*., 2004) or chronic obstructive pulmonary disease (Vieira *et al*., 2011), and for athletes specifically attempting to mechanically overload their musculoskeletal system with a reduced metabolic consequence.

Three mechanistic theories have been posited to explain the reduced metabolic cost of eccentric cycling; 1) Contribution of passive structures to energy storage and return, 2) Non ATP-dependant mechanical detachment of cross bridges, and 3) greater muscular force per level of muscle fibre recruitment (Peñailillo *et al*., 2017a). During other forms of locomotion, e.g. running, muscle fascicles can act in an isometric manner allowing tendons to elongate and recoil thus storing and returning elastic energy, this is termed the stretch shortening cycle (SSC). During eccentric cycling however, there is minimal SSC function (Peñailillo *et al*., 2015) which suggests that this mechanism of energy storage and return might not be a primary factor in the reduced metabolic cost of eccentric cycling. Furthermore there is little difference in tendon and fascicle lengthening between eccentric and concentric cycling (Peñailillo *et al*., 2015) which further suggests that tendon mechanics do not significantly influence energy utilisation. Current evidence suggests that the most likely cause of the lower metabolic cost during eccentric cycling (versus concentric cycling) is a reduction in muscle activation. Penailillo *et al* (2017) observed 6 – 10% lower agonist and antagonist activation during eccentric cycling compared to concentric cycling at the same power output. Based on the work of Herzog (2014), a calcium dependent increase in the stiffness of the muscle tendon complex would increase passive force production for a given degree of stretch thus requiring less motor units to be innervated to achieve a required force. Interestingly, when performed at a similar $\dot{V}O_2$, eccentric cycling exhibits greater cardiac output and heart rate in comparison to concentric cycling (Dufour *et al.*, 2007). As a result, when comparing eccentric and concentric cycling at the same power output there is usually a reduced $\dot{V}O_2$ and HR during eccentric cycling (Peñailillo et al., 2017a).

2.2 Eccentric training modalities

Eccentric training can be split into two broad categories; accentuated eccentric loading (AEL) and eccentric only training. Accentuated eccentric loading consists of loaded eccentric and concentric contractions during which the eccentric phase is loaded or emphasised to a greater extent than the concentric phase. This type of training attempts to balance the intensities of the eccentric and concentric phase relative to their respective maximal force capability. Examples of AEL include flywheel resistance machines, variable resistance weight stacks, manual removal of a proportion of the eccentric load, and weight releaser hooks. An advantage of AEL is the increased stress on the eccentric phase of a complex movement which would be under-stressed during isotonic conditions (relative to contraction specific maximal force). However, AEL still comprises a large concentric component which, if seeking an eccentric-specific stimulus, is redundant. Furthermore, AEL is not a suitable exercise modality for the determination of mechanistic differences between eccentric and concentric training due to the inclusion of both contraction types in the modality.

Eccentric only training consists of repeated eccentric loading with no accompanying concentric phase. For eccentric contractions to occur there must be external force acting on the desired muscle, only when this external force exceeds the force produced by the muscle does an eccentric contraction occur. During eccentric only training the external force can come from a variety of sources, for example; the effect of gravity on a mass (e.g. dumbbell or body weight), or from a device designed to create mechanical movement e.g. motorised cycle ergometer or dynamometer. A common challenge with eccentric only training is how this external force is made to be repetitive without the need for a concentric action. The use of dynamometers has gone some way to overcoming this problem as multiple eccentric contractions can be performed repetitively without a concentric element. But even so, dynamometers do not have a particularly fast duty cycle and thus limit the study of high volume eccentric training. Dynamometers also do not allow for the study of multi joint/limb eccentric training, which is likely to be more applicable to functional movements in sport and life. This has led to the development of motorised leg presses (Franchi *et al*., 2014) and eccentric bikes (Elmer *et al*., 2010a; Leong *et al*., 2013). Whilst both remove the requirement for a significant concentric phase only the eccentric bike facilitates high volumes of eccentric contractions in a practical and easy to implement manner, i.e. due to its fast duty cycle, e.g. 120rpm.

Compared to conventional cycle ergometers there are few commercially available eccentric ergometers, and those that do exist are relatively new to the market e.g. Cyclus 2 (RBM elektronik-automation GmbH, Leipzig, Germany) and LODE Corival Eccentric (LODE B.V., Groninghen, Netherlands). As a result, the majority of eccentric cycling research has been performed using customised ergometers bespoke to each research group (Leong *et al*., 2013). Typically these eccentric ergometers are recumbent in nature and have isokinetic pedals. The recumbent design of eccentric ergometers enables users to resist the pedals by pushing against a backrest. The isokinetic nature of the pedals allows the operator to accurately control cadence but does mean overall power/torque is controlled by the degree of user exertion. Using real-time power output data, users can tailor the resistance effort to meet a pre-selected target power output.

2.3 Acute response to eccentric exercise

2.3.1 Muscle damage and the repeated bout effect

It is well documented that repeated eccentric contractions can cause exercise-induced muscle damage (EIMD) (Clarkson and Hubal, 2002; Douglas *et al*., 2017a). In particular, novel eccentric exercise can induce severe sarcomere disruption, muscle oedema, and excitation-contraction coupling disturbances (Proske and Morgan, 2001). Direct assessment of these phenomena requires muscle biopsies, however these are highly invasive and often prohibitively expensive. More commonly, the magnitude of EIMD is determined by indirect measures such as muscle function, muscle soreness, range of motion, and an increase in specific circulating muscle proteins (Warren *et al*., 1999). Muscle damage after eccentric exercise can be split into two phases, primary phase muscle damage and secondary phase muscle damage. Primary muscle damage occurs during eccentric exercise, whilst secondary damage manifests in the hours and days after the cessation of exercise (McHugh, 2003).

It has been suggested that both metabolic and mechanical factors contribute to the development of primary muscle damage during eccentric exercise (Armstrong *et al*., 1991). The metabolic theory dictates that EIMD occurs as a result of free radical production or insufficient mitochondrial respiration (Armstrong *et al*., 1991). However, given that eccentric exercise elicits greater muscle damage compared to concentric exercise, but at a reduced metabolic cost, it is unlikely that metabolic factors play a critical role in EIMD during eccentric exercise (Peñailillo *et al*., 2013). The greater mechanical tension generated per muscle fibre during eccentric contractions can cause significant mechanical disruption to the muscle-tendon unit (Proske and Allen, 2005). Eccentric exercise can disrupt the Z-bands within a sarcomere and cause disturbances to the transverse t-tubules and sarcoplasmic reticulum (Proske and Allen, 2005). There is some debate as to whether sarcomere disruption or excitation-contraction coupling disturbances is the primary stimulus for EIMD (Proske and Morgan, 2001). The inhomogeneity of sarcomeres theory dictates that Z-band streaming occurs via the "popping" of sarcomeres on the descending limb of the length-tension relationship (Morgan, 1990). On the descending limb of this relationship sarcomeres lengthen to different extents, some lengthen to such a degree that the actin and myosin filaments no longer overlap (Morgan, 1990). When this occurs the passive components of the sarcomere, titin, desmin, and nebulin, maintain muscle tension (Morgan, 1990). With repeated eccentric actions a greater number of sarcomeres "pop" and muscle damage increases. When the number of disrupted sarcomeres reaches a critical level it is thought that membrane damage, and therefore E-C coupling disturbances, occur within the muscle (Proske and Morgan, 2001). These E-C disturbances are thought to be a mechanism of the low frequency fatigue observed after damaging exercise (Clarkson and Hubal, 2002). Low frequency fatigue is the decreased ability of the muscle to generate force at low frequencies of electrical stimulation (10 – 20 Hz) and has been observed up to a week after damaging exercise (Hill *et al*., 2001; Newham *et al*., 1987). A further, and immediate, consequence of muscle damage during eccentric exercise is an increase in the optimum muscle length for active tension (Brockett *et al*., 2001). It is thought that upon muscle relaxation some over-stretched sarcomeres fail to return to their original length and therefore other sarcomeres must compensate by returning to a shorter length compared to pre-exercise (Proske and Morgan, 2001). In this scenario, to generate optimal muscle tension a greater degree of stretch is required to elicit passive force from these shorter sarcomeres.

In the 2-3 hours after damaging eccentric exercise there is an improvement in muscle function, after which, a second, smaller reduction in muscle function begins to occur (MacIntyre *et al*., 1996). This second decrease in muscle function is a result of the secondary phase of muscle damage associated with eccentric exercise. Secondary phase muscle damage causes increases in pain, swelling, plasma creatine kinase concentration ([CK]), and decreased range of movement (Clarkson and Hubal, 2002; Proske and Allen, 2005). Each of these symptoms follows a unique time course in response to the same exercise stimulus, for example, force recovers linearly every 24 h post exercise, however, blood [CK] increases from day one to a peak at day three to five (Damas *et al*., 2016). Peak muscle swelling tends to occur approximately 4-7 days post exercise whereas muscle soreness peaks 2 – 3 d post exercise (Damas *et al*., 2016). The muscle soreness associated with this secondary phase of muscle damage is known as delayed onset muscle soreness (DOMS). Delayed onset muscle soreness and the associated symptoms are exacerbated by novel eccentric tasks (Peñailillo *et al*., 2013), and increases in contraction velocity (Chapman *et al*., 2006), intensity (Chen *et al*., 2007), and volume (Howatson *et al*., 2007) of the stimulus. Additionally, resistance trained individuals appear to experience reduced markers of muscle damage following eccentric training (Ewton *et al*., 2008). Functional multi-joint consequences of secondary phase muscle damage include reductions in running economy (Chen *et al*., 2017, 2009) and changes in gait kinematics (Paschalis *et al*., 2007). Although the mechanism of secondary phase muscle damage is not fully understood, it is thought that the cumulative effect of multiple “popping” sarcomeres during eccentric contractions can lead to the death of a myofibril (Proske and Morgan, 2001). The resulting inflammatory response causes an increased sensitivity in the nociceptors (hence increased pain), muscle oedema, and decrements in range of movement and force production.

The repeated bout effect (RBE) is a term used to describe the ability of a single bout of eccentric exercise to confer a protective effect on a subsequent bout of eccentric exercise and reduce EIMD and the associated symptoms (Hyldahl *et al*., 2017; Meneghel *et al*., 2013; Nosaka and Aoki, 2011). The level of protection granted by the initial bout varies depending on the marker of muscle damage being observed (Hyldahl *et al*., 2017). Using two previous studies (Chen *et al*., 2007, 2012) Hyldahl *et al*. (2017) quantified the effect of the RBE on measures of MVC, DOMS, and [CK]. Where 100% equates to total protection i.e. no marker of muscle damage after the second bout, the protective effect of a prior bout of maximal eccentric exercise was 100%, 83%, and 30% for [CK], DOMS, and MVC, respectively. A recent review paper suggested that the greater the potential for muscle damage in the initial bout of eccentric exercise the greater the magnitude of the RBE (Hyldahl *et al*., 2017). This is based upon observations of an enhanced RBE following eccentric exercise that generates greater muscle damage, i.e. performed at greater intensity, volume, longer muscle lengths, and contraction velocity (Hyldahl *et al*., 2017). Despite this positive relationship between muscle damage and a larger RBE, a RBE effect, albeit reduced, is still evident even when there is minimal muscle damage after the initial bout (Chen *et al*., 2012). Interestingly there is also a contralateral repeated bout effect whereby the damage response to single limb eccentric exercise is blunted by an initial bout of eccentric exercise performed on the other limb, however, this effect is not as strong as the ipsilateral RBE (Howatson and van Someren, 2007). This reduced contralateral RBE suggests that this phenomenon is mediated by both neural factors (which are conferred to a contralateral limb), and mechanical factors (not conferred to the contralateral limb). The differing response of the many symptoms of muscle damage to the RBE also suggests that there could be multiple mechanisms involved (Hyldahl *et al*., 2017).

A recent review has described the potential mechanisms involved in the RBE (Hyldahl *et al*., 2017). Briefly, it is suggested that the central nervous system can enhance motor unit synchronisation (Dartnall *et al*., 2011) and shift recruitment to lower threshold motor units (McHugh, 2003), thus distributing tension from the second eccentric bout over a greater number of motor units. Another possible mechanism is an increase in tendon compliance following the initial bout of exercise, which would reduce the strain on the muscle fascicles during the second bout (Hyldahl *et al*., 2017). There has also been observation of up-regulation of genes that correspond to extracellular matrix (ECM) structure and function after eccentric exercise (Hyldahl *et al*., 2011). It is suggested that re-modelling of the ECM could increase passive stiffness of the muscle-tendon complex. Finally, evidence of a greater inflammatory response following a second bout of eccentric exercise (Deyhle *et al*., 2016) could indicate a mechanism of enhanced recovery, although this hypothesis lacks experimental evidence.

2.4 Physiological and anatomical responses to chronic eccentric exercise

2.4.1 Hypertrophy and MTU morphology

Many studies have observed muscle hypertrophy after a period of eccentric training (Blazevich *et al*., 2007; Farthing and Chilibeck, 2003a; Higbie *et al*., 1996; Hortobágyi *et al*., 2000; Roig *et al*., 2009; Vikne *et al*., 2006). The exact magnitude of eccentric induced hypertrophy is likely dependent on the contraction velocity (Farthing and Chilibeck, 2003b; Sharifnezhad *et al*., 2014; Shepstone *et al*., 2005), intensity (English *et al*., 2014), and volume (Lastayo *et al*., 2000) of training. The primary drivers of this hypertrophy are thought to be the high level of mechanical tension and EIMD associated with eccentric training (Douglas *et al*., 2017b; Schoenfeld, 2010). Interestingly, there is evidence to suggest that eccentric exercise preferentially confers hypertrophy at the distal portion of skeletal muscle (Franchi *et al*., 2014; Seger *et al*., 1998). Ten weeks of eccentric leg press training (3 × per week) increased distal *vastus lateralis* (VL) anatomical cross sectional area by 8% compared to an increase of 2% in a concentric control group (Franchi *et al*., 2014).

Additionally a 6% increase in distal quadriceps cross sectional area (significantly greater than control leg) has been observed after 10 weeks of isokinetic eccentric knee extensor training (Seger *et al*., 1998). Both these studies used magnetic resonance imaging (MRI) to determine muscle size. Franchi *et al* (2014) suggested that distal hypertrophy after eccentric training could be a result of the preferential addition of sarcomeres in series. Using B-mode ultrasonography they found muscle hypertrophy after eccentric exercise occurred primarily via the elongation of muscle fascicles. Although no work has been done on the location of these additional sarcomeres in humans; evidence from animal models suggest that longitudinal muscle growth occurs via the addition of sarcomeres and increased satellite cell frequency at the periphery of the muscle (Allouh *et al*., 2008; Williams and Goldspink, 1971). In contrast, after concentric resistance training hypertrophy is underpinned by increases in pennation angle. Ten weeks of concentric leg press training increased VL pennation angle by 30% compared to 5% in the eccentric group (Franchi *et al*., 2014). Highly pennate muscles have a greater physiological cross sectional area and therefore produce greater force compared to muscles with more sarcomeres in series which have a greater velocity of shortening (Wickiewicz *et al*., 1984). These contraction specific adaptations should be considered when prescribing resistance training in order to elicit most desirable response for a given athlete/sport.

Several studies have examined the effect of eccentric cycling on lower limb muscle hypertrophy and morphology in populations with existing physical limitations, such as Parkinsons Disease (Dibble *et al*., 2006) and sarcopenia (Mueller *et al*., 2009). In these populations eccentric cycling increased quadriceps muscle volume by approximately 3% over 12 weeks. More importantly, this increase was greater in comparison to a program of standard Parkinsons care or traditional concentric gym exercises. Eccentric cycling also increased muscle volume and quadriceps anatomical cross sectional area to a greater extent than a traditional rehabilitation program after ACL surgery (Gerber *et al*., 2007b). However, due to the physical limitations of these individuals, these data do not necessarily represent that which would occur in non-physically limited populations. Using healthy, but untrained participants, increases in pennation angle, muscle thickness, and muscle fibre area have been observed after 8 weeks of eccentric cycling (Lastayo *et al*., 2000; Leong *et al*., 2013). Although these studies had either no control group (Leong *et al*., 2013) or a control group consisting of concentric cycling (Lastayo *et al*., 2000), which does not offer a comparison with typical resistance training methods. To our knowledge only one study has examined the effect of eccentric cycling on muscle volume in elite athletes using a resistance training control group. In national level Swiss junior skiers, substituting two sets of lower limb concentric resistance training for 20 min of eccentric cycling three times per week increased lean thigh mass by ~2%. The control group performed two additional sets of lower limb resistance training (i.e. squats and lunges) and experienced no increase in lean thigh mass. Although, there was no significant interaction effect of experimental group and time on lean thigh mass. Eccentric cycling appears to induce muscle hypertrophy but more work is required to ascertain its efficacy compared to concentric methods designed to elicit similar responses.

A 2009 meta-analysis concluded that eccentric training is more effective at increasing muscle mass than concentric training (Roig *et al*., 2009), a position shared by a more recent review (Hedayatpour and Falla, 2015). However, this assertion has been disputed by a recent meta-analysis (Schoenfeld *et al*., 2017) and review (Franchi *et al*., 2017). A key facet of this discussion is whether there is an eccentric specific mechanism that induces greater hypertrophy or whether it is simply that eccentric contractions can produce greater force and therefore a greater hypertrophic response compared to concentric contractions. Generally speaking, when eccentric and concentric contractions are matched for absolute intensity there is little difference in hypertrophy (Franchi *et al*., 2017). However, when they are matched for relative intensity (i.e. to mode specific 1RM), eccentric exercise tends to show greater hypertrophic gains (Roig *et al*., 2009). These findings suggest that the greater level of force elicited in eccentric training might be a key factor for greater hypertrophy. From an applied perspective however, the mechanisms are redundant, even if eccentric hypertrophy is primarily driven by greater mechanical tension it still has practical applications for individuals looking to elicit muscle hypertrophy.

2.4.2 Muscle fibre composition

It is widely accepted that resistance training causes a shift in myosin heavy chain composition towards type 2a muscle fibres regardless of contraction type i.e. away from type 1 and type 2b (Folland and Williams, 2007). Two recent review papers have suggested that eccentric training might increase type 2a muscle fibre CSA to a greater degree than concentric training (Douglas *et al*., 2017b; Franchi *et al*., 2017). This eccentric induced shift towards type 2a fibre types might be augmented by exercise intensity (Friedmann-Bette *et al*., 2010) and contraction velocity (Shepstone *et al*., 2005). Greater type 2a muscle fibre hypertrophy after eccentric versus concentric training has been observed in the elbow flexors (Vikne *et al*., 2006) and knee extensors (Hortobagyi *et al*., 1996; Hortobágyi *et al*., 2000), although not all studies have observed this (Mayhew *et al*., 1995; Seger *et al*., 1998). Relative exercise intensity and velocity of contraction were similar between these investigations, however, preferential type 2a hypertrophy was only seen in those studies that lasted 12 weeks (Hortobagyi *et al*., 1996; Hortobágyi *et al*., 2000; Vikne *et al*., 2006), versus no effect after four (Mayhew *et al*., 1995) or ten weeks (Seger *et al*., 1998). This raises the possibility that eccentric training might only exert a greater type 2a hypertrophic response over a period of training that exceeds 10 weeks, however, further work is needed to elucidate the timing of this adaptation. One study has investigated this response in a multi-joint mode of exercise; an eccentric/concentric leg press, although they did not compare eccentric-only and concentric contractions (Hather *et al*., 1991). The intervention group was a mix of concentric and eccentric leg press exercises which was compared to a concentric only control group. There was no difference in type 2a muscle fibre percentage between groups despite a prolonged 19 week training period. Although, it is worth noting that type 1 fibre percentage area did increase in the eccentric plus concentric training group.

To our knowledge only one study has examined changes in muscle fibre type distribution after a period of eccentric cycling (Mueller *et al*., 2009). After 12 weeks of eccentric cycling, twice per week, there was a significant decrease in the type

IIx/type II muscle fibre ratio which was not observed in a concentric resistance training group. However, it should be noted that this research was conducted on elderly men (80+ years) and the pre to post difference in type IIX/type II ratio was not significantly different between the control and intervention group. A shift towards type II muscle fibre type is to be expected after resistance training (Folland and Williams, 2007), but given that the control and intervention group were not matched for total work done it is equally possible that this slight discrepancy in type IIX/type II muscle fibre ratio is an artefact of different training volumes rather than training modality. Overall, there is good evidence indicating that eccentric training can shift myosin heavy chain composition towards type 2a fibres in isolated eccentric muscle training. However, it is unclear as to whether this happens to a greater extent when compared with concentric resistance training. More work is required to understand if the same muscle fibre adaptations seen in isolated joint exercises translate to multi-joint exercise.

2.4.3 Tendons

Eccentric exercise is a popular treatment for patellar (Visnes and Bahr, 2007) and Achilles (Kingma *et al*., 2007) tendinopathy. Because of this, many studies have investigated the effect of eccentric training on tendon structure in individuals with existing tendinopathies (Souza and Araújo, 2016). In this population eccentric exercise, typically plantar flexion, has been observed to decrease Achilles tendon cross sectional area (CSA) (Grigg *et al*., 2012; Nørregaard *et al*., 2007) and increase tendon vascularisation (de Vos *et al*., 2011). The decrease in tendon CSA is thought to occur via the re-organisation of tendinous tissue which is often disrupted in injured individuals (Souza and Araújo, 2016). These findings are critical for rehabilitation but do not necessarily indicate tendon responses to eccentric exercise in individuals without existing tendinopathies. For individuals without prior tendinopathies it might be more desirable to achieve an increase in tendon CSA i.e. the tendon structure is already organised and any increase in CSA is a reflection of a stronger tendon. For example, cross-sectional data has shown that in habitual runners Achilles CSA is 36% greater than a non-athletic control group (Magnusson and Kjaer, 2003). Furthermore, there are observations of longitudinal increases in patellar tendon CSA (+9.7%) after maximal eccentric knee extensor training in healthy men (Farup *et al.*, 2014), an increase that was augmented by the supplementation of whey protein hydrolysate (+14.9%). Interestingly, concentric training also elicited an increase in patellar tendon CSA (+14.9%) but only when whey protein hydrolysate was supplemented. This provides weak evidence that eccentric training might be a more positive stimulus for gains in tendon CSA compared to concentric training. Eccentric knee extensor training (80% of ECC max knee extension) has also been shown to increase tendon stiffness by 84% after 12 weeks, although there were no changes in tendon CSA (Malliaras *et al.*, 2013). Similarly, Achilles tendon stiffness increased after 7 weeks of eccentric soleus and gastrocnemius training at 120% of concentric 1RM (Duclay *et al.*, 2009). In contrast, a 6 week heel drop protocol caused a reduction in Achilles tendon stiffness in healthy individuals (Morrissey *et al.*, 2011). Such contrasting findings may result from differences in the intensity of eccentric exercise prescribed. Where exercise intensity is high i.e. 80% ECC max knee extension, the stimulus may be over a critical threshold to elicit increases in tendon stiffness whereas at low intensity i.e. body weight heel drops this threshold may not be reached. No research has yet examined changes in tendon stiffness or CSA after a period of eccentric cycling, however, authors have speculated it might increase (Lindstedt *et al.*, 2001). Methods of estimating whole leg stiffness have shown increases after eccentric cycling but this is unlikely to accurately reflect changes in tendon structure (Elmer *et al.*, 2012).

2.5 Functional responses to eccentric training

Eccentric training of various modalities has frequently been shown to increase eccentric, concentric, and isometric strength (Roig *et al.*, 2009). The time course and magnitude of these strength gains depends on the frequency, duration, intensity, and modality of the eccentric stimulus and the training history of the sample population (Douglas *et al.*, 2017b; Franchi *et al.*, 2017; Roig *et al.*, 2009). The majority of studies have used single joint training modalities such as isokinetic dynamometers, however, research utilising multi-joint modalities is becoming more frequent. Eccentric ergometers (Elmer *et al.*, 2012; Gross *et al.*, 2010), leg press machines (Franchi *et al.*, 2014) and flywheel devices (Norrbrand *et al.*, 2008) have offered a more practical method of delivering eccentric training than dynamometry. A common finding following eccentric training is that the greatest strength gains are contraction-type specific; i.e. eccentric training increases eccentric strength to a greater degree than it increases concentric or isometric strength (Colliander and Tesch, 1990; Higbie *et al*., 1996; Hortobagyi *et al*., 1996; Roig *et al*., 2009; Vikne *et al*., 2006).

Additionally, improvements in strength and power after eccentric training usually occur to a greater degree in the range of motion and contraction velocity of the training stimulus (Roig *et al*., 2009). This observation of modality specific strength gains raises the question as to whether eccentric training can enhance eccentric dominant SSC function and concentric function, or only the former. More specifically, can eccentric training in a cycling movement pattern enhance performance across different sporting movements reliant on SSC function? Research into the efficacy of eccentric training for improving sports performance can be categorised into three broad areas:

1) Can eccentric training be used to reduce injury incidence in athletes?
2) Is eccentric training more effective than concentric training at eliciting increases in concentric muscle strength and power?
3) Can eccentric training be used to enhance the eccentric component of critical sporting actions and thus improve athletic performance?

Eccentric exercises are commonly prescribed during a period of rehabilitation, typically for injuries to the Achilles and patellar tendons (Kingma *et al*., 2007; Visnes and Bahr, 2007). However, there is evidence to suggest that chronic eccentric training could have a protective effect and reduce the risk of hamstring muscle injury in athletic populations (de Hoyo *et al*., 2015). The hamstring muscle group is often used to examine the effect of eccentric training on injury prevalence due to its propensity for injury and the ease of which an eccentric training programme can be implemented and assessed. It has been shown that individuals with a history of hamstring strains present with greater weaknesses in eccentric strength, although this does not imply a causative relationship (Croisier *et al*., 2002). A study on 942

Danish football players observed a reduced risk of new and re-occurring hamstring injuries following a 10-week Nordic hamstring programme (Petersen *et al*., 2011). Similar work, also in football, has observed a reduction in muscular injuries after 10-weeks of eccentric flywheel leg curl and half squat training (de Hoyo *et al*., 2015).

The mechanism by which eccentric exercise might reduce injury rates is likely to comprise of multiple factors. Hypotheses include increased muscle flexibility (O'Sullivan *et al*., 2012), increased muscle stiffness (Lindstedt *et al*., 2002, 2001; Reich *et al*., 2000), increases in non-contractile tissue (i.e. greater collagen production) (Birch *et al*., 1999; Liu *et al*., 1995), and a more compliant muscle tendon complex i.e. a decrease in stiffness (Brockett *et al*., 2001; Proske and Morgan, 2001). Hamstring complexes with a history of injury have a much shorter muscle length for optimum force production compared to un-injured hamstrings (Brockett *et al*., 2004). Therefore, it is suggested that by increasing the length at which the hamstring produces peak force the risk of hamstring injury could be reduced (Proske *et al*., 2004). Eccentric training can shift the force length curve of a muscle to the right i.e. greater forces can be produced at longer muscle lengths (Brockett *et al*., 2001; Brughelli and Cronin, 2007). No work has yet been published with regards to the efficacy of eccentric cycling to alter the length-tension relationship of lower limb muscles or to reduce injury rates in elite athletes. Although, observations of increased leg stiffness (Elmer *et al*., 2012), enhanced eccentric force modulation (Gross *et al*., 2010), and greater isometric leg strength (Lastayo *et al*., 2000) suggest that eccentric cycling might elicit adaptive responses that could be considered beneficial for injury prevention, however, longitudinal studies are required to directly assess this hypothesis.

It is well established that eccentric training elicits greater increases in eccentric strength compared to concentric strength (Farthing and Chilibeck, 2003a; Higbie *et al*., 1996; Roig *et al*., 2009; Seger *et al*., 1998). There is also good evidence indicating that eccentric training elicits greater cumulative improvements in isometric, eccentric, and concentric strength compared to concentric training (Roig *et al*., 2009; Vikne *et al*., 2006). However, this only occurs when eccentric and concentric training is prescribed at the same relative intensity, i.e. absolute eccentric load is greater (Roig *et al*., 2009; Vikne *et al*., 2006). At similar absolute training intensities eccentric and concentric training elicit similar increases in concentric strength (Ben-Sira *et al*., 1995; Roig *et al*., 2009). When using concentric strength as the primary outcome measure a 2009 meta-analysis concluded that eccentric training offers no additional benefit to concentric training (Roig *et al*., 2009). This has been observed even when the majority of studies have used a greater absolute intensity during eccentric training (Blazevich *et al*., 2007; Farthing and Chilibeck, 2003a; Higbie *et al*., 1996; Miller *et al*., 2006; Nickols-Richardson *et al*., 2007; Seger *et al*., 1998; Tomberlin *et al*., 1991). Some studies have suggested that eccentric training at faster contraction velocities may translate to better concentric strength gains (Farthing and Chilibeck, 2003a; Paddon-Jones *et al*., 2001). However, these increases in concentric strength were not compared against concentric training of a similar velocity.

To our knowledge only one study has examined the effect of eccentric cycling on concentric strength (Gerber *et al*., 2007b). Post ACL surgery a 12 week period of eccentric cycling improved concentric quadriceps strength to a greater extent than a standardised, mainly concentric, rehabilitation program (Gerber *et al*., 2007b). However, groups were not matched for total work which makes inferences about the efficacy of eccentric versus concentric training for concentric strength gains unclear. Additionally, there was no difference between groups for changes in hamstring strength which highlights the quadriceps dominance of eccentric cycling. All other research examining strength changes after eccentric cycling have used isometric-only strength tests (Dibble *et al*., 2006; Gross *et al*., 2010; Lastayo *et al*., 2000; Mueller *et al*., 2009). In an elderly population, 12 weeks of eccentric cycling improved maximal isometric leg extension strength more than a primarily concentric resistance training program (Mueller *et al*., 2009). However, in Parkinson's patients there was no difference in quadriceps strength gains between 12 weeks of eccentric cycling and a standard concentric rehabilitation program, although both groups did improve (3.5% and 0.1% respectively). In healthy untrained men, 8-weeks of eccentric cycling increased isometric knee extensor strength to a greater degree than a concentric cycling control group (Lastayo *et al*., 2000). Whereas in trained national junior skiers there was no difference in isometric strength improvements of the knee extensors between groups performing eccentric cycling and concentric resistance training (Gross *et al*., 2010). However, in the same skiers, isometric leg press force increased to a greater extent after concentric resistance training rather than eccentric cycling. Overall, current research indicates that eccentric training does not increase concentric strength to a greater degree than concentric training. This notion has yet to be tested using eccentric cycling in a population without existing physical limitations. On the weight of current evidence in isolated muscle studies, concentric strength gains should not be the primary rationale for prescribing eccentric cycling. Coaches, athletes, and practitioners should be mindful of other possible beneficial adaptations following eccentric cycling such as hypertrophy or positive changes in SSC function.

When acting eccentrically the muscle tendon complex behaves as a shock absorber or as a spring (Lindstedt *et al*., 2001). As a shock absorber the muscle absorbs mechanical energy and dissipates this as heat. As a spring the muscle returns mechanical energy to a subsequent concentric contraction. This process of muscle pre-activation, stretch, and then shortening in quick succession forms the mechanical components of the SSC and comprises a fundamental element of numerous types of human locomotion (Figure 2.5). Some sports, i.e. skiing, require high levels of eccentric strength to perform shock absorbing muscle actions whereas other sports such as running and jumping heavily utilise the SSC to store and return elastic energy. It has been suggested that eccentric training could enhance sporting performance across both types of sport; i.e. those that use eccentric contractions in a shock absorbing and/or a SSC capacity (Vogt and Hoppeler, 2014).

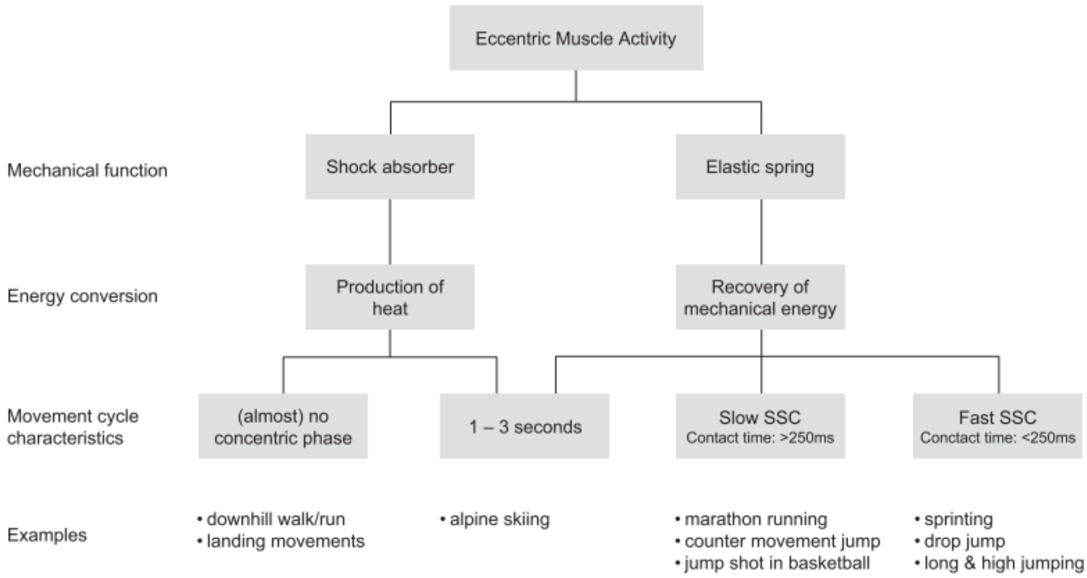


Figure 2.6. Classification of eccentric , muscle action in sports from Vogt and Hoppeler, 2014

It is clear that eccentric training can increase the eccentric strength of isolated muscle groups (Douglas *et al*., 2017b; Roig *et al*., 2009). However, this does not necessarily translate to an improvement in the performance of functional movements with a large eccentric component, such as CMJ. Lower limb training with a large eccentric component has been shown to improve CMJ height to a greater extent than squat jump performance, suggesting an improvement in SSC function (Cormie *et al*., 2010; Liu *et al*., 2013). However, training in both these studies incorporated a concentric component thus making it difficult to ascribe the results solely to eccentric training. Eight weeks of eccentric leg press training improved drop jump height and peak power whilst also reducing ground contact time (Papadopoulos *et al*., 2014). Simultaneously, changes in ankle, knee, and hip kinematics were observed which the authors attributed to changes in leg stiffness. Ten weeks of eccentric flywheel training increased CMJ height and sprint ability in team elite junior football players (de Hoyo *et al*., 2015) although over a shorter three week period of eccentric squatting the addition of over-speed work (downhill running and assisted CMJ) was required to elicit similar performance improvements (Cook *et al*., 2013). Aside from more traditional eccentric strength training it has been proposed that a period of downhill running could enhance SSC function and therefore running economy. However, no differences in running economy were seen after 8 weeks of downhill running in well trained runners (Shaw *et al*., 2018). It could be that the gradient used (−5%) did not offer a sufficient eccentric stimulus to elicit positive adaptations in SSC function. When a greater eccentric stimulus has been previously used, e.g. seven weeks of eccentric cycling, increases in estimated leg spring stiffness have been observed (Elmer et al., 2012). Overall, evidence indicates that eccentric training can benefit performance in SSC dominant activities, although this only appears to occur when the training modality is highly eccentric specific.

Several investigations have examined the effect of eccentric cycling on leg stiffness and SSC function (Elmer *et al*., 2012; Gross *et al*., 2010; Lindstedt *et al*., 2002). After 8 weeks of eccentric cycling (three times per week) participants increased their self-selected sub-maximal hopping frequency by 12%, whilst a control group of concentric cycling experienced no change (Lindstedt *et al*., 2002). The authors attributed this change in hopping frequency to an increase in muscle stiffness, citing research that observed an increase in the triceps stiffness of rats after 24 sessions of downhill treadmill running at −36% (Reich *et al*., 2000). Other research has also estimated an increase in leg stiffness after a 7 week period of eccentric cycling (Elmer *et al*., 2012), however, neither of these studies measured stiffness of the muscle directly. Several studies have used CMJ performance after a period of eccentric cycling to infer SSC performance increases (Elmer *et al*., 2012; Gross *et al*., 2010; Lindstedt *et al*., 2002). In Swiss national junior skiers CMJ jump height increased by 6.5% after 6 weeks of eccentric cycling, whereas it remained unchanged in a resistance training control group. However, there was no interaction effect of group and time on CMJ performance which makes these findings ambiguous. Squat jump (SJ) performance did improve to a greater extent after eccentric cycling compared to the control group, although this was due to a reduction in SJ performance in the control group. This decrease in SJ performance for a group performing lower limb concentric resistance training is surprising. The authors suggest that the athletes were in a period of detraining and that the reduction in SJ performance was attenuated to a greater extent after eccentric cycling. However, the fact that athletes might have detrained casts doubt on the precision of the study to detect meaningful differences in performance. In trained basketball players eccentric cycling has been demonstrated to increase CMJ height by 8% compared to a concentric cycling control group (Lindstedt *et al*., 2002). However, these data were part of a review article which lacks methodological details thus making accurate interpretation difficult. One study has observed a significant increase in CMJ power after 7 weeks of eccentric cycling compared to a concentric cycling control group, albeit in healthy, untrained, individuals (+7% vs -2%, Elmer *et al*., 2012). This was concomitant with an increase in estimated leg stiffness for the eccentric cycling group. Such results indicate that eccentric cycling might have the capability to increase CMJ performance more than a concentric cycling control group. However, there is a scarcity of reliable data indicating whether a similar effect would be expected in elite athletes, in comparison to a resistance training control group, or in faster SSC activities such as drop jumps and sprinting (Figure 2.5).

2.6 Summary

Eccentric resistance training is an attractive modality for muscular training primarily due to its ability for high force production at a low metabolic cost (Isner-Horobeti *et al*., 2013; Peñailillo *et al*., 2014). Eccentric cycling represents a modality of exercise capable of administering high volumes of repetitive, multi-joint, lower limb eccentric contractions. Previous research has shown that using eccentric cycling as a training modality over a sustained period of time can improve muscle structure and function (Elmer and LaStayo, 2014; Gross *et al*., 2010; Lastayo *et al*., 2000; Leong *et al*., 2013). However, there is little consensus on the optimum protocol for eccentric cycling prescription or whether it can be advantageous to already well-trained athletes. Therefore, the focus of this thesis was to systematically investigate the neuromuscular responses and application to performance of a bespoke eccentric cycling instrument, which was carried out in the following experimental chapters:

Chapter 4 – Familiarisation to maximal recumbent eccentric cycling

Aims: To identify the reliability of power output and lower limb muscle activation during the familiarisation to recumbent eccentric cycling and over a range of cadences, in order to recommend the number of practice trials required to minimise variation.

Chapter 5 – Torque, power and muscle activation of eccentric and concentric isokinetic cycling

Aims: To establish the effect of cycling mode (concentric and eccentric) and cadence on torque, power, and lower limb muscle activation during maximal, recumbent, isokinetic cycling.

Chapter 6 – Metabolic and mechanical consequences of interval and continuous eccentric cycling

Aims: To determine the effect of session structure on the subsequent central and peripheral fatigue and the time course of recovery from a single bout of eccentric cycling.

Chapter 7 – The effect of 8-weeks eccentric cycling interval training on lower limb strength and running economy in trained distance runners

Aims: To examine the effect of an 8 week training programme of interval based eccentric cycling on running economy, stretch shortening cycle function, and lower limb strength in well-trained distance runners.

CHAPTER 3

GENERAL METHODS

The methodological details of each data collection are included in the individual experimental chapters. However, more complex procedures are described here in greater detail, e.g. development of the eccentric ergometer and femoral nerve stimulation. Additionally, any protocols common to multiple chapters are also covered here to avoid repetition; for example, sEMG (chapters 4 - 6), respiratory gas analysis (chapters 6 & 7), and blood lactate (chapters 6 & 7).

3.1 Development of an eccentric ergometer

In all experimental chapters eccentric cycling was conducted on a custom built ergometer developed by BAE Systems in collaboration with UK Sport (Figure 3.1 & 3.2). This ergometer was not built specifically for this thesis and at the onset of this project information regarding its provenance, functionality, and validity was extremely limited. This section will describe how the ergometer was made fit for purpose through a series of tests and modifications designed to maximise the validity of both torque and power measurements.

Ergometer description

The following description of the eccentric ergometer describes the state in which it was used during all experimental chapters. Later sections of this chapter will refer back to previous versions of the ergometer that were modified as a result of pilot work, associated with this doctoral work, to improve its validity. The ergometer is a recumbent bike powered by a 2200 W motor which drives the cranks at a pre-set cadence. Participants either pushed with, or resisted against, the direction of crank motion in order to perform concentric or eccentric cycling, respectively. In order to prevent the possibility of knee hyper-extension the seat position was adjusted and a goniometer was used to ensure participants could not, at any point of the pedal revolution, extend their knee beyond 160^{o} (full extension = 180^{o}). Additionally the ergometer only functioned if the participant constantly held buttons located on each handlebar, should the participant release either set of buttons the ergometer stopped immediately. A second, separate, emergency stop button was accessible to the researcher. Rigid, carbon fibre soled, cycling shoes (Bontrager Riot RR-45, Trek, USA) and Look Keo pedals (Look Cycle, France) were used to achieve a consistent participant-ergometer interface.

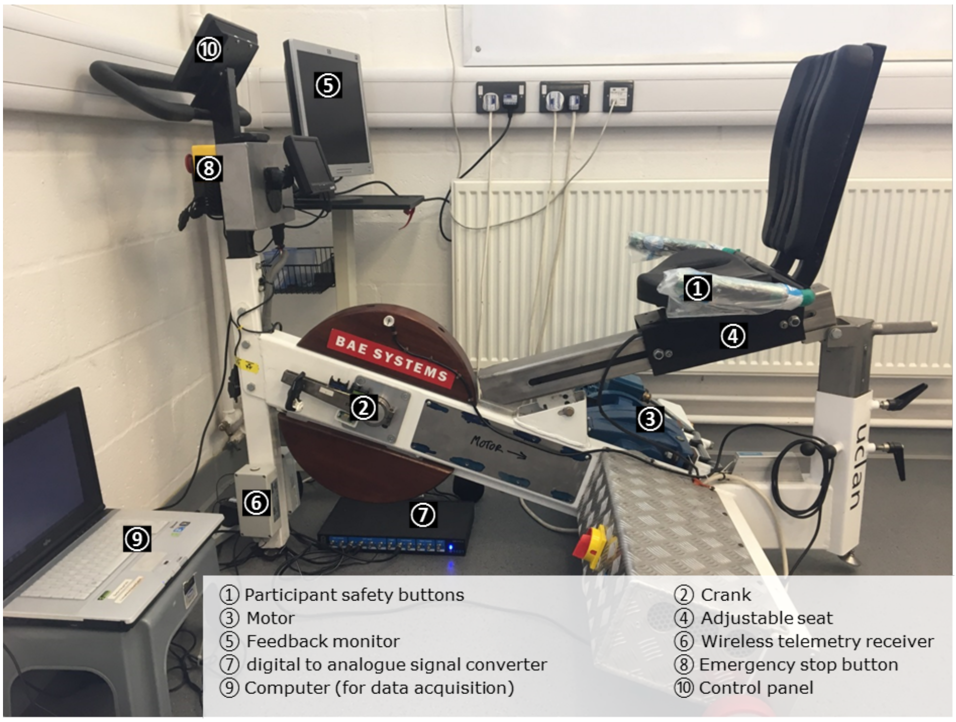


Figure 3.1: Recumbent isokinetic eccentric cycle ergometer. Inset legend denotes aspects of the ergometer with functional significance.

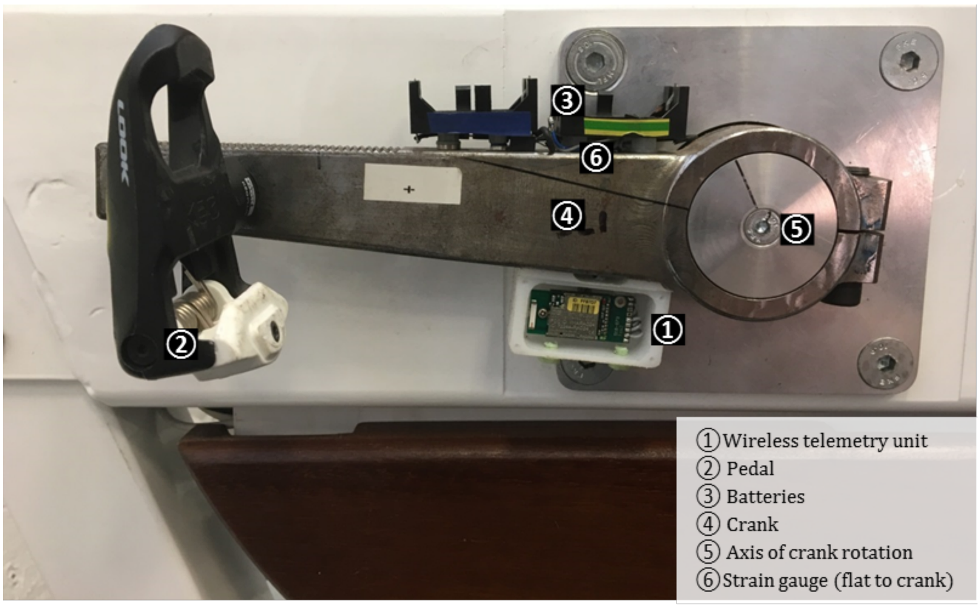


Figure 3.2: Crank/strain gauge setup of the eccentric ergometer.

Validity of measurements of torque and velocity

Given the critical nature of torque, and power derived from said torque, throughout this thesis it was imperative that both measurements were valid. Due to this being a custom built ergometer it did not possess the same level of quality assurance associated with commercially manufactured products. Initial concern focussed on the provenance of the torque and power data calculated by the ergometer. All individuals involved in the production of the ergometer were unavailable and therefore it was not possible to find detailed documentation about the existing on-board torque or power calculations. Therefore, it was proposed that the ergometer should be validated against an existing, valid, measure of torque and power. Conventional crank based power-meters were not compatible with the ergometer so an attempt was made to validate the ergometer against Garmin Vector pedals (Garmin, Kansas, USA). However, the Garmin pedals only function when rotating in the conventional concentric direction, and not when rotating in reverse (i.e. eccentric cycling). This inability to externally validate the on-board torque and power measurements led to the decision to access the raw strain gauge data and calculate torque and power directly. Access to the raw strain gauge data was achieved using a stand-alone wireless telemetry receiver (T24-BSi, Mantracourt Electronics, UK) which received the strain gauge output from the wireless telemetry transmitter attached to each crank (T24-Sai, Mantracourt Electronics, UK; Figure 3.3). Data was then digitised (200 Hz; Power 1401, Cambridge Electronic Design, UK) and acquired for off-line analysis (Spike 2 version 8.02, Cambridge Electronic Design, UK). Cadence was simultaneously processed through the same data acquisition unit and software from a reed switch that pulsed when the pedal reached top dead centre.

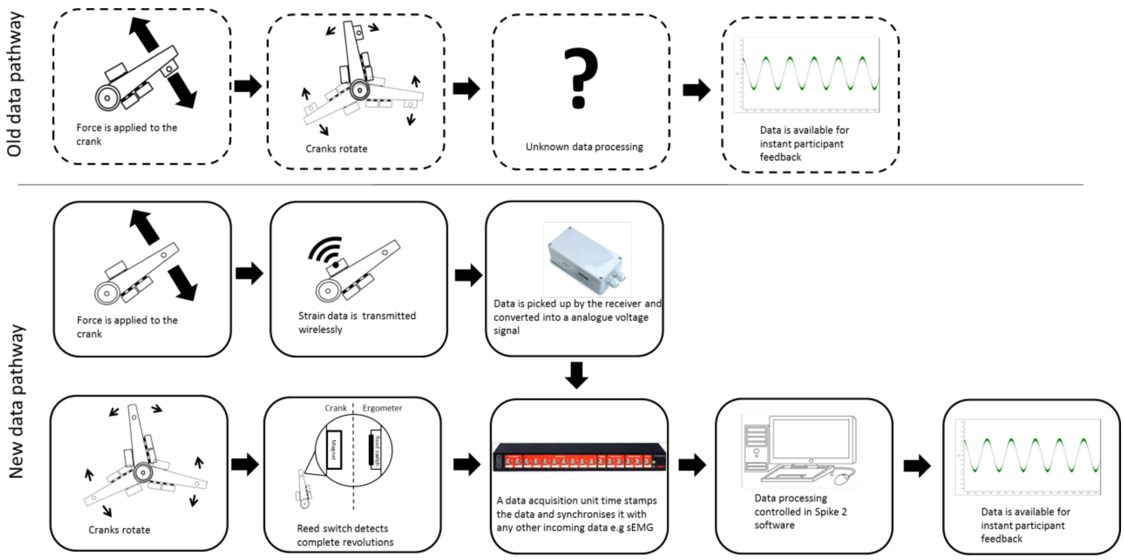


Figure 3.3: Schematic of the original, and updated, force and cadence data acquisition process.

Access to the raw strain gauge data enabled complete control over the data processing pathway. With a single strain gauge located on each crank the only logical method to calculate torque is to assume that strain gauge output is proportional to crank torque i.e. any change in strain gauge output reflects a proportional change in crank torque. Fundamental to this assumption is that any force applied to the pedal which does not increase crank torque will also not increase strain gauge output. A strain gauge measures the amount of strain on a material by assessing the magnitude of distortion caused by a given force. A single gauge can measure strain in one plane of motion and should, theoretically, be unaffected by force applied in any other plane. Therefore, a strain gauge correctly placed on the crank should only measure strain in the plane of crank rotation. In reality, strain gauge output does fluctuate slightly when exposed to forces in different planes of motion but the effect is negligible (tested later in this chapter). A more significant problem with the strain gauge was its location, i.e. not directly on the moment arm of the crank. The moment arm of the crank is the imaginary line between the point of force application (i.e. the pedal) and the centre of rotation of the crank. Torque is calculated as a product of perpendicular force applied to the moment arm and the length of the moment arm. In most instances the crank would align with the moment arm, however, due to an adjustable pedal on the eccentric ergometer, the crank arm and moment arm are not one and the same in this instance (Figure 3.4).

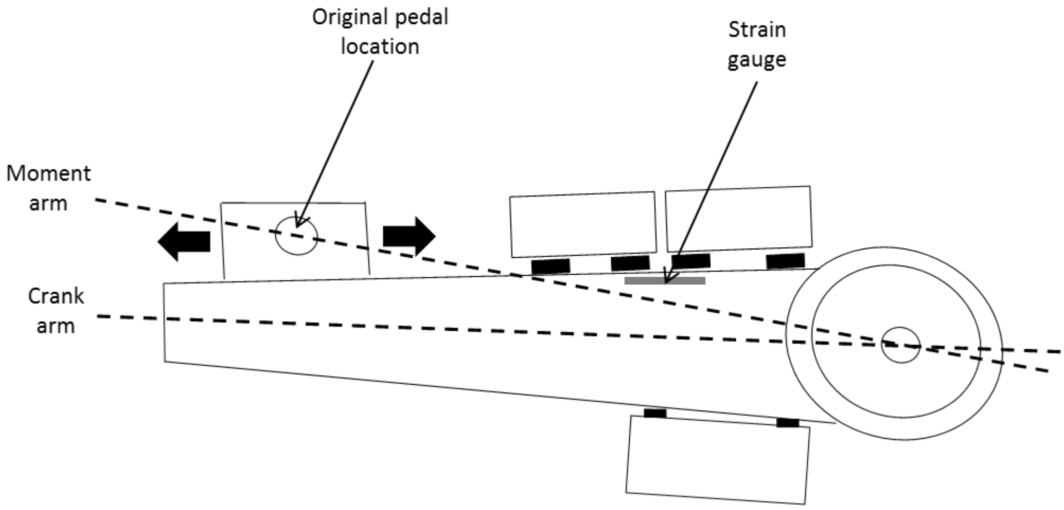


Figure 3.4. Schematic of the crank setup prior to any adjustments made as a result of validity testing. Note the adjustable pedal location, offset from the crank.

The primary concern regarding the offset pedal was that it would create a scenario in which forces that did not contribute to crank torque would significantly alter the output of the strain gauge i.e. torque not being proportional to strain gauge output. To test this concern a mathematical model of the crank-strain gauge system, including the offset pedal, was developed (Appendix A). This model simulated strain gauge output for an entire pedal revolution with any given mass attached to the pedal. Using the strain gauge output from this model and an experimentally derived relationship between strain gauge output and torque (described later) it was possible to calculate torque values from this model. As previously mentioned, it was assumed that strain gauge output was proportional to crank torque.

Figure 3.5a displays the percentage error between the torque calculated from the model (with the pedal offset) and true torque. True torque was calculated as the product of perpendicular force applied to the moment arm and the length of the moment arm (n.b. this calculation assumes a perfect strain gauge with no error – discussed later). It is clear that error in torque can be very high, most notably when force is applied directly down onto the crank at top and bottom dead centre of the pedal revolution. At these pedal locations crank strain is clearly detected despite the fact that the moment arm is zero, a problem created by the offset pedal. This problem was rectified by moving the pedal directly onto the middle of the crank thus ensuring the strain gauge was located directly on the moment arm. Moving the pedal to be directly on the moment arm removes this error in torque (Figure 3.5b). The cranks were re-drilled and the pedal was placed, permanently, at a crank length of 175mm (Figure 3.6).

3.5a

3.5b

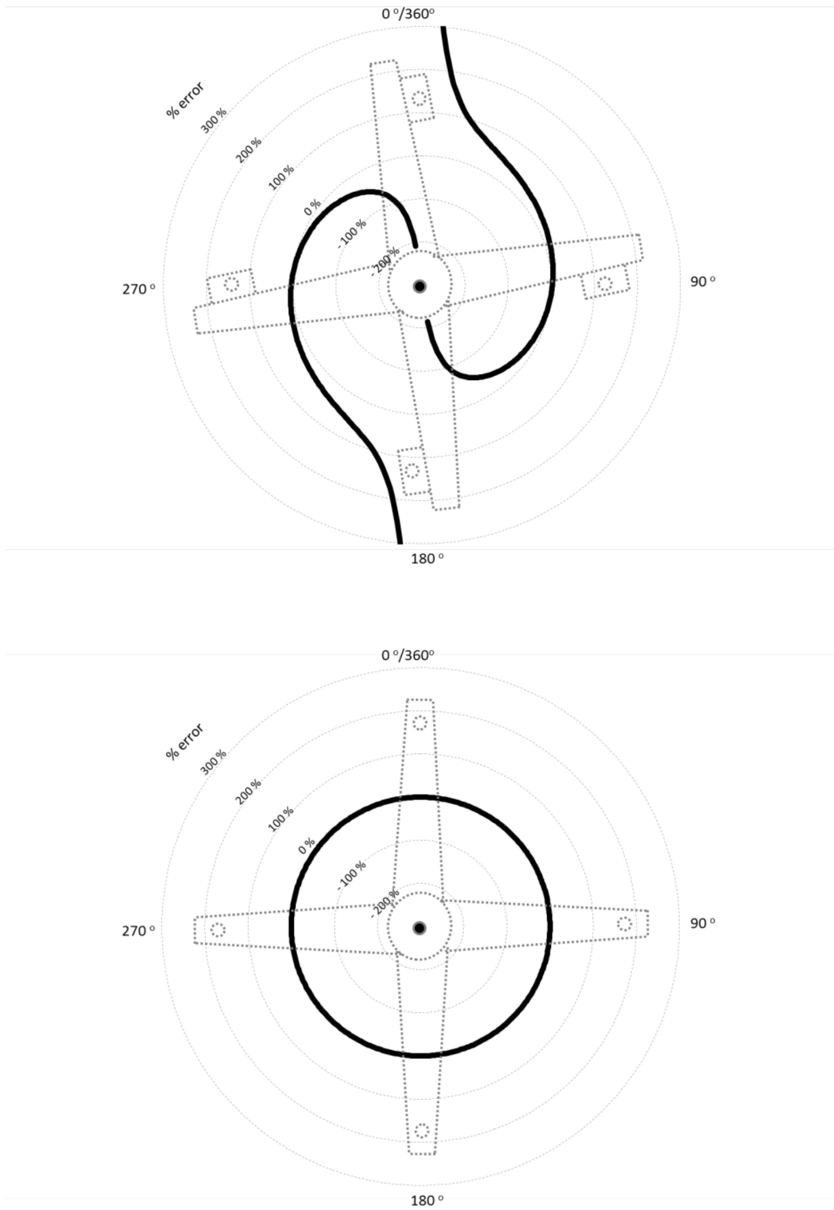


Figure 3.5. Percentage error between modelled torque, with the pedal in an offset position, and true torque around a single pedal revolution (Panel a). Percentage error between modelled torque, with the re-positioned pedal, and true torque around a single pedal revolution (Panel b).

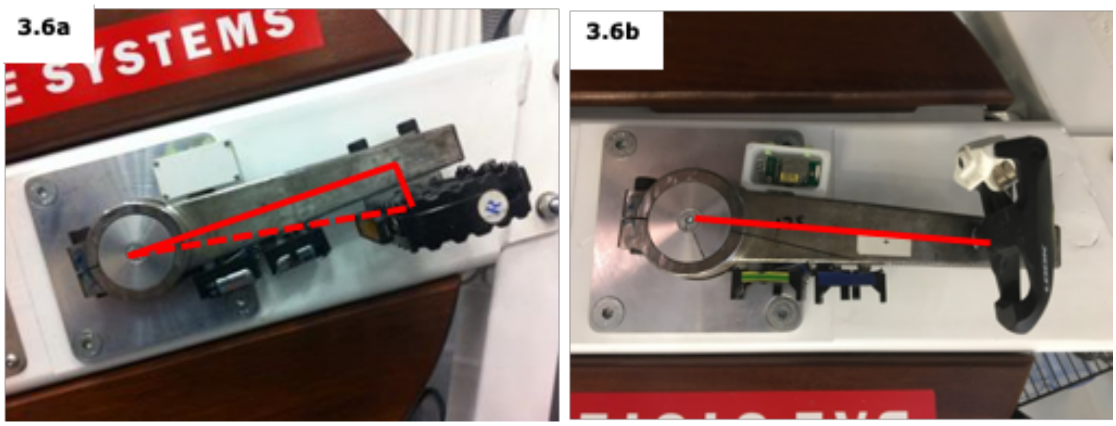


Figure 3.6: Original crank set up including the offset pedal (Panel a). The crank arm and offset are shown in red (solid); the moment arm is shown in red (dashed). The final crank setup as used throughout this thesis (Panel b); the crank arm, and the moment arm are shown in red (solid).

Determining the relationship between strain gauge output and crank torque

In order to calculate torque in the aforementioned mathematical model the relationship between strain gauge output and crank torque needed to be determined experimentally. This was achieved by locking the crank in a horizontal position and suspending 0, 5, 10, 15, 20, 25, 50, and 75 kg from the pedals. This was done with the pedals in their original offset position. However, once the pedals were relocated the procedure was repeated to ensure the greatest validity for use in the experimental chapters. Figures 3.7 & 3.8 show the linear relationship between torque and strain gauge output for the left and right crank respectively as used in the experimental chapters of this thesis.

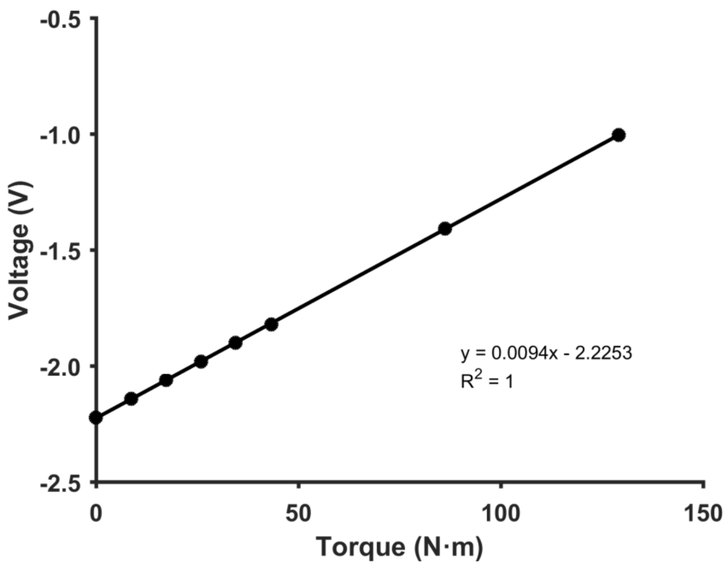


Figure 3.7. Relationship between strain gauge voltage and torque applied to the left crank with the pedals located directly on the moment arm of the crank.

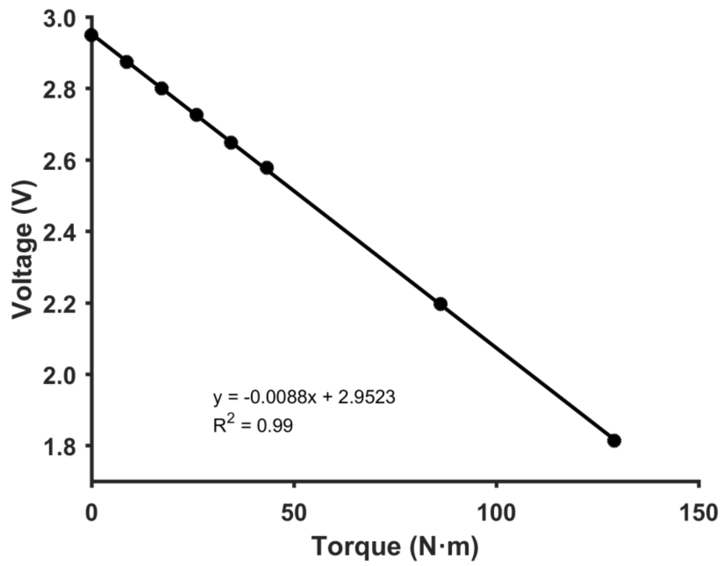


Figure 3.8 Relationship between strain gauge voltage and torque applied to the right crank with the pedals located directly on the moment arm of the crank.

Validating torque calculations

Relocating the pedal to the middle of the crank provided a more valid system for measuring torque. However, whilst theoretically more valid, this needed to be confirmed experimentally. Errors within a data collection/processing system can come from multiple locations, known and unknown. The possibility remained that despite the improvement in pedal location strain gauge output may still not have been proportional to crank torque.

To test this, masses of 5 kg and 10 kg were attached to the pedal and a 1 rpm revolution was performed. The experimental torque data was compared to the aforementioned true torque model. Figures 3.9 and 3.10 showed these comparisons over a pedal revolution for the right crank (5 kg and 10 kg respectively). Absolute error between the model and the experimental data was greatest at pedal angles of 90° and 270° i.e. when the crank was parallel to the ground. However, this error was similar between the 5 kg (+1.3 N·m at 90° and -1.4 N·m at 270°) and 10 kg trials (+1.4 at 90° and -1.8 at 270°). An absolute error of ~1.5 N·m mass translates to ~10 W at 60 rpm. It is likely that this is due to the weight of the crank exerting a force on the strain gauge, which is located on one side of the crank. At a crank angle of 90° the weight of the crank exerts a slight positive effect on torque and at 270° a slight negative effect. Consequently, when the offset was set prior to each testing session the crank was orientated in the vertical position due to the greater level of agreement between the model and the experimental data at this pedal angle. Average error for experimental torque over an entire revolution was negligible as the process of offsetting the pedals ensured the absolute error at 90° and 270° negated each other. The error calculation process was repeated for the left crank and the calculated error between the model and experimental data was similar to the right crank in the 5 kg (+1.1 N·m at 90° and -1.1 N·m at 270°) and 10 kg trials (+1.4 at 90° and -0.8 at 270°).

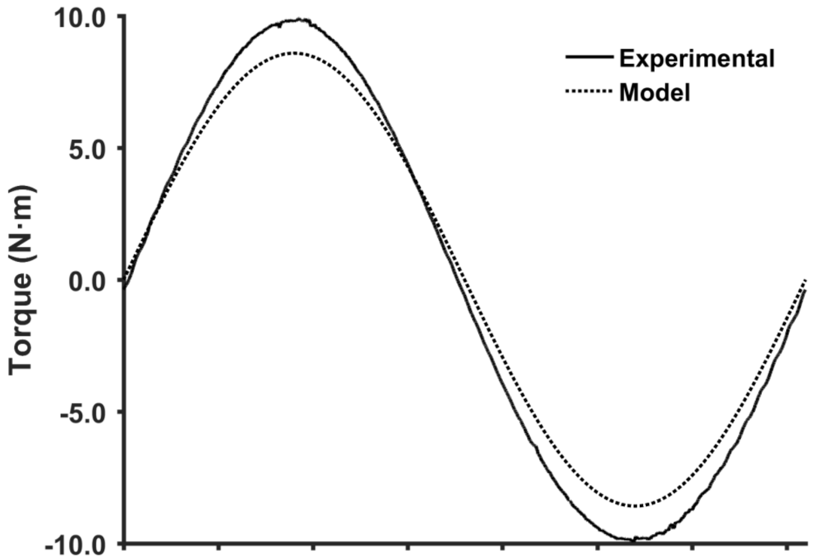


Figure 3.9. Experimentally recorded torque (-) and model torque (--) over a single revolution at 1 rpm with a mass of 5 kg applied to the right pedal.

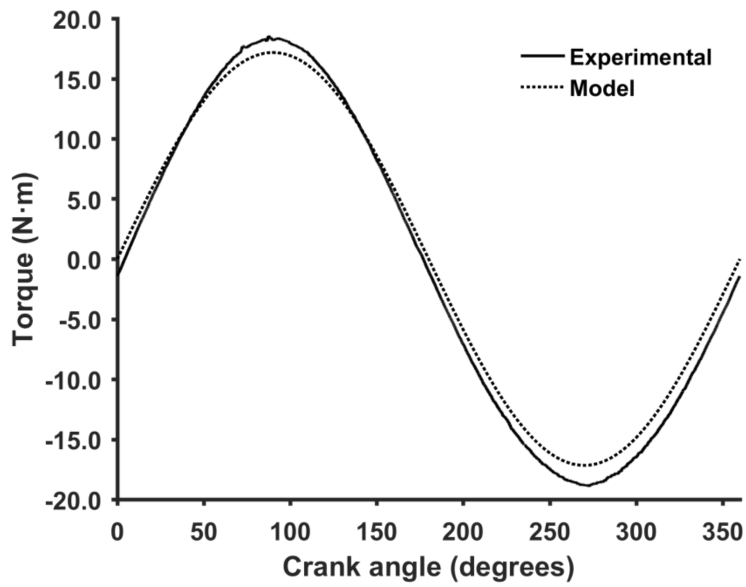


Figure 3.10. Experimentally recorded torque (-) and model torque (--) over a single revolution at 1 rpm with a mass of 10 kg applied to the right pedal.

Reliability

To ensure the greatest between-session reliability a zero offset was performed on each crank prior to testing. Each crank was placed at top dead centre and the offset of the voltage-torque calculation was adjusted in order that torque was consistently reading 0 N·m. To assess the within-session reliability of the strain gauge the pedals were run, unloaded, at 60 rpm and the strain gauge was monitored for drift. Strain gauge drift was considered negligible for the left (-9.6×10^{-5} N·m/h) and right crank (3.8×10^{-4} N·m/h).

3.2 Surface electromyography

Two, 20 mm diameter, electrodes (Ag/AgCl; Kendall 1041PTS, Covidien, Mansfield, MA, USA) with an inter-electrode distance of 20 mm were placed on the muscle of interest according to the SENIAM guidelines for EMG placement (Hermens *et al*., 2000). The skin was prepared by shaving, and abrasion with an alcohol swab. When required, electrode positions were marked with indelible ink to ensure a consistent placement between trials. A reference electrode was placed on the patella. Surface EMG signals, recorded concurrently with torque data, were sampled at 4 kHz (Power 1401; Cambridge Electronic Design, UK), then amplified (×1000; 1902, Cambridge Electronic Design, Cambridge, UK), band-pass filtered (20-2000 Hz), and rectified (Spike 2, version 8.02; Cambridge Electronic Design, UK) according to ISEK standards (Merletti, 1999). Surface EMG signals were also notch filtered (50 Hz). Specific analyses unique to individual data collections are described in the relevant experimental chapters.

3.3 Femoral nerve stimulation

Single electrical stimuli (200 μs duration) were delivered to the right femoral nerve via surface electrodes (CF3200; Nidd Valley Medical Ltd., Harrogate, United Kingdom) using a constant-current stimulator (DS7AH; Digitimer Ltd., Welwyn Garden City, United Kingdom) at rest and during MVC. The cathode was placed over the nerve high in the femoral triangle; the anode was positioned midway between the greater trochanter and the iliac crest (Goodall *et al*., 2009). The exact positioning was determined by the response that elicited the maximum quadriceps twitch amplitude ($Q_{tw,pot}$) and M-wave (M_{max}) at rest. To determine stimulation intensity, single stimuli were delivered in 20 mA increments from 100 mA until a plateau in $Q_{tw,pot}$ and M-wave were observed. To ensure a supramaximal stimulus, the final intensity was increased by 30%. Membrane excitability was determined by measuring the peak-to-peak amplitude and area of the electrically evoked M_{max} (Fowles *et al*., 2002). Voluntary activation was calculated using the amplitude of the potentiated twitch ($Q_{tw,pot}$) at rest and the superimposed twitch elicited during an MVC (SIT).

Voluntary activation (%) = $(1 - SIT/\ Q_{tw,pot}) \times 100$

Measures of muscle contractility were derived for each resting twitch. These measures of muscle contractility have been used previously to determine peripheral and central components of fatigue after time-trial cycling (Thomas et al., 2015), match-play football (Brownstein et al., 2017), and exposure to hypoxia (Goodall et al., 2010), and were calculated as follows (Figure 3.11):

- Twitch amplitude – maximum amplitude of force attained during the twitch.

- Maximum rate of force development (MRFD) – largest positive gradient of the force trace during the potentiated twitch.
- Maximum relaxation rate (MRR) – largest negative gradient of the force trace during the potentiated twitch.
- Contraction time (CT) – time between the stimulation and the attainment of peak force.
- One-half relaxation time ($RT_{0.5}$) – time between attaining peak force and relaxing to 50% of that peak.

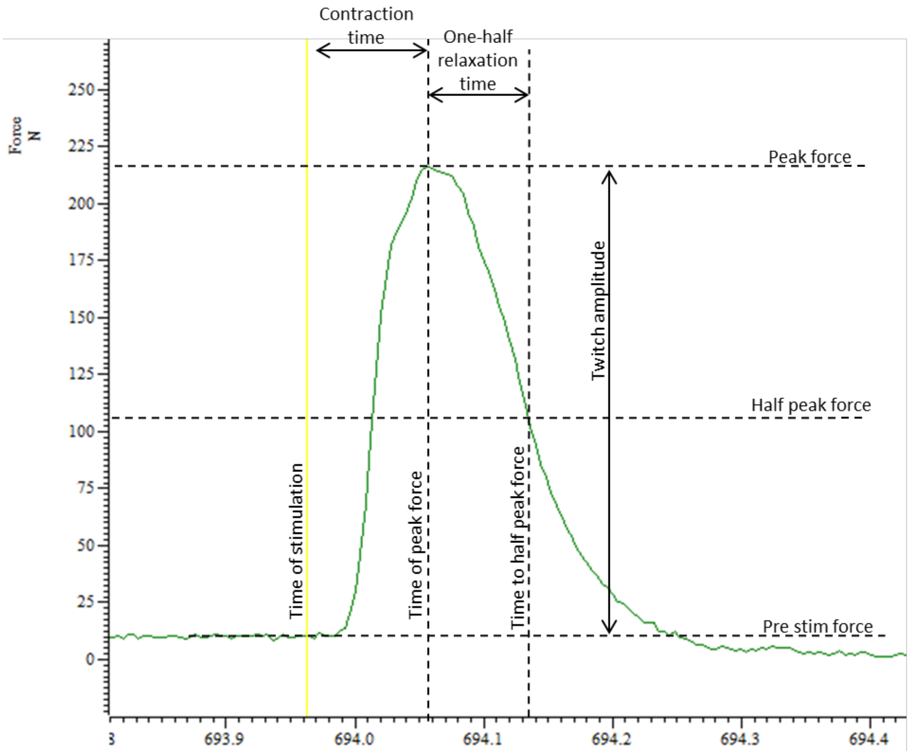


Figure 3.11. Potentiated twitch force of the knee extensor at rest.

3.4 Respiratory gas analysis

Breath-by-breath gas exchange data was quantified with an automated open circuit metabolic cart (Vyntus CPX, Vyaire Medical, Illinois, USA) and the corresponding software package (Sentry Suite V2.19.2). Prior to each use a two-point calibration was perfumed using ambient air and a known gas mixture (~16% O_2 and ~5% CO_2). Ventilatory volume was calibrated using a 3 L (± 0.4%) syringe (Carefusion, San Diego, USA).

3.5 Blood lactate analysis

Blood lactate concentration [BLa] was determined from a 20 μL capillary blood sample from the earlobe using an automated device (Biosen C_line Clinic, EKF, Germany). The capillary sample was mixed in a pre-prepared eppendorph with a 2 mL heparinised phosphate buffered solution (pH 7.2) in order to hemolyse and thin the sample. Once placed in the analyser L-Lactate contained in the sample is converted by the immobilized enzyme lactate oxidize. The product of the reaction is gluconic acid, pyruvate and hydrogen peroxide. The magnitude of rise in hydrogen peroxide concentration is detected at the electrodes. When in use, the analyser was calibrated with a 12 mmol standard solution at 60 minute intervals. Additionally, on a weekly basis, quality control samples of 3 and 15 $mmol.L^{-1}$ samples were run in quadruplet.

CHAPTER 4

FAMILLIARISATION TO MAXIMAL RECUMBENT ECCENTRIC CYCLING

The data from this chapter has been published:

Green, D.J., Thomas, K., Ross, E., Pringle, J., Howatson, G., 2017. Familiarisation to maximal recumbent eccentric cycling. *Isokinetics and Exercise Science*. 25, 17–24. doi:10.3233/IES-160640

4.1 Introduction

It is well documented that isolated eccentric contractions can produce up to twice the force of concentric or isometric contractions (Crenshaw *et al*., 1995; Drury *et al*., 2006; Kellis and Baltzopoulos, 1998; Westing *et al*., 1988). Similar findings have also been observed in eccentric cycling where, for the same metabolic cost, up to three times greater power can be produced compared to concentric cycling (Abbott *et al*., 1952; Peñailillo *et al*., 2013). Furthermore the electrical activity (detectable with surface electromyography) at any given power or force production is less during eccentric compared to concentric exercise (Kellis and Baltzopoulos, 1998; Peñailillo *et al*., 2013). Collectively these indicate that eccentric cycling may offer a potent stimulus for musculoskeletal adaptation by being a training modality that is non weight bearing, 'relatively' low in metabolic cost, but can also put greater stress on the muscle-tendon complex through higher levels of tension not possible under concentric loading. An additional advantage of eccentric cycling ergometry is the ability to prescribe high-volume, specific eccentric work that minimises the concentric contractions typically associated with other types of cyclical eccentric training, such as traditional free-weight resistance exercise. Training studies utilising eccentric cycling have observed notable increases in VL cross-sectional area (Lastayo *et al*., 2000), jump power, leg stiffness (Elmer *et al*., 2012), concentric power, pennation angle (Leong *et al*., 2013), and jump height (Gross *et al*., 2010), supporting the posit that eccentric cycling can offer a potent training stimulus.

Given eccentric cycling is likely a novel stimulus for the majority of participants, it is important for both researchers and practitioners to understand the time-course of familiarisation in order to optimise measurement and exercise prescription. Brughelli and Van Leemputte (2013) concluded that two familiarisations are required to ensure a good level of within-subject reliability for power output in maximal eccentric cycling. However, this research was conducted on an upright ergometer as opposed to a recumbent bike, the latter being more commonly used in eccentric cycling research (Elmer *et al*., 2012; Leong *et al*., 2013; Peñailillo *et al*., 2014). In concentric cycling, differences in body orientation (between conventional cycling position and recumbent) are known to significantly alter power output and muscle activation (Savelberg *et al*., 2003; Too, 1994). Therefore, it is reasonable to suggest that similar differences might also be present in the eccentric domain.

The evidence around the learning response to recumbent eccentric cycling is limited. For example, greater consistency maintaining a given power output was observed after six weeks of recumbent eccentric cycling at 60 – 80 rpm (Gross *et al*., 2010), however, this does not offer insight to the initial, session-by-session, learning effect. Penailillo *et al* (2013) reported reductions in VL activation for a set power output at 60 rpm after two sessions, indicating a change in neuromuscular activation, but no other muscles or cadences were tested. Additionally, very little is known about cadence effects on the familiarisation process to recumbent eccentric cycling. It has been suggested that during upright eccentric cycling the between-session power output at low cadences (40 rpm) is less reliable in comparison to higher cadences (60 – 120 rpm; Brughelli and Van Leemputte, 2013), however this posit has yet to be tested in recumbent eccentric cycling. A greater understanding of the muscle activation that underpins pedalling technique, across a range of cadences, would help optimise the prescription of eccentric cycling. Furthermore, when combined with power output data, it would highlight the number of pre-trials required to attain repeatable results after which interpretations can be made on interventions and progression. Therefore, the aim of this study was to identify the reliability of power output and lower limb muscle activation during the familiarisation to recumbent eccentric cycling and over a range of cadences, to recommend the number of practice trials required to minimise variation. These aims contribute to the thesis by determining the appropriateness of this protocol to monitoring eccentric cycling ability. A reliable monitoring protocol will aid the application of eccentric cycling by ensuring exercise intensity can be prescribed at an intensity that will provide mechanical overload. Furthermore, it will determine the appropriate number of familiarisation sessions that should be employed in future chapters to ensure a consistent technique.

4.2 Methods

4.2.1 Participants

Twelve recreationally active males (mean ± SD; age = 27 ± 3 years; body mass = 77.3 ± 10.1 kg; stature = 177 ± 5 cm) with no history of lower limb injuries or neurological disorders volunteered to undertake this investigation. All participants provided written informed consent and were deemed healthy as determined by a physical activity readiness questionnaire. Participants were asked to refrain from caffeine, alcohol and exercise in the 24 hours preceding each trial and maintained their habitual training throughout the testing process. Ethical approval was granted prior to the start of all procedures by the Northumbria University Faculty of Health and Life Sciences Ethics committee, in accordance with the Declaration of Helsinki.

4.2.2 Experimental design

To establish the familiarisation time-course of the variables under investigation, participants performed maximal eccentric recumbent cycling at a range of cadences on four separate trial days. Ten days separated trials one and two with the remaining trials each separated by seven days. During each visit participants completed six, 10 s maximal bouts of eccentric cycling in a randomised, counterbalanced (Latin squares method) order at 20, 40, 60, 80, 100 and 120 rpm with 5 min recovery between each cadence. The dependant variables were peak power output (PO), average PO, and muscle activation of the RF, VL, BF, and MG. All exercise was performed on a custom built, recumbent, isokinetic cycle ergometer.

4.2.3 Protocol

Eccentric ergometery

All exercise was conducted on the custom built cycling ergometer described in Chapter 3. In order to establish a relationship between torque and sEMG activity, torque and sEMG values from the left limb and crank were used for analysis.

Power values were calculated from torque data using the following equation:

$$\text{Power (W)} = \text{Torque (N·m)} \times \text{Cadence (rad·s}^{-1}\text{)}$$

Peak PO was derived from the peak instantaneous power during each 10 s effort and average PO was calculated for the entirety of each 10 s effort. Immediately prior to each 10 second maximal sprint, participants were given 30 seconds to familiarise themselves with the cadence (i.e. not resist the pedals but instead be passively moved by them); this was the only eccentric familiarisation afforded to them. Participants were instructed to resist the pedals in the opposite direction of motion. After this familiarisation a one minute rest was observed before commencing the 10 s maximal effort. For each 10 s effort the participant began by having their legs passively turned by the ergometer, to ensure the correct cadence was attained, before being counted down to initiate the effort. The elapsed time was hidden from the participant, but the participant was informed when each 10 s epoch had expired and the ergometer was subsequently stopped.

Surface electromyography (sEMG)

Surface electromyography protocols are described in Chapter 3. The muscles used for analysis in this chapter were the RF, VL, BF, and MG. For normalization of sEMG measures participants completed three 8 s maximal voluntary concentric contractions at the start of each trial (separated by 5 mins). Each maximal contraction was conducted on the ergometer described above. Contractions started at a pedal angle of 0º (top dead centre) and ceased at 48º (a function of the 8 s duration and 1 rpm cadence). Using a 0.2 s root-mean–square (RMS) window, the maximum sEMG activity from the three MVC efforts for each muscle was used to obtain a reference value for normalization purposes. Muscle activation during the maximal 10 s efforts was calculated as the average RMS value for the two whole revolutions that corresponded to the greatest power output. This was in order to compare different cadences over an identical range of motion.

Statistical analyses

All statistical testing was performed using Graph Pad Prism 7.00 (GraphPad Software Inc, California, USA) and Microsoft Excel 2010 (Microsoft, Washington, USA). To assess systematic error between trials for peak PO, average PO, and EMG, data were analysed using one-way (1 × 4) repeated measures analysis of variance at each cadence (e.g. Cadence: 40rpm and trials: T1, T2, T3, T4). Where appropriate, Tukey's *post-hoc* test was used to locate any significant differences. Significance was set at an alpha level of 0.05. The random error associated with familiarisation of the task was assessed across successive trials using coefficient of variation (CV, %) calculations ± 95 confidence limits. Reliability was defined as the extent to which the experimental trials yielded the same results on repeated trials. Coefficient of variation values were classed as good (< 5%), moderate (5–10%), or poor (> 10%) based upon values observed previously in maximal concentric cycling < 10 s (Brughelli and Van Leemputte, 2013; McGawley and Bishop, 2006; Mendez-Villanueva *et al*., 2007).

4.3 Results

Power data

Figure 4.1 shows the mean values (± SD) for peak PO and average PO across all trials. There was a significant effect of trial on average PO at 40 rpm ($F_{(3, 33)} = 3.006$, $p = 0.044$) and 60 rpm ($F_{(3, 33)} = 4.913$, $p = 0.006$). *Post-hoc* testing revealed that at 60 rpm average PO at T2 was greater in comparison to T1 ($p = 0.004$), with no other differences thereafter (all $p > 0.05$). For 40 rpm, the Tukey *post-hoc* adjustment to limit type 1 errors from multiple comparisons resulted in no statistical differences between trials, though PO in T1 tended to be lower than subsequent observations (T1 - T2, $p = 0.15$; T1 - T3, $p = 0.07$; and T1 - T4, $p = 0.07$), but with no change thereafter (T2 - T3, $p = 0.98$; T3 - T4, $p = 0.99$, Figure 4.1, panel B). There were no other differences in average PO or peak PO between trials at the other cadences. Between-trial CV for peak PO and average PO, including 95% confidence limits, are displayed in Figure 4.2. The greatest reduction of between-session CV for peak PO (T1 - T2, 8-26%; T2 - T3, 9-20%) and average PO (T1 - T2, 11-28%; T2 - T3, 4-

15%) was seen after one familiarisation session, i.e. between T2 – T3, with little further improvement thereafter (peak PO, T3 – T4, 8 – 18%; average PO, T3 – T4, 5 – 15%). Between cadences, the lowest CV values were observed at 60 rpm for both peak PO (T2 - T3, 9%; T3 – T4, 8%) and average PO (T2 - T3, 4%; T3 – T4, 5%). Furthermore, there was a tendency for faster cadences (≥ 80 rpm) to initially (T1 - T2) display larger CVs in comparison to slower cadences (≤ 60 rpm) in both peak PO (11% vs 19%, Figure 4.2, panel A) and average PO (14% vs 25%; Figure 4.2, panel B).

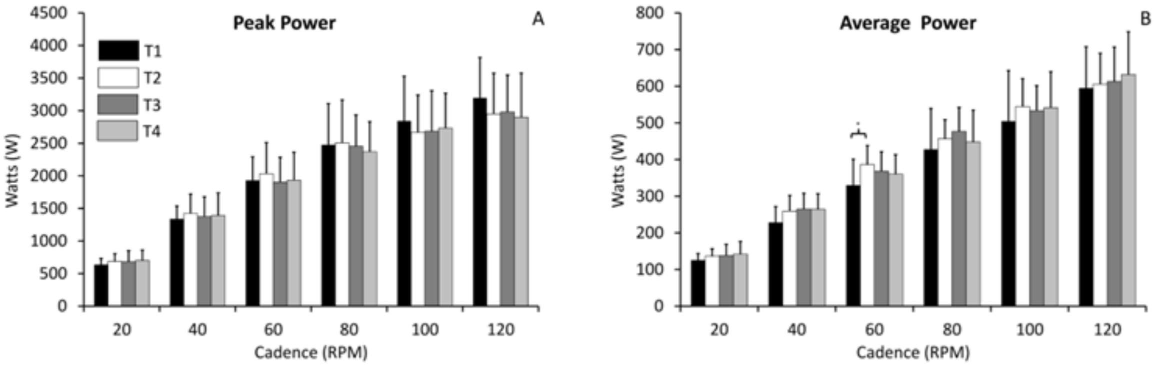


Figure 4.1. Peak power (A) and average power (B) data during repeated trials of maximal recumbent eccentric cycling exercise at varying cadences (n = 12). Values are mean (SD) * denotes significant difference at $p < 0.05$.

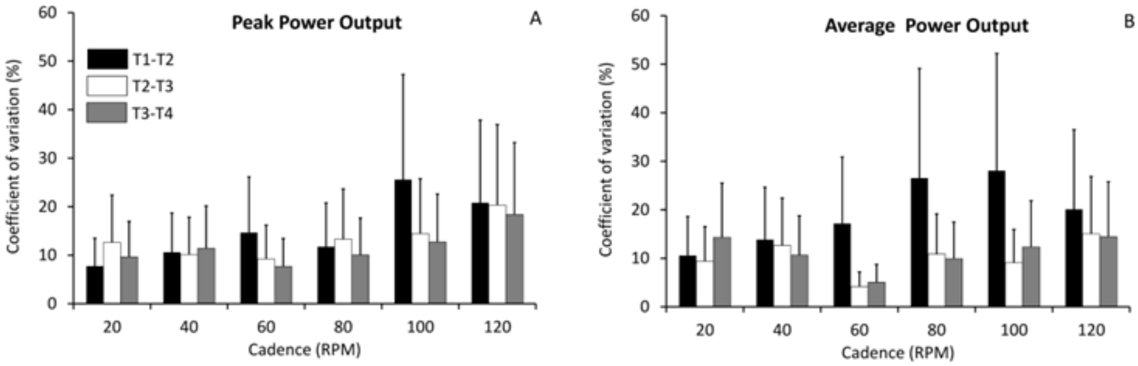


Figure 4.2. Between-session coefficient of variation data for peak power (A) and average power (B) output for repeated trials of maximal recumbent eccentric cycling exercise at varying cadences (n = 12). Values are mean (95% CI) * denotes significant difference at $p < 0.05$.

EMG data

Mean values (± SD) for all muscle activation variables are displayed in Figure 4.3. There was a significant effect of trial on RF activation at 20 rpm ($F_{(3, 33)} = 6.038$, p = 0.002). *Post-hoc* analysis revealed greater activation at T2 (p = 0.003), and T4 (p = 0.006) in comparison to T1, and generally RF activation tended to increase with repeated trials (Figure 4.3, panel C). Similarly, at all cadences, MG activation tended to increase with repeated trials (Figure 4.3, panel D), although this difference was not statistically significant at any cadence (all p > 0.05). No such patterns were observed in BF or VL activation. Between-trial CV data for muscle activation, with 95% confidence limits, are displayed in Figure 4.4. The majority of EMG CV variables decreased with repeat trials (Figure 4.4). This reduction in CV was consistently observed after one familiarisation, before plateauing, with the VL (T2 – T3, 9 - 16%; T3 – T4, 8 – 15%) and RF (T2 – T3, 14 - 26%; T3 – T4, 12 – 20%) across all cadences. However, no such plateau was observed with BF (T2 – T3, 30 - 48%; T3 – T4, 15 – 35%) and MG (T2 – T3, 27 - 51%; T3 – T4, 13 – 32%; Figure 4.4).

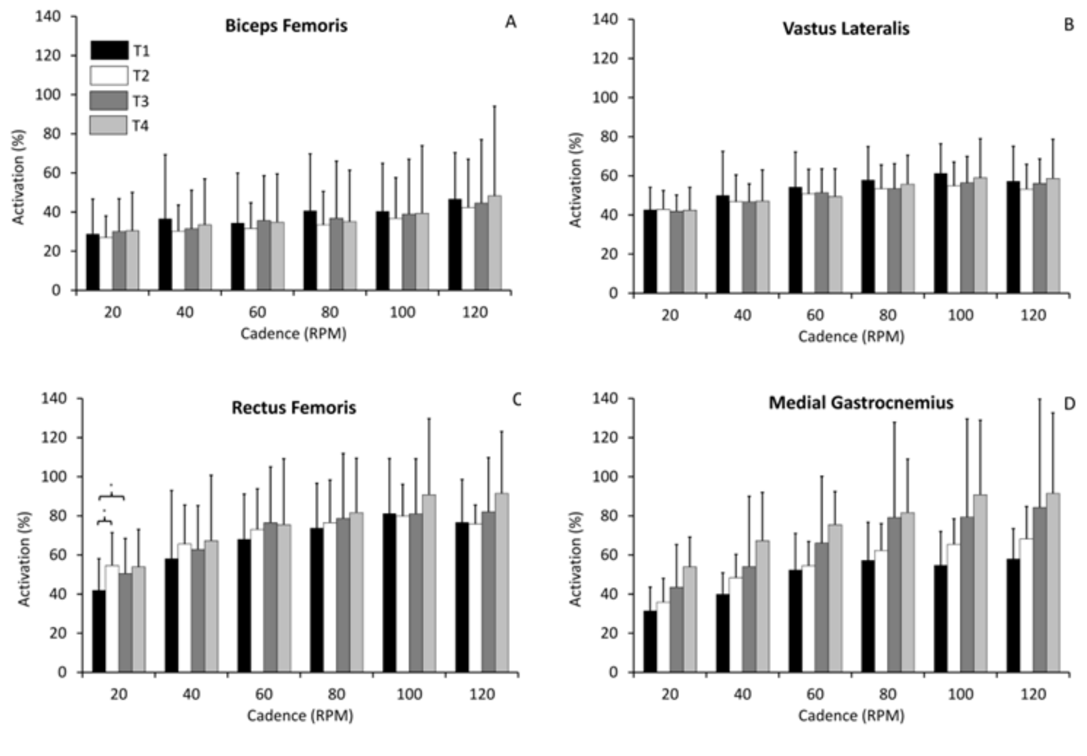


Figure 4.3. *Biceps femoris* (A), *Vastus lateralis* (B), *Rectus femoris* (C), and Medial *gastrocnemius* (D) activation data during repeated trials of maximal recumbent eccentric cycling exercise at varying cadences (n = 12). Values are mean (SD) * denotes significant difference at p < 0.05.

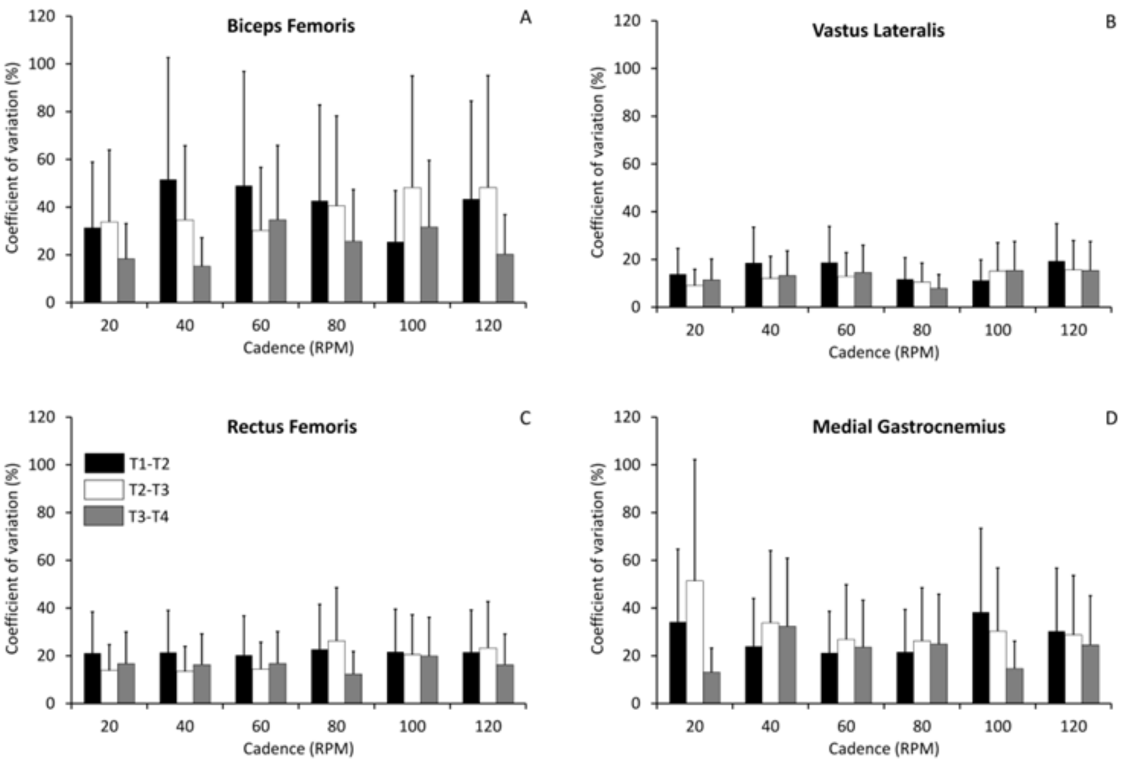


Figure. 4.4. Between-session coefficient of variation data the *biceps femoris* (A), *Vastus lateralis* (B), *Rectus femoris* (C), and Medial *gastrocnemius* (D) for repeated trials of maximal recumbent eccentric cycling exercise at varying cadences (n = 12). Values are mean (95% CI) * denotes significant difference at $p < 0.05$.

4.4 Discussion

The aim of this study was to establish the time-course of familiarisation to maximal recumbent isokinetic eccentric cycling, and to determine the reliability of this mode of exercise for a range of cadences. The data suggests that at least one practice trial is required to achieve consistent group means and good to moderate between-session reliability in peak PO and average PO, with 60 rpm displaying the greatest reliability. To improve the reliability of selected lower limb muscle activation variables at least one practice trial should be employed (VL and RF). However, to increase the reliability of sEMG in other lower limb muscles (BF and MG) further familiarisations would be prudent, and even with this level of experimental control between-session variability could still be unacceptably high.

The absence of significant changes in average and peak PO after T2 indicates that one familiarisation reduces variation sufficiently to attain consistent PO data. This notion is supported by the plateau in average and peak PO CV between T2 – T3 and T3 – T4 which further indicates that only one familiarisation would be sufficient to minimise the initial, large, variability observed in the current investigation. A similar time-course of familiarisation has been previously observed in upright eccentric cycling where a plateau in average PO was identified after one familiarisation session, although consistent between-session CVs required an additional familiarisation (Brughelli and Van Leemputte, 2013). Brughelli and Van Leemputte also observed an increase in peak PO and its reliability after two and four sessions respectively. In contrast, the current study found no change in peak PO, and little discernible change in peak PO reliability after T2. This discrepancy in peak PO and peak PO reliability might stem from the larger absolute peak PO in the current study (↑~100%), even though a similar population was sampled. One possibility is that different factors limit peak PO during upright and recumbent eccentric cycling and that these factors are reduced during recumbent cycling, hence the greater power output. Furthermore, greater initial peak PO would reduce the capacity for improvement which may explain the absence of changes in peak PO in the current study in comparison to (Brughelli and Van Leemputte, 2013). This absence of change in peak PO, combined with the increases in average PO, suggest that participants developed a more consistent pedalling technique, rather than a more powerful technique, as they became familiarised to maximal recumbent eccentric cycling.

We demonstrated a trend for increased RF and MG activation during the initial stages of familiarisation to maximal, recumbent, eccentric cycling. Similar findings have also been observed in isolated eccentric contractions and attributed to a reduction in neural inhibition (Babault *et al*., 2001; Beltman *et al*., 2004). Neural inhibition is thought to limit muscle activation to protect the muscle-tendon unit from high forces that would otherwise cause damage. However, for the purposes of eliciting a training response, it is likely that these high power outputs make eccentric cycling a potent stimulus. The ability to fully activate the muscle during eccentric cycling could promote greater adaptation. Therefore, before the full potential of eccentric cycling as a training stimulus can be realised, or studied, a thorough familiarisation plan should be considered. Although the significant changes in RF activation (20 rpm) ceased after T2 there was a tendency for MG and RF activation to increase from T1 to T4. This tendency for increased activation across trials was not evident with the BF or VL. It is possible that because maximal recumbent eccentric cycling did not elicit the same high muscle activation in the VL and BF in comparison to the RF and MG that these muscles did not experience a large enough stress to elicit an increase in activation with subsequent trials. Given that all monitored muscles do not have the same role in this unique movement it is not surprising that they have responded differently to the familiarisation process. At any given cadence, or trial, muscle activation was, in the majority, greatest in the RF (~77%) followed by the MG (~62%), VL (~52%), and BF (~37%). This supports work by Elmer *et al* (2010) that found eccentric actions of the knee extensors and ankle extensors absorb significantly more power during eccentric cycling in comparison to the knee flexors.

Previous research has observed the between-session CV of sEMG to be 16% during maximal isometric contractions (Yang and Winter, 1983), and between 16 – 78% during a dynamic movement such as cutting (Fauth *et al.*, 2010), walking (Murley *et al.*, 2010), or back squats (Clark et al., 2016). This suggests that the CV values of ~13% (VL) and ~16 % (RF), in the current study, are favourable when compared with other dynamic movements. However, more concurrent with previous research are the poor CV values observed in the BF (~24%) and MG (~22%). Considering that the BF does not play a key role in power absorption during eccentric cycling (Elmer *et al.*, 2010a) this poor reliability is not surprising. However, the MG does play a role in power absorption yet displays markedly poorer reliability in comparison to other prime movers such as the VL and RF. Anecdotally participants found coordinating the ankle joint the most difficult task during each maximal eccentric effort. It is possible that a large portion of the variability in power output could be a result of high variability in MG activation. Therefore, it may be prudent to focus a user on maintaining a consistent ankle joint orientation during familiarisation to recumbent isokinetic eccentric cycling.

To account for the acute changes in PO and lower limb muscle activation during the familiarisation to maximal recumbent isokinetic eccentric cycling it is recommended that at least one familiarisation session be prescribed. Furthermore, after one familiarisation session, moderate between-session reliability can be attained in peak and average PO, and VL and RF activation. However, in order to improve the reliability of BF and MG activation it may be prudent to adopt at least two familiarisations, although this is unlikely to result in improving reliability to acceptable levels. Finally, a cadence of 60 rpm is recommended in order to achieve the greatest reliability in the aforementioned variables.

The overall aim of this thesis was to systematically investigate the neuromuscular responses and application to performance of a bespoke eccentric cycling instrument. More specifically, the aim of this chapter was to characterise the familiarisation process to eccentric cycling and thus determine a reliable method of assessing the mechanical stimulus afforded by eccentric cycling. The primary implication arising from this chapter is that maximal effort eccentric cycling is not a reliable tool for monitoring performance and therefore cannot be used with any confidence to track performance throughout an intervention period. Additionally, this level of reliability makes maximal eccentric cycling a poor method for prescribing eccentric cycling. Whilst eccentric cycling clearly provides a large mechanical stimulus which might benefit athletic performance its prescription should not be based upon maximum or average power during 10s maximal efforts. Future chapters should use other methods of prescribing exercise intensity in order to have greater confidence that training is of a suitable intensity to elicit desired adaptations. A secondary practical finding of this chapter is that, after one familiarisation session, 60 rpm is the cadence which produces the greatest technical consistency and would therefore be a sensible choice for use when training in future chapters.

CHAPTER 5

TORQUE, POWER AND MUSCLE ACTIVATION OF ECCENTRIC AND CONCENTRIC ISOKINETIC CYCLING

The data from this chapter has been published:

Green, D.J., Thomas, K., Ross, E.Z., Green, S.C., Pringle, J.S., Howatson, G., 2018. Torque, power and muscle activation of eccentric and concentric isokinetic cycling. *Journal of Electromyography and Kinesiology*. 40, 56-63.

5.1 Introduction

The time course of familiarisation to eccentric cycling was determined in Chapter 4, however, the mechanical stimulus it can afford, and the associated muscle activation characteristics are unknown. As discussed in Chapter 2 eccentric muscle actions produce greater force than concentric contractions for a lower metabolic cost and sEMG activity, thus making them an attractive training modality. A large number of studies have used isokinetic dynamometers for eccentric exercise prescription in order to isolate specific joints and limit extraneous movements (Blazevich *et al*., 2007; Cadore *et al*., 2014; Higbie *et al*., 1996). However, isokinetic dynamometry does not necessarily represent cycling or weight bearing locomotion given that multiple joints and muscle groups are activated concurrently in these human movements. The prescription of dedicated eccentric training using traditional resistance training exercises poses logistical challenges; for example, the loads prescribed could exceed what can be lifted concentrically and thus require external assistance to complete the concentric phase. In addition, there is typically a concentric component that can elicit greater metabolic stress which might be undesirable for patients with poor cardiorespiratory fitness. Additionally, for athletes specifically attempting to mechanically overload their musculoskeletal system a substantial metabolic stress may only serve to compromise existing cardiovascular training. The advent of the eccentric cycling ergometer allows repeated eccentric muscle actions to be performed with minimal concentric contractions (Abbott *et al*., 1952; Elmer *et al*., 2010a). This makes eccentric cycling a potentially valuable tool to prescribe high volume, multi-joint, eccentric exercise and to understand the potential benefits of eccentric muscle training. Typically, eccentric cycling is performed in a recumbent position in order to increase torso stability via the use of a back rest (Elmer *et al*., 2012; Leong *et al*., 2013).

The benefits of eccentric cycling have become the focus of a small, but growing number of research articles. After 6-8 weeks of submaximal eccentric cycling, increases in VL muscle fibre cross sectional area, leg stiffness during sub-maximal hopping, vertical jump power (external power), isometric knee extensor strength, and pennation angle of the VL and RF have been observed (Elmer *et al*., 2012; Gross *et al*., 2010; Lastayo *et al*., 2000; Leong *et al*., 2013). Although these studies highlight the potency of eccentric cycling as a training stimulus, little is yet known about the characteristics of the eccentric task and the effect of manipulating cadence on torque (pedal torque unless stated otherwise) and power, and muscle activity. The majority of eccentric cycling studies have utilised a narrow range of cadences between 50 – 70 rpm; which is likely due to the desire for high volumes of eccentric contractions whilst avoiding the greater technical proficiency required for faster cadences (observed in Chapter 4). However, evidence from maximal eccentric cycling suggests that greater power outputs can be attained at higher cadences (Brughelli and Van Leemputte, 2013) which, after the appropriate familiarisation, could be advantageous for athletes seeking to overload the musculoskeletal system.

The underpinning torque-cadence relationship and muscle activation characteristics of eccentric cycling remain unknown. During concentric cycling, maximal torque production decreases with increasing cadence in a linear manner and the corresponding external power output is a parabolic function of cadence (McCartney *et al*., 1983). However, given the fundamental force-velocity differences between eccentric and concentric contractions of individual muscle fibres *in-vitro,* it is reasonable to suggest that differences might also exist with a complex multi-joint task such as cycling (Katz, 1939). Non-cycling *in-vivo* observations suggest that as angular velocity increases single-joint eccentric torque production remains stable or marginally increases in the knee and elbow extensors/flexors (Carney *et al*., 2012; Chapman *et al*., 2005; Ghena *et al*., 1991; Kramer *et al*., 1993; Westing *et al*., 1988). The expectation during eccentric cycling is that the rate of torque decline at higher cadences will be reduced compared to concentric cycling.

At submaximal intensities, eccentric cycling elicits lower electromyographical activity than concentric cycling (Bigland-Ritchie and Woods, 1976; Peñailillo *et al*., 2013). Furthermore, during submaximal eccentric cycling peak RF and VL activation occur at similar knee angles to peak torque (~ 70°) whereas during concentric cycling, at a similar workload, peak RF and VL activation occur at different knee angles compared to peak torque (~40° and ~100° respectively) (Peñailillo et al., 2017a). How these differences in the magnitude and timing of lower limb muscle activation contribute to torque production at maximal intensities of eccentric cycling is not currently well understood. Furthermore, it is unknown what effect altering cadence might have on these parameters during maximal recumbent isokinetic eccentric and concentric cycling. A greater understanding of these muscle activation patterns, and the corresponding torque and power production, would facilitate interpretation of any ensuing neuromuscular adaptation following a period of training and inform future research in which eccentric and concentric cycling are typically used concurrently. Consequently, the aim of this study was to establish the effect of cycling mode (concentric and eccentric) and cadence on torque, power, and lower limb muscle activation during maximal, recumbent, isokinetic cycling. Addressing this aim will provide quantifiable data to critically evaluate the prescription of eccentric cycling by cadence throughout future chapters. Furthermore, it will provide data on the technical (muscle activation) characteristics of eccentric cycling across a range of cadences which will serve to evaluate the fatigue and adaptation responses assessed in future chapters.

5.2 Methods

5.2.1 Participants

Following institutional ethical approval, twelve recreationally active males (mean ± SD; age = 27 ± 3 years; body mass = 77.3 ± 10.1 kg; stature = 177 ± 5 cm) with no history of lower limb injuries or neurological disorders participated in the study. All participants provided written informed consent and completed a pre-exercise physical activity readiness questionnaire and were asked to refrain from caffeine, alcohol and exercise in the 24 hours preceding each trial. The study adhered to the guidelines set out by the World Medical Association Declaration of Helsinki.

5.2.2 Experimental design

Participants reported to the laboratory on five separate occasions, separated by at least 7 days but no more than 11, to perform maximal effort cycling on a custom-built recumbent eccentric cycling ergometer (BAE systems, London, UK; Figure 5.1). A single exercise bout consisted of 6 × 10 s efforts, presented in a randomised, counterbalanced order (Latin squares method) across a range of cadences (20, 40, 60, 80, 100 and 120 rpm), interspersed with 5 min recovery between efforts. In order to familiarise participants with the novelty of the eccentric task a single eccentric practice bout (6 × 10 s) was conducted during each of the first three visits (Green *et al.*, 2017). Visit 4 comprised an eccentric experimental bout followed by 10 minutes rest and a concentric familiarisation bout. Visit five consisted of a single concentric experimental bout (6 × 10 s).

5.2.3 Protocol

Eccentric Ergometry

All exercise was conducted on the custom built eccentric cycling ergometer described in Chapter 3. To establish the temporal relationship between torque and sEMG activity, respective values from the left-hand crank and left-side limb were used for analysis. The left side was selected because the motor of the dynamometer was situated on the right side and pilot testing revealed interference with the sEMG signal. The effect of possible leg asymmetries was considered minimal as all participants were injury free and dependent variable comparisons were made within participants. A crank angle of zero represented top dead centre and crank angle increased with a counterclockwise movement (Figure 5.1). Due to the isokinetic nature of the ergometer crank angles were calculated as the product of angular velocity and elapsed time from pedal top dead centre, which was detected by a reed switch and magnet attached to the ergometer and left crank, respectively.

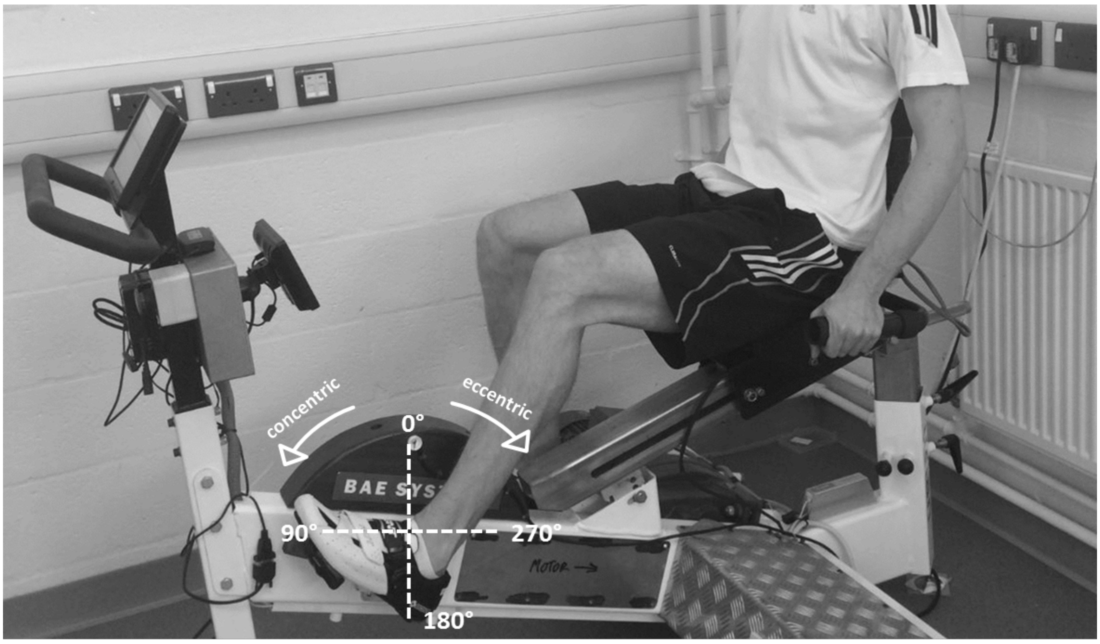


Figure 5.1 Isokinetic eccentric cycle ergometer. Depending on direction of crank rotation the participant either pushes with or resists against the pedals to conduct concentric or eccentric muscle actions respectively.

Instantaneous power values within the pedal revolution were calculated from torque data using the following equation:

$$\text{Power (W)} = \text{Torque (N}\cdot\text{m)} \cdot \text{Cadence (rad}\cdot\text{s}^{-1}\text{)}$$

$$\textit{where}\ \ \text{Cadence (rad}\cdot\text{s}^{-1}\text{)} = \text{Cadence (rpm)} \cdot \frac{2\pi}{60}$$

Experimental protocol

Each session commenced with a 5-min self-selected sub-maximal warm up in the modality to be utilised for testing e.g. eccentric or concentric. This warm-up was monitored and replicated prior to each session. Prior to each 10-s maximal effort, participants were given 30-s to familiarise themselves with the up-coming cadence, by undertaking a passive (i.e. no resistance) movement, driven by the ergometer. After this, a 60 s rest was observed before commencing the 10 s maximal effort. Prior to the start of each 10 s effort, participants were instructed to relax and have their legs passively turned by the ergometer (~3 s) to ensure the correct cadence was attained. During the maximal effort participants stabilised themselves with the aid of the backrest and side handles on the ergometer (Figure 5.1). The elapsed time of the effort was concealed from the participant, but the participant was informed when their effort should be terminated and the ergometer was subsequently stopped. Strong, verbal encouragement was given throughout each maximal effort by the experimenter. Throughout all test trials, torque, cadence, and sEMG of selected lower limb muscles, were recorded.

Surface electromyography (sEMG)

Surface electromyography protocols are described in Chapter 3. Data was smoothed using a 24 Hz fourth-order Butterworth low-pass filter (Gazendam and Hof, 2007). For the normalization of sEMG values participants completed three 8 s maximal voluntary concentric contractions at the start of each trial. These contractions were conducted on the aforementioned ergometer (Figure 5.1) at 1 rpm, starting at a crank angle of 0^{o} (top dead centre) with 5 min rest. Using a 0.2 s root-mean–square (RMS) window, the maximum sEMG activity from the three MVC efforts for each muscle was used to obtain a reference value for normalization purposes. For temporal normalisation the filtered muscle activation data for all revolutions in the experimental sessions were plotted separately for each cadence and modality before being fitted with a 3^{rd} order sum of sines model to determine muscle activation patterns (Matlab R2015b, Mathworks, USA).

Statistical analysis

All statistical testing was performed using SPSS 22 (IBM, New York, USA). To detect any effect of cadence and/or muscle contraction type on peak torque, peak power, sEMG peak amplitude, angle of peak torque, and angle of peak sEMG, data were analysed using a 2 × 6 repeated measures ANOVA (Contraction type: ECC and CON and cadence: 20, 40, 60, 80, 100, and 120 rpm). Peak sEMG data from the sum of sines model was used for analysis. Where appropriate, pairwise differences were located using multiple t-tests corrected by the Ryan-Holm Bonferroni adjustment. Effect sizes (Cohen's *d*) were calculated for all pairwise comparisons. Pearson Correlation Coefficients were used to assess the strength of association between ECC and CON peak torque at each cadence. The magnitude of correlation was interpreted as follows; small ($r = 0.10 – 0.29$), moderate ($r = 0.30 – 0.49$), large ($r = 0.5 – 0.69$), very large ($r = 0.70 – 0.89$), and extremely large ($r >= 0.90$) (Hopkins *et al*., 2009). Significance was set at an alpha level of 0.05. Greenhouse-Geisser corrections were applied to significant F-ratios that did not meet Mauchly's assumption of sphericity. All data is presented as mean ± standard deviation unless stated otherwise. For statistical testing when crank angles spanned 360°, i.e. differences in crank angles were geometrically minimal but numerically large, crank angles were uniformly adjusted prior to analysis. All crank angles were anchored to a functionally redundant part of pedal cycle i.e. the section of the pedal cycle that clearly dissociated the end of one cycle to the start of the next for the variable in question. This ensured that greater and lesser crank angles influenced the group mean in manner that was functionally accurate during statistical testing. Subsequent to statistical analysis crank angles were converted back to geometrically correct values for reporting.

5.3 Results

Torque

Peak torque was consistently higher in ECC compared to CON (average difference, 123 N·m, range 110 – 143 N·m, $F_{(1, 11)} = 86.5$, $p < 0.05$) at all cadences ($p < 0.05$; $d = 1.7 - 3.2$). There was a significant main effect of cadence on peak torque ($F_{(5, 55)} = 35.6$, $p < 0.05$; Table 5.1). As cadence increased, peak torque reduced in both ECC ($F_{(5, 55)} = 10.6$, $p < 0.05$) and CON ($F_{(1.8, 19.8)} = 122.7$, $p < 0.05$). This decrease in torque was linear for both ECC ($r^2 = 0.99$) and CON ($r^2 = 0.99$; Figure 5.2). However, there was no significant modality*cadence interaction effect on peak torque ($F_{(5, 55)} = 1.1$, $p > 0.05$). There was a very large relationship between ECC and CON peak torque at low cadences (20 and 40 rpm, $p < 0.05$). At faster cadences this relationship was only moderate (60 rpm), large (80 rpm), and small (100 and 120 rpm) ($p > 0.05$, Table 5.1).

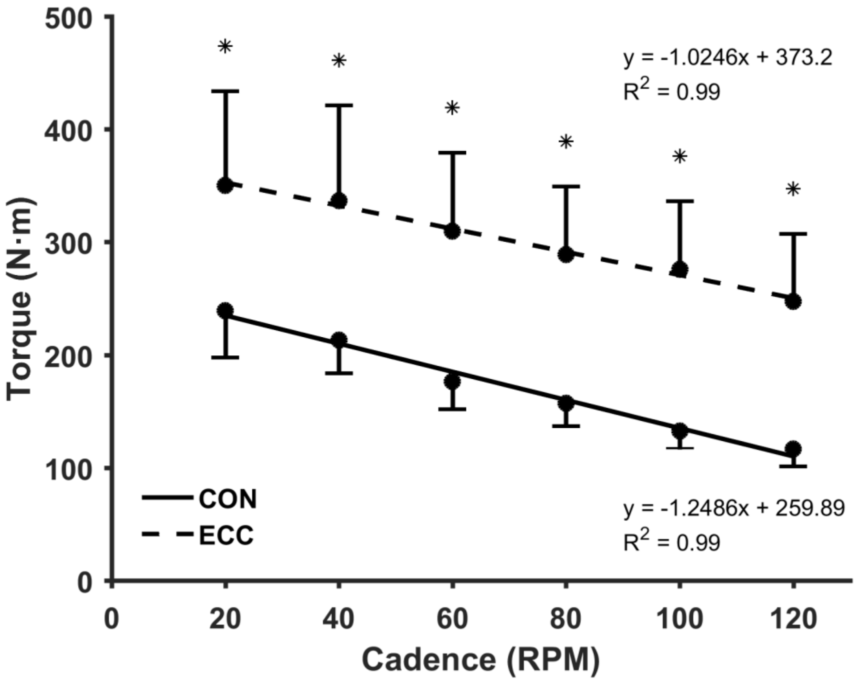


Figure 5.2. Peak instantaneous eccentric and concentric torque during isokinetic eccentric (--) and concentric (-) cycling at candences between 20 – 120 rpm (n = 12). Values are mean ± SD. * denotes significant difference at p < 0.05. Data points have been fitted with a linear line of best fit

Crank angle at peak torque

Crank angle at peak torque was significantly greater during CON compared to ECC ($F_{(1, 11)} = 134.7$, $p < 0.05$; Table 5.2), at all cadences ($p < 0.05$; $d = 1.8 – 4.2$). There was no main effect of cadence on crank angle at peak torque ($F_{(5, 55)} = 0.6$, $p > 0.05$). However, there was a modality*cadence interaction effect on crank angle at peak torque ($F_{(5, 55)} = 13.4$, $p < 0.05$); specifically as cadence increased crank angle at peak torque decreased in ECC ($F_{(2.7, 29.4)} = 4.3$, $p < 0.05$) and increased in CON ($F_{(2.7, 30.1)} = 9.9$, $p < 0.05$).

Power

Peak power was greater during ECC compared to CON ($F_{(1, 11)} = 94.2$, $p < 0.05$), across all cadences ($p < 0.05$; $d = 1.4 – 3.3$). Furthermore, peak power increased with cadence ($F_{(5, 55)} = 143.9$, $p < 0.05$; Figure 5.3, Table 5.1) for both ECC ($F_{(2.2, 24.7)} = 83.0$, $p < 0.05$) and CON ($F_{(5, 55)} = 250.0$, $p < 0.05$). There was a significant modality*cadence interaction effect as peak power increased with cadence to a greater extent during ECC compared to CON ($F_{(2.5, 27.8)} = 28.6$, $p < 0.05$; Figure 5.3). The shape of this increase was parabolic for both ECC and CON. This is illustrated by the conversion of the linear torque-cadence relationship to the concomitant power-cadence relationship and displayed in Figure 5.3.

Table 5.1. Peak power and peak torque data across all tested cadences .

Cadence (RPM)	Peak Power (W)		Peak Torque (N·m)		
	ECC	CON	ECC	CON	Pearson Correlation
20	700 ± 159*	519 ± 93	350 ± 83*	239 ± 42	0.89‡
40	1391 ± 346*	911 ± 127	337 ± 84*	213 ± 29	0.70‡
60	1935 ± 425*	1130 ± 160	310 ± 69*	176 ± 25	0.45
80	2370 ± 461*	1342 ± 177	289 ± 60*	157 ± 20	0.51
100	2733 ± 535*	1411 ± 173	276 ± 61*	132 ± 16	0.21
120	2898 ± 679*	1492 ± 201	248 ± 59*	117 ± 15	0.24

Mean (± 1 SD) eccentric and concentric peak instantaneous torque and peak instantaneous power output values and Pearsons correlation coefficients between ECC and CON peak torque measured over a range of cadences (20 – 120 rpm). * denotes significant difference to equivalent concentric value (p < 0.05). ‡ denotes significant Pearson correlation coefficient (p < 0.05).

Electromyography - Rectus femoris

Surface EMG data over a pedal revolution at each tested cadence is displayed in Figure 5.4. Peak RF activation occurred at significantly greater crank angles in ECC compared to CON ($F_{(1,11)} = 7.1$, $p < 0.05$). Pairwise comparisons located this difference at 60 rpm, 100 rpm, and 120 rpm ($p < 0.05$; d = 1.5, 1.3, and 1.5 respectively; Table 5.2). There was no main effect of cadence on the crank angle at peak RF activation ($F_{(1.8,20.2)} = 2.0$, $p > 0.05$). Although the crank angle at which peak RF activation occurred tended to increase at higher cadences in CON whilst decreasing in ECC, as evidenced by a significant modality*cadence interaction effect ($F_{(1.6, 17.2)} = 5.7$, $p < 0.05$). There was no main effect of cycling modality on peak RF amplitude ($F_{(1,11)} = 0.9$, $p > 0.05$). However, peak RF amplitude did increase at higher cadences ($F_{(2.1,22.9)} = 4.1$, $p < 0.05$). This increase was similar in ECC and CON as highlighted by a non-significant modality*cadence interaction effect ($F_{(2.9,32.4)} = 2.8$, $p > 0.05$).

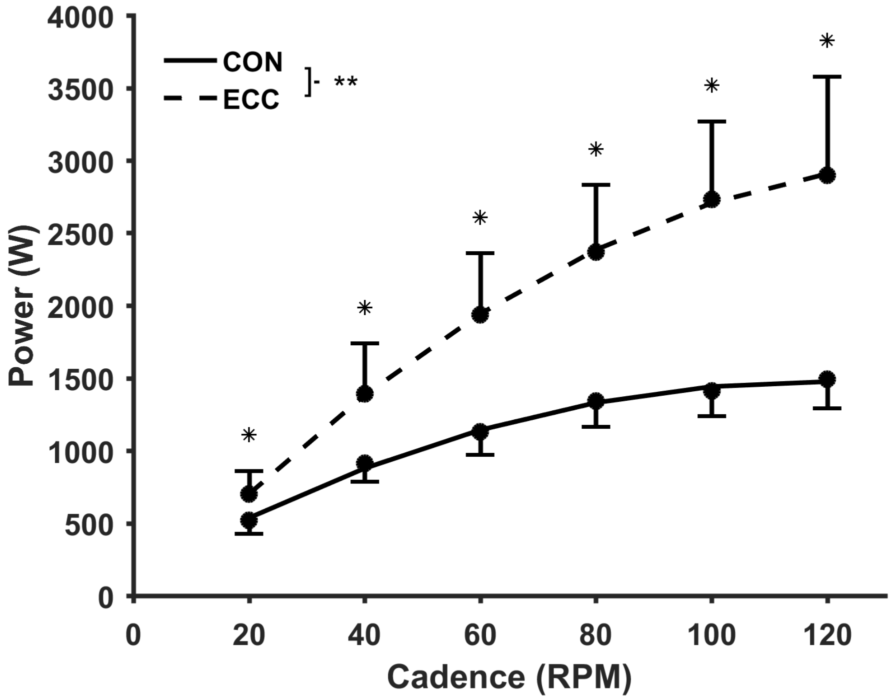


Figure 5.3. Peak instantaneuous eccentric and concentric power during isokinetic eccentric (--) and concentric (-) cycling at cadences between 20 – 120 rpm (n = 12). Values are mean ± SD. * denotes significant difference at p < 0.05. Data point have been fitted with a 2nd order polynomial line of best fit ** denotes significant interaction of cadence and contraction type at p < 0.05

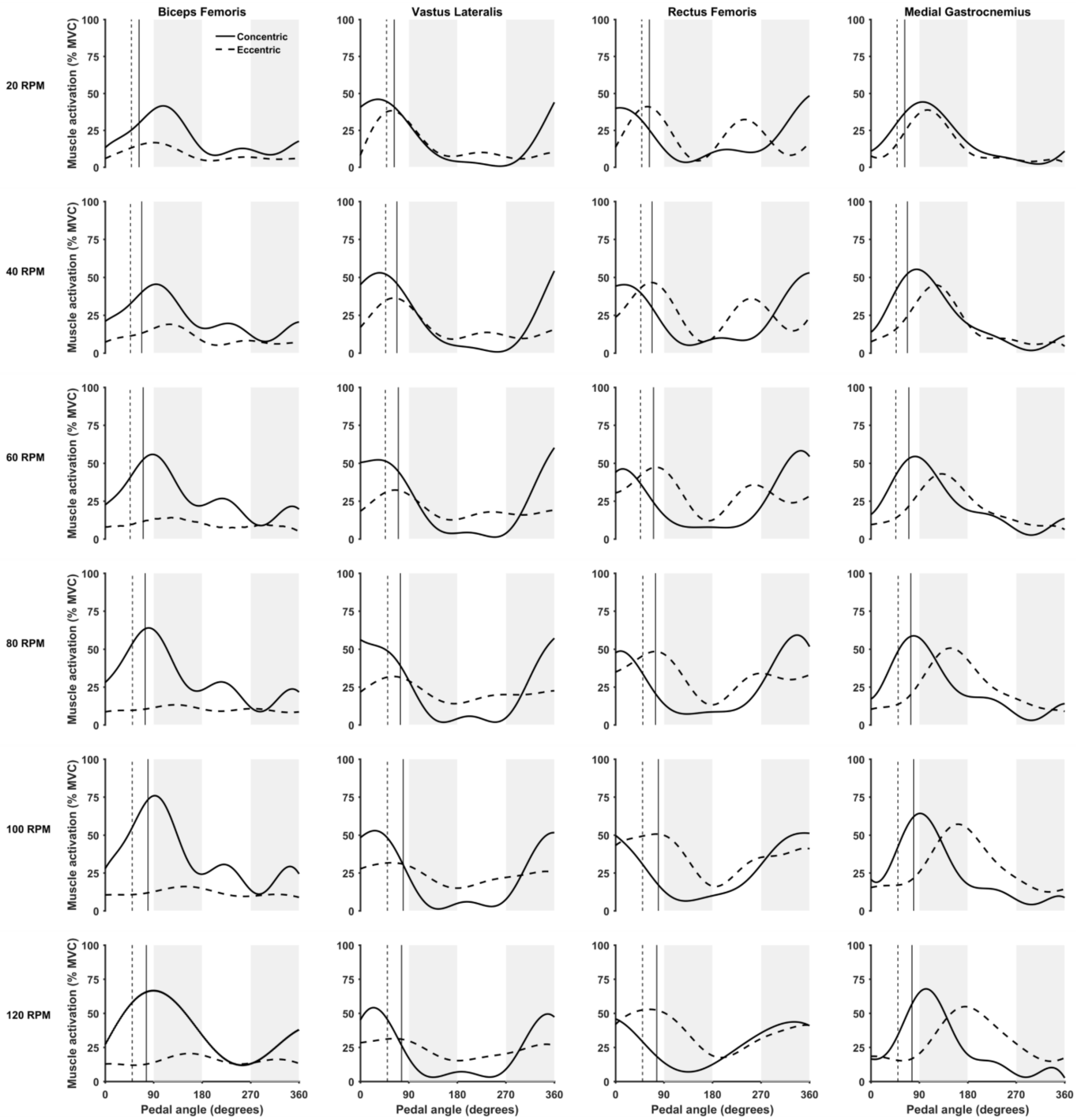


Figure 5.4. Average sEMG activation of the *biceps femoris*, *vastus lateralis*, *rectus femoris* and *medial gastrocnemius* during a pedal revolution across increasing cadences (n = 11). The pedal revolution is defined as 360^{o} of rotation from top dead centre (0) to an identical position on the subsequent cycle (360). Horizontal dashed (--) and solid (-) lines represent the muscle activation of eccentric and concentric cycling respectively. Vertical dashed (--) and solid (-) lines represent the crank angle of peak torque during eccentric cycling and concentric cycling respectively at the relevant cadence.

Table 5.2. Pedal angle at peak sEMG amplitude and peak torque data.

Cadence (RPM)	Pedal angle at peak sEMG (º)								Pedal angle at peak torque (º)	
	Rectus Femoris		*Biceps Femoris*		*Vastus Lateralis*		*Medial Gastrocnemius*			
	ECC	**CON**	**ECC**	**CON**	**ECC**	**CON**	**ECC**	**CON**	**ECC**	**CON**
20	1 ± 82	8 ± 37	92 ± 22	112 ± 71	61 ± 11*	20 ± 17	108 ± 16	102 ± 25	50 ± 10*	64 ± 5
40	19 ± 75	3 ± 40	117 ± 20	94 ± 54	80 ± 57	34 ± 12	118 ± 19*	93 ± 23	48 ± 11*	69 ± 6
60	60 ± 51*	351 ± 38	116 ± 32	90 ± 52	68 ± 73	23 ± 21	135 ± 18*	85 ± 16	47 ± 10*	72 ± 6
80	59 ± 52	345 ± 35	140 ± 56	79 ± 51	83 ± 89	10 ± 22	146 ± 27*	84 ± 19	42 ± 14*	77 ± 6
100	51 ± 55*	348 ± 38	153 ± 48*	80 ± 51	62 ± 76	19 ± 20	162 ± 24*	97 ± 25	40 ± 12*	78 ± 5
120	46 ± 55*	328 ± 53	156 ± 71	91 ± 45	64 ± 80	17 ± 22	179 ± 17*	105 ± 17	41 ± 11*	77 ± 10

Mean (± 1 SD) eccentric and concentric pedal angles at peak sEMG amplitude and peak instantaneous torque measured over a range of cadences (20 – 120 rpm). * denotes significant difference to equivalent concentric value ($p < 0.05$).

Biceps femoris

Overall there was no main effect of cycling modality ($F_{(1, 11)} = 4.1$, $p > 0.05$) or cadence ($F_{(1.9, 20.9)} = 2.9$, $p > 0.05$) on the crank angle at which peak BF activation occurred. However, there was a significant modality*cadence interaction effect on the crank angle of peak BF activation ($F_{(1.6, 17.6)} = 9.2$, $p < 0.05$). At higher cadences the crank angle of peak BF activation increased in ECC ($F_{(1.7,18.5)} = 4.1$, $p < 0.05$) and decreased in CON ($F_{(1.3, 14.1)} = 6.4$, $p < 0.05$). Pairwise comparisons located this difference at 100 rpm ($p < 0.05$; $d = 1.5$, Table 5.2). Peak BF amplitude was greater during CON compared to ECC ($F_{(1,11)} = 17.9$, $p < 0.05$), at all cadences ($p < 0.05$; $d = 1.0 – 1.8$). There was no main effect of cadence on peak BF amplitude ($F_{(1.3,14)} = 3.2$, $p > 0.05$) and there was no modality*cadence interaction effect on peak BF amplitude ($F_{(1.5,17.2)} = 2.5$, $p > 0.05$).

Vastus lateralis

The crank angle at which peak VL activation occurred was significantly greater in ECC compared to CON ($F_{(1, 11)} = 10.8$, $p < 0.05$) at 20 rpm ($p < 0.05$; $d = 2.8$, Table 5.2). There was no main effect of cadence on the crank angle of peak VL activation ($F_{(2.3, 25.6)} = 0.6$, $p > 0.05$). Additionally, there was no modality*cadence interaction effect on the crank angle of peak VL activation ($F_{(2.5, 27.6)} = 0.5$, $p > 0.05$). Peak VL amplitude was greater during CON compared to ECC ($F_{(1,11)} = 52.3$, $p < 0.05$) at all cadences ($p < 0.05$; $d = 1.3 – 2.5$). There was no main effect of cadence on peak VL amplitude ($F_{(2, 22)} = 1.1$, $p > 0.05$), however, there was a significant modality*cadence interaction effect ($F_{(5,55)} = 3.9$, $p < 0.05$). As cadence increased VL activation increased in CON ($F_{(5,55)} = 2.9$, $p < 0.05$) between 20 – 40 rpm and 40 – 60 rpm but remained similar across all cadences in ECC ($F_{(5, 55)} = 1.4$, $p > 0.05$).

Medial gastrocnemius

Crank angle at peak MG activation was greater during ECC compared to CON ($F_{(1, 11)} = 102.4$, $p < 0.05$). This was significant at all cadences between 40 – 120 rpm ($p = < 0.05$; d = 1.2 – 4.3, Table 5.2). There was a significant main effect of cadence on the crank angle of peak MG activation ($F_{(5,55)} = 22.2$, $p < 0.05$) which increased with cadence in both ECC ($F_{(5,55)} = 24.0$, $p < 0.05$) and CON ($F_{(3,33.2)} = 3.2$, $p < 0.05$).

However, this increase was greater in ECC as evident by a significant modality*cadence interaction effect ($F_{(5,55)} = 10.3$, $p < 0.05$). There was no main effect of cycling modality on peak MG amplitude ($F_{(1,11)} = 3.6$, $p > 0.05$). However, there was a main effect of cadence on peak MG amplitude ($F_{(5,55)} = 10.5$, $p < 0.05$). Peak MG amplitude increased with cadence in ECC ($F_{(2.5,27.8)} = 7.5$, $p < 0.05$) and CON ($F_{(1.8,19.5)} = 6.5$, $p < 0.05$). This increase was similar between ECC and CON as evidenced by a non-significant modality*cadence interaction effect ($F_{(5,55)} = 0.8$, $p > 0.05$).

5.4 Discussion

This investigation examined the differences in torque production, power output, and lower limb muscle activation during maximal eccentric and concentric isokinetic cycling and their changes over a range of cadences. For the first time, we present data showing 1) the relationship between pedal cadence, torque, and power output, which was similar between eccentric and concentric isokinetic cycling; 2) torque decreased linearly with cadence, and power increased in a parabolic fashion; 3) at equivalent cadences, the absolute peak torque was 1.4 – 2.1 times greater during ECC compared to CON; 4) peak torque occurred at smaller crank angles during ECC compared to CON whereas peak muscle activation (RF, VL, MG, BF) occurred at greater crank angles in ECC compared to CON; and 5) concentric cycling elicited greater peak muscle activation in the VL and BF.

As cadence increased, peak torque decreased in both ECC and CON. The gradient of this trend line was similar between groups (ECC, −1.0246; CON −1.2486) and is similar to the rate of torque decline previously described in concentric cycling (-1.016) (McCartney *et al.*, 1983). Additionally, in further agreement with our findings, multiple studies have observed a linear decline in torque with increasing cadences during concentric cycling (Capmal and Vandewalle, 1997; Dorel *et al.*, 2010; McCartney *et al.*, 1983; Seck *et al.*, 1995; Vandewalle *et al.*, 1987). Importantly, this is the first study to observe a similar relationship during eccentric cycling. Our observed eccentric torque-cadence relationship deviates from the classic *in-vitro* force-velocity, and the single joint *in-vivo* torque-velocity relationships. As contraction velocity increases, in-vitro force increases (Katz, 1939)] and individual joint torque marginally increases or remains constant (Carney *et al*., 2012; Chapman *et al*., 2005; Ghena *et al*., 1991; Kramer *et al*., 1993; Westing *et al*., 1988). Evidence of the opposite, i.e. decreasing joint torque as muscle lengthening velocity increases, is limited, although it has been observed in the elbow flexors (Colson *et al*., 1999). Although it is important to note that the range of lengthening is not uniform across these studies. Our findings clearly demonstrate a linear decrease in eccentric torque from slow cadences (20 rpm) to fast cadences (120 rpm), which is comparable to concentric cycling (McCartney *et al*., 1983), i.e. the torque-velocity relationship is inverse, linear and does not mirror the *in vitro* or isolated muscle *in vivo* torque-velocity relationship. This similarity between the ECC and CON torque-cadence relationships, combined with their distinctly different *in vitro* curves, suggests that this relationship is shaped by a technique dependant cycling factor rather than an intrinsic muscle characteristic associated specifically with either eccentric or concentric muscle actions (Bobbert *et al*., 2016; McDaniel *et al*., 2014).

Similar eccentric - concentric torque ratios to the current study have been observed during isolated knee extension; at 30, 150, and 270 deg·s^{-1} maximal knee extensor eccentric torque can exceed concentric torque by 1.2, 2.0 and 2.3 times, respectively (Kellis and Baltzopoulos, 1998; Westing *et al*., 1988). In absolute terms the torque observed in the current study exceeds that previously observed with eccentric (up to 299 N·m) and concentric (up to 237 N·m) muscle actions of the knee extensors (Pain *et al*., 2013; Westing *et al*., 1988). This is likely due to the cumulative contribution of multiple leg extensor muscles in the current study, compared to isolated knee extensors. However, when considered as a tangential force (crank length = 175 mm), peak ECC torque in the 20 rpm condition equates to ~2000 N which, given the body mass of the cohort, is approximately 2.6 times body weight, and similar to the force observed during maximal vertical jumping (Cuk *et al*., 2014). Although the contribution of the stretch shortening cycle to this force will differ between jumps and eccentric cycling. This highlights the potency of eccentric cycling as a potential training stimulus – the participant can achieve high levels of peak torque/force that are seen during maximal jumps, but in a more repetitive manner and a closed kinetic chain movement pattern.

At each cadence, peak power was higher in ECC compared to CON and this difference increased as cadence increased. Our observed peak eccentric power values are approximately twice that previously described by Brughelli *et al*. (2013). We speculate that such a discrepancy in torque could be due to the recumbent nature of the bike used in the current study which provides a fixed “backrest” to push against, thus potentially augmenting torque production, via increased torso stability, when compared with an upright bike. However, our observed concentric peak power values are similar to previous work in upright cycling (Martin and Spirduso, 2001). It is possible that the effect of a recumbent cycling position on power output might be different between eccentric and concentric cycling. Given the discrepancy in absolute torque production between modalities it is possible that the greater stability offered by a backrest might be more beneficial during eccentric cycling, however, further investigation would be required to determine if such an effect exists.

In agreement with previous literature, peak power during CON was greatest between 100-120 rpm (McCartney *et al*., 1983) – the peak of the parabolic relationship between cadence and power. In contrast, the parabolic trend line between peak power and cadence during ECC was still increasing at 120 rpm (our highest cadence used), which suggests the optimum cadence for power production occurs at higher cadences in eccentric cycling, and beyond the range studied here. Due to safety features on our cycle ergometer it was not possible to investigate cadences greater than 120 rpm. At cadences above 60 rpm, peak power was greater during ECC (~1900 W) compared to that attained at any cadence during CON (~1400 to 1500 W at 100 to 120 rpm). Therefore, if achieving peak power is the primary aim of a training session, maximal eccentric cycling at cadences above 60 rpm would provide a more potent stimulus (in terms of mechanical load to the lower limb) than maximal concentric cycling at any cadence.

The weakening correlation between ECC and CON peak torque as cadence increases indicates a potential divergence in the mechanisms of torque production. Greater differences in the crank angle at peak torque between ECC and CON at higher cadences also support the notion that mechanisms of torque production diverge (n.b.

Due to the isokinetic nature of the ergometer the angle at peak torque is equivalent to the angle at peak power). Additionally, eccentric torque production can display greater variability at higher cadences (Green *et al*., 2017), which suggests that the technical characteristics of eccentric cycling, such as muscle activation strategies, might limit torque production to a greater extent at faster cadences. Our data show that as cadence increases during ECC the crank angle of peak RF activation and peak torque converge. In contrast, as cadence increases during CON the crank angle of peak RF activation and peak torque diverge. This suggests the RF might play a more prominent role in torque production during eccentric, compared to concentric, cycling, especially at higher cadences. Furthermore, peak RF activation was similar between ECC and CON, whereas peak VL activation was greater in CON. This greater eccentric muscle activation in the RF (relative to the concentric equivalent) also indicates a greater role for the RF in eccentric cycling when compared with concentric cycling. Identification of lower limb kinematics would help to further elucidate muscle activation during eccentric cycling.

Although the crank angle of peak VL activation was greater during ECC compared to CON, when considered relative to the crank angle at peak torque it occurred earlier in the pedal cycle during both modalities. As cadence increased peak VL activation occurred progressively earlier than peak torque in both ECC and CON. This occurred due to peak torque occurring later in the pedal cycle as cadence increased in both ECC and CON (lesser and greater crank angles respectively due to the difference in pedal direction). This mirrors the findings of Bobbert *et al*. (2016) who observed that as cadence increased during concentric cycling muscle activation occurred earlier in the pedal cycle, relative to peak torque, to allow sufficient time for muscle de-activation to occur (muscle activation dynamics). Our observation of earlier VL activation relative to peak torque at higher cadences supports the theory that muscle activation dynamics might contribute to the decrease in torque at higher cadences during concentric cycling. Furthermore, our data suggests that similar muscle activation dynamics might also contribute to the decline in torque observed at greater cadences during eccentric cycling.

Also of note was the difference in the crank angle of peak activation between ECC and CON in the VL, RF, and MG. In the longer term these differences might affect the ability of the lower limb to express force at different crank angles, which should be considered when interpreting changes in torque or power after eccentric and concentric isokinetic cycling. With respect to the implications for training, it is possible that such differences in crank angles at peak activation might induce differing adaptations within the muscle. Improvements in strength after isometric knee extensor training can be specific to the angle utilised in training (Kitai and Sale, 1989). Also, increases in squat performance can be specific to the depth of squat utilised during training (Rhea *et al*., 2016). Therefore, when using isometric tests within task specific ranges of motion to examine the efficacy of an eccentric or concentric isokinetic cycling program it might be prudent to utilise a range of knee angles.

To conclude, maximal recumbent eccentric cycling elicits power output and torque that is approximately two-fold greater than that observed during concentric cycling. The shape of the torque-cadence and power-cadence relationships is similar between eccentric and concentric cycling. In contrast to previous *in-vivo* observations of the eccentric force-velocity profile, a linear decrease in torque occurs during eccentric cycling as movement velocity (cadence) increases. A very similar decrease is seen during concentric cycling which suggests the shape of this relationship is not controlled by the type of muscle contraction, at least in this closed-chain cycling movement pattern. Peak torque was elicited at lesser crank angles during eccentric cycling compared to concentric cycling, a difference that increased with cadence. Additionally, peak muscle activation occurred at greater crank angles during eccentric, compared to concentric, cycling, a difference that also increased with cadence. These differences in muscle stimulation should be considered when comparing these two exercise modalities or when utilising them for training as they might impact subsequent adaptation.

The overall aim of this thesis was to systematically investigate the neuromuscular responses and application to performance of a bespoke eccentric cycling instrument. The purpose of Chapter 5 was to investigate the stimulus provided by eccentric cycling over a range of cadences. Based on the results of this study it is clear that faster cadences offer a greater mechanical stimulus. However, these findings should be considered in combination with those of Chapter 4. Although faster cadences provide a greater mechanical stimulus, the greater technical proficiency required (Chapter 4) may be a prohibiting factor for prescription. This balance between mechanical stimulus and technical proficiency will inform the selection of cadence in future chapters. Additionally, this chapter has highlighted muscle activation patterns during eccentric cycling which will serve to facilitate the interpretation of acute (Chapter 6) and chronic (Chapter 7) responses. Lastly, the discrepancies in technique between eccentric and concentric cycling provide a greater understanding of the consequences of using concentric cycling as a control group in a prolonged period of eccentric cycling training.

CHAPTER 6

METABOLIC AND MECHANICAL RESPONSES TO INTERVAL AND CONTINUOUS ECCENTRIC CYCLING

6.1 Introduction

In Chapter 5 we demonstrated that eccentric cycling can provide a far greater mechanical stimulus to the lower limb compared to a concentric equivalent. However, little is known about the effect of workload distribution on the acute responses to eccentric cycling. During eccentric cycling, a motor drives the pedals towards the user, typically on a recumbent bike (Elmer *et al*., 2012). The cyclical nature of this exercise allows a high volume of eccentric contractions to be performed in a relatively short timeframe compared to other modes of eccentric training. Eccentric cycling has been shown to improve CMJ height, SJ height, peak concentric cycling power, and isometric knee extensor strength after 6 – 8 weeks of training (Elmer *et al*., 2012; Gross *et al*., 2010; Lastayo *et al*., 2000; Leong *et al*., 2013). The duration of these eccentric sessions varied between 5 – 30 minutes and eccentric cycling was generally performed as a single continuous bout with a constant target power output. Gross *et al* (2010) employed a target power output that varied irregularly and continuously and observed improvements in CMJ in elite junior level skiers after 6 weeks of training. Additionally, in Chapter 5 it was demonstrated that eccentric cycling can produce high levels of mechanical tension when performed maximally and it has recently been shown that perceived enjoyment is similar between interval and continuous eccentric cycling (Lipski *et al*., 2018). Therefore, in order to provide a greater mechanical stimulus it may be advantageous to perform eccentric cycling as a series of high intensity intervals as opposed to a continuous lower intensity bout.

Compared to a constant workload session, prescribing eccentric cycling as a series of intervals can increase metabolic load (Lipski *et al*., 2018). Despite an increase in metabolic load during shorter, higher intensity intervals, $\dot{V}O_2$ still remains relatively low during interval eccentric cycling (< 60% of $\dot{V}O_{2peak}$, Lipski *et al*., 2018). This highlights that eccentric cycling can provide a large mechanical stimulus for a low metabolic cost (Peñailillo *et al*., 2014). However, it is unclear how changes in session intensity or structure affect post-session fatigue and recovery. Continuous eccentric cycling between 8 – 30 min in duration can cause an immediate reduction in SJ height, CMJ height, isometric knee extensor force, and concentric cycling power output (Elmer *et al*., 2010b; Peñailillo *et al*., 2013), and can persist for several days post exercise (Elmer *et al*., 2010b). Although, this can be reduced when participants are familiarised to eccentric cycling (Peñailillo *et al*., 2013). Muscle soreness and muscle damage have also been shown to increase in the 24 – 48 hrs following eccentric cycling (Peñailillo *et al*., 2013). However, it is unclear if altering the distribution of work done within a session (i.e. continuous or interval) affects the magnitude or duration of fatigue, muscle damage and muscle soreness following eccentric cycling.

Using eccentric contractions of the biceps brachii no difference in post-session central or peripheral fatigue was observed between low intensity and high intensity training (Gauche *et al*., 2009). However, no work has yet examined the aetiology of fatigue after eccentric cycling. After concentric cycling lower limb fatigue has been apportioned to a reduction in the contractile capability of the muscle (peripheral fatigue) and an inability to voluntarily activate (centrally derived fatigue) the muscle (Bentley *et al*., 2000; Theurel and Lepers, 2008; Thomas *et al*., 2015). When power output is varied during concentric cycling (50 – 200% MAP) greater decrements in voluntary activation and peak doublet force have been observed post session compared to a continuous bout (70% MAP, Theurel *et al*., 2008b), which was indicative of greater central and peripheral fatigue, respectively. However, when power output is only varied by ± 15% (of constant workload), then no difference in central or peripheral fatigue were observed compared to a continuous session (Lepers *et al*., 2008). Understanding the aetiology of reductions in force generating capacity after eccentric cycling, and the effect of structuring the session as interval or continuous training is critical in understanding how best to utilise eccentric cycling as a training modality. Therefore, the aim of this study was to determine the effect of session structure on the contributors to ECC-induced strength loss following a single bout of eccentric cycling and how this might affect the time course of recovery. It was hypothesised that structuring eccentric cycling in an interval manner would increase strength loss post exercise and increase recovery time compared to a work matched continuous bout. This work addresses the third aim of this thesis, to examine the effect of session structure, i.e. intervals or a continuous bout of eccentric cycling, on the metabolic and mechanical strain during exercise and the fatigue and muscle damage response post exercise. Addressing this aim will provide data with which to facilitate the decision to use interval or continuous eccentric cycling in Chapter 7.

6.2 Methods

6.2.1 Participants

Fourteen recreationally active males (interval; n = 7, mean ± SD; age = 23 ± 3 years; body mass = 78.4 ± 7.1 kg; stature = 181 ± 5 cm, continuous; n = 7, mean ± SD; age = 25 ± 6 years; body mass = 78.9 ± 5.6 kg; stature = 182 ± 6 cm) unaccustomed to eccentric cycling and with no history of lower limb injuries or neurological disorders volunteered to undertake this investigation. All participants provided written, informed consent and were deemed healthy as determined by a physical activity readiness questionnaire. Ethical approval was granted prior to the start of all procedures by the Northumbria University Faculty of Health and Life Sciences Ethics committee, in accordance with the Declaration of Helsinki.

6.2.2 Experimental design

Participants attended the laboratory on seven separate occasions in a rested state, having been asked to avoid exercise, caffeine and alcohol in the preceding 24 hrs (Figure 6.1). During two preliminary visits, participants completed a laboratory-based cycle ergometer test to determine $\dot{V}O_{2peak}$ and MAP (visit 1), and undertook two eccentric cycling familiarisation sessions (visits 1 and 2). Participants were then split into two groups, matched for MAP (n = 2 × 7), and performed a session of either interval (INT) or continuous (CONT) eccentric cycling (visit 3). To compare the time course of recovery after INT and CONT exercise, neuromuscular fatigue and serum creatine kinase concentration ([CK]) were measured pre, immediately post, and 24, 48 and 72 hours post exercise. Additionally, perceived leg soreness was recorded 24, 48 and 72 hours post exercise. In the final laboratory session (visit 7) participants completed the eccentric cycling session they had not undertaken in visit 3. This was in order to compare the within session demands between INT and CONT in a repeated measures cross over design. Recovery was not assessed after this second bout of eccentric cycling as it was considered more appropriate to compare recovery using an independent measures design to remove any confounding influence of the repeated bout effect.

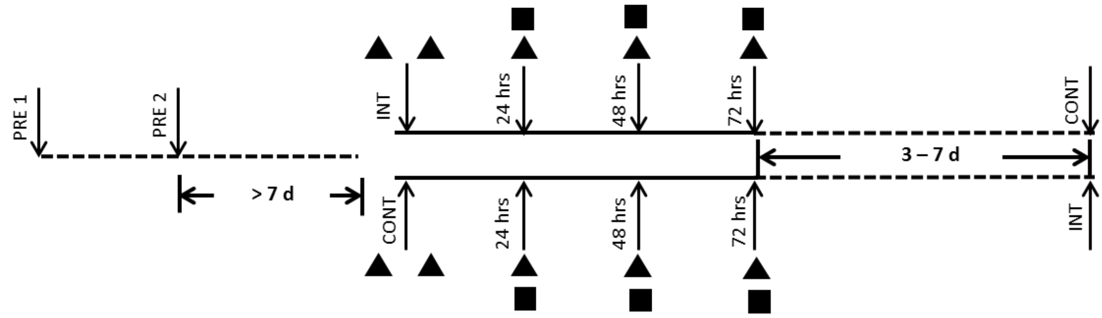


Figure 6.1. Schematic overview of the study. Filled triangles (▲) represent assessments of neuromuscular fatigue and serum [CK]. Filled squares (■) represent assessment of perceived muscle soreness.

6.2.3 Protocol

Incremental cycle test

The $\dot{V}O_{2peak}$ was determined by a continuous incremental cycling ramp test to volitional exhaustion on an electro-magnetically braked cycle ergometer (Schoberer Rad Messtechnik [SRM], Germany). After a 10 min warm-up at 100 W the power output was increased by 30 W per minute (5 W every 10 s) until volitional exhaustion or a drop of > 10 rpm in cadence. Maximum aerobic power was defined as the highest average power output achieved during a 60 s epoch. Breath-by-breath gas exchange data was quantified via the method described in Chapter 3. Respiratory gases were measured throughout the maximal cycling assessment test, with $\dot{V}O_{2peak}$ defined as the greatest continuous sample of O_2 averaged over 30 s.

Familiarisation trials

All eccentric cycling was conducted on an eccentric ergometer described in Chapter 3. Following the $\dot{V}O_{2\ peak}$ test a 15 min rest period was observed prior to a 5 minute bout of ECC cycling at 80% MAP and 60 rpm. The second familiarisation (visit 2) consisted of 10 min continuous ECC cycling (80% MAP) followed by 2 × 2 min (120% MAP) of interval based eccentric cycling with one minute recovery. These familiarisation sessions where undertaken so that the subsequent muscle damage response was comparable to that which would be expected if regularly partaking in eccentric cycling. They also served to minimise the difference in metabolic demand between the two experimental bouts of eccentric cycling, which can occur in un-familiarised individuals (Peñailillo *et al*., 2013).

Experimental trials

During two separate experimental trials, participants completed 30 min of continuous eccentric cycling (CONT) or 30 min of interval eccentric cycling (INT), which consisted of 10 × 2 min repetitions with 1 min passive recovery. In order to match the sessions for work done the CONT session was conducted at 80% MAP and the INT session at 120% MAP. Pilot work suggested that 80% MAP was a realistic training intensity for the cohort to achieve and is above that considered sustainable during concentric cycling (Peñailillo *et al*., 2013), thus utilising the greater power output attainable during eccentric cycling, which was observed in Chapter 5. During recovery, the ergometer was stopped and no work was done. Throughout each session cadence was set to 60 rpm to maximise reliability of power output and muscle activation as determined in Chapter 4. Capillary blood samples, as described in Chapter 3, were obtained at 5 minute intervals throughout each exercise session to measure blood lactate concentration [La]. Ratings of perceived exertion were also collected at 5 min intervals using the Borg RPE 6-20 scale (Borg, 1982). Respiratory gasses were measured throughout as previously detailed in Chapter 3.

Surface electromyography

Surface electromyography protocols are described in Chapter 3. Though, in brief, two, 20 mm diameter, electrodes (Ag/AgCl; Kendall 1041PTS, Covidien, Mansfield, MA, USA) with an inter-electrode distance of 20 mm were placed on the muscle of interest according to the SENIAM guidelines for EMG placement (Hermens *et al*., 2000). The muscles used for analysis in this chapter were RF and VL. Prior to the start of each experimental training session participants completed three, 5 s maximal voluntary isometric knee extensions of the right leg on a custom built isometric rig. Isometric knee extensions were performed at a knee angle of 90° (separated by 3 mins). Using a 200 ms root-mean–square (RMS) window, the maximum sEMG activity from the three MVC efforts for each muscle was used to obtain a reference value for normalization purposes. Muscle activation throughout each session was calculated as the average RMS value for each 10% section of work done (i.e. 3 min time period).

Femoral nerve stimulation

The peripheral nerve stimulation protocol and data analysis methods are described in detail in Chapter 3. On average peripheral nerve stimulation was initiated ~ 1min after the cessation of exercise. All sEMG parameters were determined from the VL.

Muscle soreness

Participants were asked to complete a squat to a knee angle of 90^{o} and rate perceived muscle soreness on a 200 mm visual analogue scale (Goodall and Howatson, 2008). The scale consisted of a line from 0 mm (no pain) to 200 mm (unbearably painful).

Creatine kinase

An 8 mL venous blood sample was taken from the antecubital vein and treated with a clot accelerator before clotting at room temperature. The sample was centrifuged at 1,500g for 10 min at 5°C and serum was drawn and frozen immediately at –35^{o}C. Serum samples were analyzed in triplicate for [CK] by use of a commercial kit applied in a multi-analyzer system (RX Daytona, Randox, Co. Antrim, UK, 2.5 % CV).

Statistical analyses

Statistical testing was performed using SPSS 24 (IBM, New York, USA). Mean responses during exercise were compared between groups using a paired samples t-test ($\dot{V}O_2$, RER, time under tension (TUT), average torque, lactate, RPE, and RF and

VL activation). To examine the degree of similarity between groups in the independent measures design, work done and all baseline recovery measures were compared using independent samples t-tests. Neuromuscular and creatine kinase responses were compared between experimental groups using a 5 × 2 mixed model ANOVA (Time: PRE, POST, 24, 48, 72 hrs, and group: INT, CONT) with a focus on the interaction effect to determine whether session structure had an effect on fatigue and recovery. A 3 × 2 mixed model ANOVA was used to compare muscle soreness between groups (Time: 24, 48, 72 hrs, and group: INT, CONT). To assess the effect of eccentric cycling on all measures, pre-planned a-priori paired t-tests were performed on within group data and combined CONT and INT data (PRE v POST, 24HRS, 48HRS, and 72HRS). All pairwise comparisons were corrected for multiple comparisons using a Bonferroni adjustment. Significance was set at an alpha level of 0.05. Greenhouse-Geisser corrections were applied to significant F-ratios that did not meet Mauchly's assumption of sphericity. All results are presented as mean ± standard deviation.

6.3 Results:

Exercise responses

As intended, the prescribed sessions resulted in a similar work done between experimental groups (n = 14; INT, 473 ± 71 kJ; CONT, 478 ± 69 kJ). Total time under tension was 48% greater in CONT (983 ± 142 s) compared to INT (664 ± 131 s, $p < 0.001$), whereas average torque production during cycling (excluding rest periods) was greater during INT compared to CONT (56 ± 13 N·m vs. 40 ± 9 N·m, $p < 0.001$; Figure 6.2). Greater physiological strain was observed during INT compared to CONT by means of increased average $\dot{V}O_2$ (% of $\dot{V}O_{2peak}$, 32.0 ± 5.9% vs. 28.4 ± 5.6%, $p < 0.001$), blood [La] (1.0 ± 0.4 vs. 0.8 ± 0.2 mmol·L^{-1}, $p < 0.001$), and RPE (12 ± 1 vs. 11 ± 1, $p < 0.001$). Respiratory exchange ratio was similar between INT (0.87 ± 0.05) and CONT (0.86 ± 0.07) ($p > 0.05$) and average RF and VL activation was greater during INT compared to CONT (12.9 ± 5.4% vs. 9.7 ± 5.2%, $p < 0.05$ and 13.7 ± 5.9% vs. 11.3 ± 4.6%, $p < 0.05$ respectively). Total work done within the session was also similar between the independent recovery groups, which were subsequently utilised for the determination of fatigue and recovery (n = 2 × 7; INT, 466 ± 79 kJ vs. CONT, 485 ± 71 kJ; $p > 0.05$).

Neuromuscular function

All neuromuscular measures are presented in Table 6.1. There were no differences between experimental groups for baseline measures of neuromuscular function. Eccentric cycling resulted in significant peripheral fatigue (reductions in $Q_{tw,pot}$), central fatigue (reductions in VA) and alterations in muscle contractility immediately post exercise (Table 6.1). There was a decrease in MVC_{rms} and membrane excitability during the MVC and potentiated twitch (M_{max} area and M_{max} amplitude) post exercise. There was an interaction effect of time and session structure on peripheral fatigue as $Q_{tw,pot}$ reduced to a greater extent after INT compared to CONT ($F_{(4, 48)} = 4.9$, $p < 0.05$, actual power = 0.95). Furthermore, *post-hoc* analysis revealed that the time course of $Q_{tw,pot}$ recovery was greater after INT (48 hrs) compared to CONT (24 hrs). All other measures of neuromuscular function and muscle contractility had returned to baseline by 24 hrs.

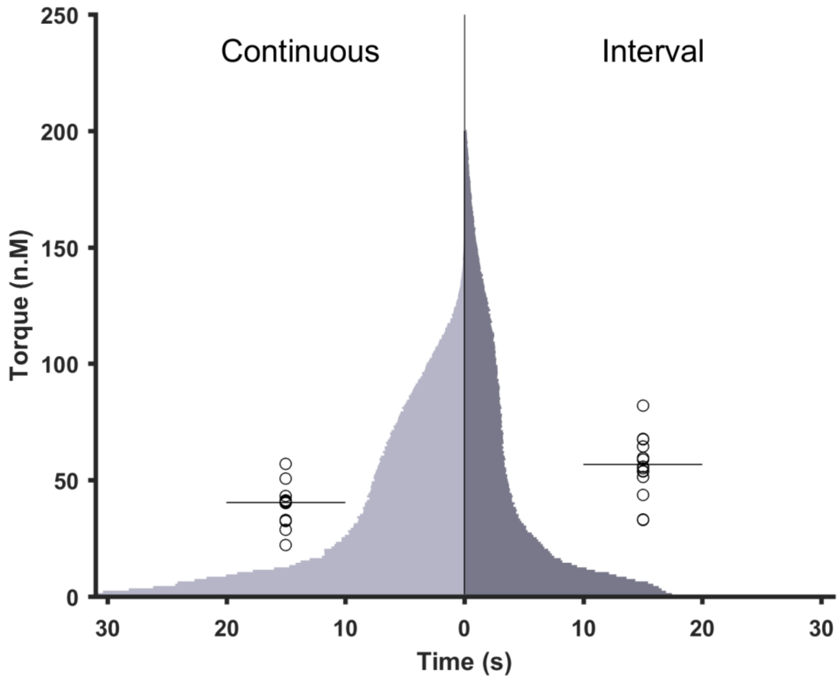


Figure 6.2. Average torque during time spent cycling for each participant (○) during INT (20 min) and CONT (30 min). Shaded areas represent a histogram of time spent at different levels of torque during cycling for INT (dark grey) and CONT (light grey). Values are for the left leg only (n = 14).

Muscle soreness

There was a significant interaction effect of session structure and time on muscle soreness after eccentric cycling ($F_{(2, 24)} = 5.3$, $p < 0.05$). Between 24 – 48 hrs post exercise muscle soreness increased to a greater extent post-INT compared to post-CONT (+3.3 ± 2.9 cm and -0.4 ± 1.7 cm respectively). Thereafter (48 – 72 hrs), muscle soreness reduced in both INT and CONT (−4.2 ± 2.7 cm and −3.0 ± 1.7 cm respectively). Overall muscle soreness peaked at 48 hrs after INT (8.4 ± 4.5 cm) and 24 hrs after CONT (4.7 ± 1.9 cm, Figure 6.2).

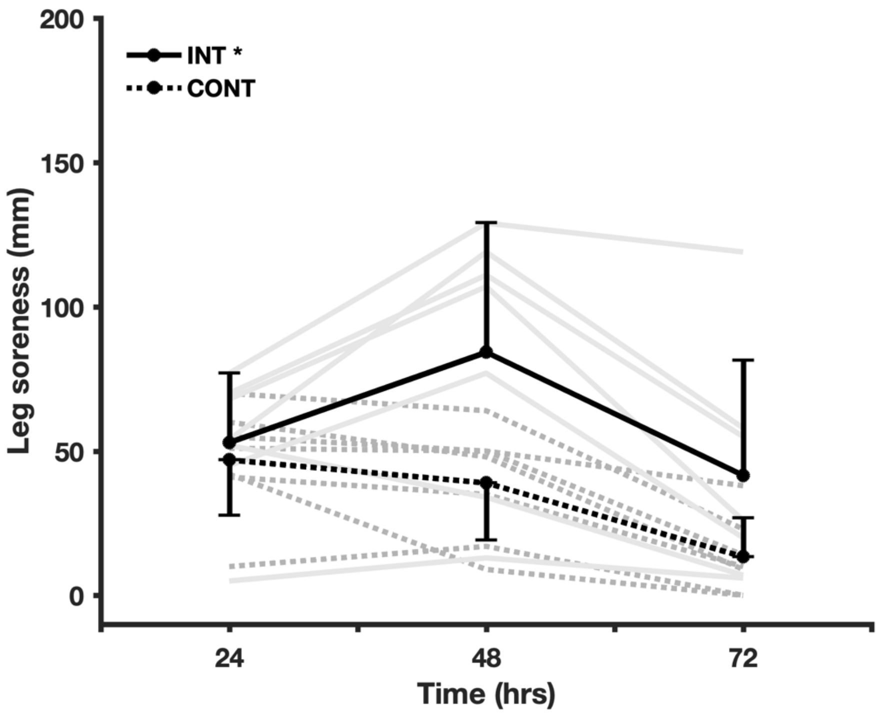


Figure 6.3. Muscle soreness at 24, 48, and 72 hours post interval (INT) and continous (CONT) eccentric cycling, asseseed using a 200 mm visual analogue scale. * denotes significant INT × CONT interaction effect p < 0.05.

Table 6.1. Neuromuscular responses to interval (INT) and continuous (CONT) eccentric cycling.

		Baseline	Post	24hrs	48 hrs	72 hrs
Global fatigue						
MVC (N)	INT	660 (160)	537 (163)* †	608 (194)	653 (204)	683 (209)
	CONT	686 (59)	596 (82)*	673 (94)	697 (89)	693 (88)
Peripheral fatigue						
$Q_{tw,pot}$ (N)	INT **	178 (49)	122 (42)* †	152 (44)* †	187 (52)	182 (52)
	CONT	181 (25)	148 (31)*	170 (26)	184 (31)	181 (23)
MRFD ($N \cdot ms^{-1}$)	INT	5.22 (1.68)	3.57 (1.69) †	4.52 (1.95)	5.66 (2.30)	5.31 (1.91)
	CONT	5.61 (1.64)	4.71 (1.34)	5.18 (1.45)	6.21 (1.93)	6.11 (1.81)
CT (ms)	INT	82 (3)	68 (4)* †	80 (3)	82 (4)	80 (5)
	CONT	81 (9)	71 (5)	82 (5)	82 (8)	87 (9)
MRR ($N \cdot ms^{-1}$)	INT **	-2.08 (0.79)	-1.98 (0.69)	-1.82 (0.69)	-2.15 (0.80)	-1.94 (0.77)
	CONT	-1.89 (0.30)	-2.38 (0.55)	-1.76 (0.29)	-1.89 (0.38)	-1.83 (0.22)
$RT_{0.5}$ (ms)	INT	68 (15)	44 (8)* †	63 (13)	65 (15)	75 (9)
	CONT	77 (12)	43 (6)*	77 (11)	77 (12)	80 (7)
Central fatigue						
VA (%)	INT	90 (3)	81 (13) †	89 (5)	91 (5)	91 (5)
	CONT	90 (5)	85 (12)	90 (7)	90 (9)	90 (7)
Surface EMG (vastus lateralis)						
Resting responses						
M_{max} amplitude (mV)	INT	7.26 (4.45)	5.19 (3.72)* †	5.65 (3.10)	6.40 (2.59)	6.03 (3.05)
	CONT	5.44 (3.15)	4.84 (3.28)*	5.43 (3.98)	5.11 (3.02)	4.69 (3.00)
M_{max} area ($\mu V \cdot s^{-1}$)	INT	49.8 (25.1)	33.4 (19.4)* †	40.1 (20.0)	44.6 (14.7)	44.0 (17.2)
	CONT	41.7 (22.0)	32.0 (18.7)*	43.3 (28.9)	39.8 (19.7)	37.8 (21.0)
During MVC						
MVC_{RMS} (mV)	INT	0.37 (0.16)	0.25 (0.09)* †	0.30 (0.11)	0.34 (0.11)	0.33 (0.13)
	CONT	0.43 (0.24)	0.27 (0.11)	0.45 (0.35)	0.32 (0.18)	0.30 (0.20)
M_{max} amplitude (mV)	INT	6.86 (3.54)	4.68 (3.11)* †	5.06 (2.29)	5.99 (1.91)	5.85 (3.13)
	CONT	5.10 (1.43)	4.27 (1.93)	4.95 (2.12)	4.91 (2.07)	4.32 (2.07)
M_{max} area ($\mu V \cdot s^{-1}$)	INT	51.8 (21.4)	33.5 (14.4)* †	39.6 (15.3)	46.5 (15.8)	43.6 (16.3)
	CONT	40.0 (12.6)	31.1 (13.2)*	39.5 (20.0)	37.5 (13.1)	34.2 (14.5)

** session structure × time interaction effect.

* difference from baseline, within group.

† difference from baseline, INT and CONT groups combined.

Creatine kinase

Creatine kinase levels are shown in Table 6.2. There was no significant interaction effect of session structure and time on CK levels ($F_{(2.0, 24)} = 0.7$, $p > 0.05$). Nor was there an overall effect of session structure ($F_{(1, 12)} = 0.1$, $p > 0.05$) on CK levels. Paired t-tests revealed no difference from baseline values to all subsequent time points for pooled group data ($p > 0.05$).

Table 6.2. Serum creatine kinase concentrations pre, post, and 24, 48, and 72 hrs post, interval (INT) and continuous (CONT) eccentric cycling sessions.

	[CK] (IU·L^{-1})				
	Baseline	**Post**	**24 hrs**	**48 hrs**	**72 hrs**
INT	190 ± 104	206 ± 111	243 ± 159	172 ± 75	149 ± 59
CONT	197 ± 128	197 ± 112	190 ± 78	160 ± 68	147 ± 46

6.5 Discussion

The aim of the present study was to examine the effect of structuring eccentric cycling as either an interval or continuous session on subsequent neuromuscular fatigue, muscle damage, and muscle soreness. Despite a greater time under tension during continuous eccentric cycling the interval session caused greater peripheral fatigue and muscle soreness. These data indicate that during eccentric cycling absolute mechanical tension had a greater influence on post exercise fatigue and muscle soreness than total time under tension. Furthermore, we have highlighted that with the appropriate familiarisation, greater power outputs can be achieved during eccentric cycling (compared to concentric cycling) with only small increases in muscle soreness and a negligible CK response. Although, despite the inclusion of two familiarisation sessions, muscle function can take up to 48 h to recover after interval eccentric cycling. Collectively, these data suggest that interval eccentric cycling causes a greater reduction in muscle function and increases recovery time compared to a continuous session.

Total work done and all baseline neuromuscular variables (Table 6.1) were similar between the INT and CONT exercise groups, demonstrating effective matching. Furthermore, levels of voluntary activation pre-exercise were consistent with previous research using the same twitch technique indicating that participants arrived in a rested state for testing (Brownstein *et al*., 2017; Thomas *et al*., 2015). In agreement with previous studies, eccentric exercise produced subsequent reductions in MVC, peripheral muscle contractility, and VA (Goodall *et al*., 2017; Prasartwuth *et al*., 2006, 2005). These data demonstrate that fatigue following interval and continuous sub-maximal eccentric cycling results from reductions in both the central and peripheral components that modulate muscle contractility. The overall decrease in knee extensor MVC immediately post exercise (17%) is consistent with that observed after a similar eccentric cycling protocol (~19%; Penailillo *et al*., 2013). Although the magnitude of these decreases is likely modulated by the number of familiarisation trials (Peñailillo *et al*., 2013).

Peripheral fatigue was greater compared to central fatigue after both INT and CONT sessions which is consistent with previous research examining fatigue after eccentric exercise (Goodall *et al*., 2017; Prasartwuth *et al*., 2005). Our data indicate that reductions in peripheral contractility might partially result from changes in sarcolemma excitability as demonstrated by a reduction in maximal M-wave. Proske and Allen (2005) suggest that sarcolemma disruption can occur following eccentric exercise due to an accumulation of mechanically damaged sarcomeres (z-band streaming). However, M-wave was depressed only immediately post exercise whereas muscle function remained suppressed at 24 h. Therefore, whilst decreased sarcolemma excitability might contribute to peripheral muscle fatigue immediately following eccentric exercise it is unlikely to be the primary mediator of prolonged muscle function impairment (Sayers *et al*., 2003). It is likely that peripheral fatigue observed in the current study stems from non-sarcolemma related impairment of the excitation-coupling process (Corona *et al*., 2010; Warren *et al*., 2001) or sarcomere disruption (Lauritzen *et al*., 2009; Proske and Morgan, 2001), both resulting from high mechanical tension.

Interval eccentric cycling induced greater peripheral fatigue (reduction in $Q_{tw,pot}$) compared to the continuous session. Similar effects of session structure have been observed after concentric cycling where varying power output increased fatigue and recovery time compared to an even paced session (Theurel and Lepers, 2008). It has been suggested that the greater fatigue after a variable concentric workload could be due to increased metabolite accumulation, greater RPE, or increased muscle tension (Theurel and Lepers, 2008). However, due to the relatively low metabolic stress that eccentric cycling elicits in comparison to concentric work (Peñailillo et al., 2017a), we consider metabolite accumulation an unlikely candidate for reductions in force producing capacity between groups. This is substantiated by the low [La] and $\dot{V}O_2$ throughout the exercise in both groups (< 1.5 $mmol \cdot L^{-1}$ and < 40% $\dot{V}O_2$ peak, respectively). Given the low metabolic cost and the relatively short exercise duration it is also unlikely that glycogen depletion contributed to fatigue. More likely, the discrepancy in fatigue between groups is due to the increased muscle tension generated during the interval session and a subsequent increase in sarcomere disruption (although this does not seem extensive given the low CK and modest soreness). Conversely, it would appear that the greater time under tension observed during CONT did not increase post-exercise force reduction or recovery time.

Recovery of $Q_{tw,pot}$ to baseline took longer after INT (48 hrs) compared to CONT (24 hrs). This corresponds with the recovery time frame previously observed after pre-familiarised eccentric cycling of 30 min at a similar intensity (Peñailillo *et al*., 2013). Although, the precise time frame of recovery from eccentric cycling is likely dependent on intensity, duration, and number of familiarisations (Peñailillo *et al*., 2013). Muscle soreness was only elevated following INT and achieved its peak 48 h post exercise, despite the recovery of muscle function at this time point. This dis-connect between muscle function and DOMS is a common finding that substantiates the idea that there is a poor relationship between the two (Cleak and Eston, 1992; Nosaka et al., 2002). It is possible that the greater levels of muscle tension observed during an interval workload distribution contributed to the increased perceived leg soreness in the 72 hours after eccentric cycling. Of note, however, relatively modest levels of muscle soreness were observed and are in agreement with those previously observed after 30 minutes of eccentric cycling (0 – 30%, 10 mm VAS; Penailillo *et* *al*., 2013). Such findings suggest that eccentric cycling can be used as a training modality without considerably high levels of DOMS when the participants are familiarised and some RBE is conferred. Furthermore, despite the potential limitations of traditional blood borne indices of damage, the absence of elevations of CK indicates a low degree of muscle damage, which further highlights the feasibility of this training modality to provide a relatively high mechanical load, with little consequences.

In conclusion, our data indicate that fatigue following eccentric cycling consists of both central and peripheral factors. An interval session structure exacerbates peripheral fatigue and muscle soreness compared to a work matched continuous bout, which is likely due to increased muscle tension. Recovery time is greater following INT eccentric cycling and should be considered when prescribing eccentric cycling. The decision to prescribe interval based eccentric cycling, and therefore a greater absolute mechanical stimulus, should be weighed against the greater fatigue and muscle soreness it induces. If time under tension is considered a priority then a continuous session structure should be adopted. The aim of this thesis was to systematically investigate the neuromuscular responses and application to performance of a bespoke eccentric cycling instrument. This chapter aimed to examine the effect of session structure, i.e. intervals or a continuous bout of eccentric cycling, on the metabolic and mechanical strain during exercise, and the fatigue and muscle damage response post exercise. The results of this chapter indicate that changing the structure of an eccentric cycling session can alter the subsequent acute neuromuscular responses. An interval session structure causes greater disruption to muscle function (compared to a continuous structure) and therefore could be expected to elicit greater adaptation over a prolonged period of training. This data provides rationale for the use of an interval based eccentric cycling session over a continuous session during the training study in Chapter 7.

CHAPTER 7

A PILOT INVESTIGATION INTO THE EFFECT OF 8-WEEKS ECCENTRIC CYCLING INTERVAL TRAINING ON LOWER LIMB STRENGTH AND RUNNING ECONOMY IN TRAINED DISTANCE RUNNERS

7.1 Introduction

This thesis has demonstrated that eccentric cycling can provide high levels of mechanical tension in the lower limb for a lower metabolic cost than concentric cycling. It has also been shown that high intensity interval-based eccentric cycling can expose the lower limb to greater absolute levels of tension compared to a work matched continuous session. Previous research has shown that 6 - 7 weeks of steady state eccentric cycling can increase leg stiffness and countermovement jump performance (Elmer *et al.*, 2012; Gross *et al.*, 2010). In Chapter 6 we demonstrated that interval based eccentric cycling can induce a greater post-exercise reduction in muscle function compared to a continuous session, likely as a result of greater within-session mechanical tension. This provides evidence that interval based eccentric cycling can provide a greater stimulus for MTU adaptation and might further increase the enhancement of SSC function previously observed after continuous eccentric cycling.

The function of the stretch shortening cycle is a critical component of running locomotion. The ability of the lower limb musculature to produce impulse and then store and return elastic energy with each foot strike is a key component of running economy (Arampatzis *et al.*, 2006), which in turn is a key determinant of distance running performance (Bassett *et al.*, 2000; Ingham *et al.*, 2008). Therefore, interventions effective at increasing running economy in well trained distance runners are coveted by athletes and practitioners. A commonly used intervention to enhance running economy is the prescription of high velocity stretch shortening cycle plyometric exercises (Barnes and Kilding, 2014; Spurrs *et al.*, 2003). However, plyometric interventions are accompanied by large weight-bearing impact forces that might increase the risk of lower limb injury; a common problem in distance runners (Van Gent *et al.*, 2007). Chapter 6 demonstrated that eccentric cycling is both low in metabolic cost and impact force, yet can be implemented with negligible increases in muscle damage. This could make eccentric cycling a suitable low-risk addition to a distance running training programme. Eccentric training has previously been used in an attempt to enhance running economy following an 8 week downhill running intervention, but with no observable effect (Shaw *et al.*, 2018). Eccentric cycling provides a greater, more eccentric-specific, stimulus compared with downhill running and thus might have a greater effect on SSC function.

The overall purpose of this chapter was to determine the efficacy of eccentric cycling for improving performance in a group of well-trained athletes. More specifically, the aim of this study was to examine the effect of an 8-week training programme of interval based eccentric cycling on running economy, stretch shortening cycle function, and lower limb strength in well-trained distance runners. It was hypothesised that eccentric cycling would improve running economy, eccentric quadriceps strength, and jump performance compared to a control group performing habitual training.

7.2 Methods

7.2.1 Participants

Twenty-one healthy male distance runners initially volunteered to take part in the current investigation (Figure 7.1). Five athletes withdrew due to injury (one directly related to the intervention) and a further two exercised their right to withdraw without reason. The characteristics of the 14 athletes that completed the study were; age: 32 ± 8 years; stature: 183 ± 9 cm; body mass: 72.3 ± 9.1 kg; $\dot{V}O_{2peak}$: 64.2 ± 6.0 mL·kg-1·min^{-1}; 5 km seasons best: 17 min 56 s ± 66 s. Ethical approval for the study was obtained from Northumbria University research ethics committee and all participants provided written informed consent. The study adhered to the guidelines set out by the World Medical Association Declaration of Helsinki.

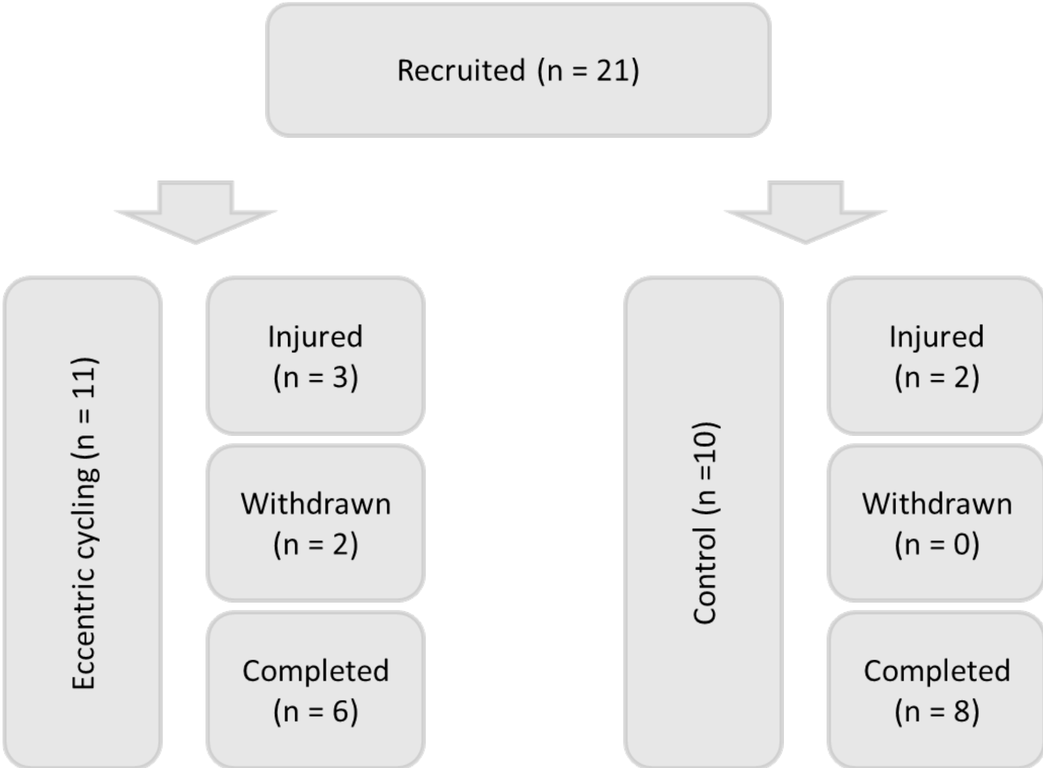


Figure 7.1. Schematic of participant recruitment in the eccentric cycling and control group. Withdrawn represents a participant removing themselves from the study for any reason other than injury. One injury was a result of the eccentric cycling training.

7.2.2 Experimental design

Participants were pair-matched based upon 5 km 'season's best' and assigned to either the control or intervention group. Six individuals completed the eccentric cycling intervention (INT) and eight individuals completed the control group (CON). The intervention group completed an 8-week progressive eccentric cycling programme and the control group maintained habitual training for the same duration. Total training load was monitored throughout in both groups using self-report training diaries. Pre and post the 8-week training period, participants visited the lab on three occasions to perform maximal and sub-maximal running assessments, jump testing, and eccentric and concentric strength testing (Figure 7.2). Participants were asked to refrain from alcohol, caffeine and heavy training in the 24 hour period prior to all testing sessions.

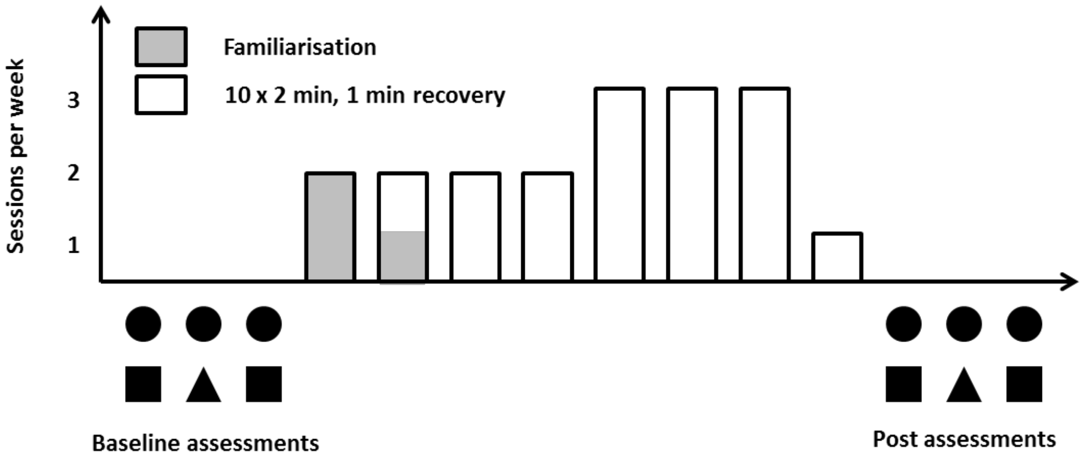


Figure 7.2. Experimental protocol of the study. Grey and open bars represent standardised familiarisation and training sessions respectively. Familiarisation sessions were: 1) 3×2 min at 3.5 W·kg^{-1}, 1 min rest, 2) 4×2 min at 4.5 W·kg^{-1}, 1 min rest, and 3) 10×2 min at 3.5 W·kg^{-1}, 1 min rest. Circles represent jump assessments; squares represent strength assessments; triangles represent running assessments.

7.2.3 Protocol

Sub maximal running assessment

After a 10 min self-selected warm up (~9-12 km·h^{-1}) participants completed a submaximal treadmill test consisting of six to eight stages of 3 minutes continuous running interspersed with 30 s rest for blood lactate sampling. The speed of the treadmill (HP cosmos Saturn, Traunstein, Germany) was increased by 1 km·h^{-1} at the start of each stage and the starting speed was determined using the heart rate response during warm up to ensure each participant completed ~4 speeds prior to the lactate turn point (LTP). First lactate threshold (LT) was defined as the first rise in blood lactate of any concentration above baseline and LTP was defined as the running speed above which blood lactate increased by > 1 mmol·L^{-1} per stage (Thoden, 1991). Throughout the test a gradient of 1% was maintained to reflect the energetic cost of outdoor running (Jones and Doust, 1996). Heart rate (FT1, Polar, Kempele, Finland) and pulmonary gas exchange (detailed in Chapter 3) were monitored throughout the pre and post running assessments.

Running economy was calculated from $\dot{V}O_2$ and $\dot{V}CO_2$ during the final minute of each submaximal stage. Substrate utilisation ($g \cdot min^{-1}$) was estimated using non-protein respiratory quotient equations (Peronnet and Massicotte, 2016). The energy derived from each substrate was then calculated by multiplying fat and carbohydrate usage by 9.75 kcal and 4.07 kcal, respectively, reflecting the mean energy content of the metabolised substrates during moderate to high intensity exercise (Jeukendrup and Wallis, 2005). Energy cost was quantified as the sum of these values, expressed in $kcal \cdot km^{-1}$. The average running economy for the four speeds prior to LTP was used for analysis. This method of determining running economy has been reported as both reliable (typical error 2.74%, Shaw *et al*., 2013) and valid (Shaw *et al*., 2014).

Maximal running assessment

$\dot{V}O_{2peak}$ was determined by a continuous incremental treadmill ramp test to volitional exhaustion. Treadmill speed was fixed at 2 $km \cdot h^{-1}$ below the final speed of the submaximal test and the initial gradient was set at 1%. Each minute, the gradient was increased by 1% until volitional exhaustion. The test duration was typically 5-8 minutes.

Eccentric and concentric strength assessment

Unilateral maximal voluntary isokinetic eccentric and concentric strength of the dominant knee extensors and flexors were measured using an isokinetic dynamometer (*ISOCOM® dynamometer*, Eurokinetics Limited, UK). Participants sat with a knee and hip joint angle of 1.57 rad (90^o) and the anatomic zero was set up at a knee angle of 3.14 rad. Extraneous movement of the upper body and the involved leg was limited by two crossover shoulder harnesses, a lap belt, a thigh strap, and an ankle cuff. The transverse axis of the knee joint was aligned with the dynamometer's power shaft. The length of the lever arm was individually determined and kept consistent across all laboratory sessions. Gravity corrected force was calculated by the on-board dynamometer software based upon lever arm length and torque data. Familiarisation trials were performed at 50, 65, 80, and 90% of maximal effort for each muscle group (ECC and CON), each separated by 1 minute rest. Maximal concentric and eccentric strength of the knee extensors and flexors was measured at 1.05 rad/s. Subjects performed three trials with a 1 second pause at either end of the range of motion to avoid the facilitating effects of the prior action. Maximal efforts were be separated by 5 minutes and participants had use of two hand grips either side of their hip for stability during the maximal contractions.

Jump assessments

Jump assessments were conducted on a portable force plate (9290AD, Kistler, Winterhur, Switzerland). Force data was acquired at 500 Hz using the software package Quattro jump (version 1.1.1.4, Kistler, Winterhur, Switzerland) and exported to Matlab for analysis (R2016b, Mathworks, Massachusetts, USA). Jump height was calculated using time of flight for the SJ, CMJ, and DJ. On each occasion of jump testing participants performed three maximal efforts of squat jump, counter movement jump, depth jump and a two footed hopping test. Each set of three maximal jumps was preceded by two sub maximal practice efforts.

- Squat jump: Participants were instructed to squat slowly to a depth that achieved a knee angle of ~90° prior to observing a 3 second pause to minimise any stretch shortening cycle contribution to jump height. Subjects were then instructed to jump as high possible whilst maintaining hands on hips. Efforts were discarded if hands became detached from hips or the experimenter observed a clear counter-movement or dip of the hips or torso immediately prior to the jump.
- Countermovement jump: Subjects were instructed to perform a maximal CMJ jump with hands placed on hips. No restrictions were placed on the knee angle during the eccentric phase of the jump.
- Depth jump: Participants stepped off a 30 cm high box onto the force plate and performed a maximal two-footed hop with emphasis placed on achieving a quick ground contact time. Participants were permitted to use their hands in order to facilitate fast ground contact times and maximal jump height. Efforts were discarded if the experimenter observed a clear jump from the box thus increasing the depth jump height beyond 30 cm.

- Hopping test: Participants were instructed to perform sub-maximal two-footed hopping at 150 bpm (2.5 beats per second). Participants began hopping and after ~5 secs for the participant to settle into the correct rhythm 10 s of force plate data was acquired. Throughout the hopping test hands remained on hips. A similar protocol has previously been used to assess estimated changes in leg stiffness after eccentric cycling (Elmer *et al.*, 2012). Estimation of leg stiffness was calculated as described by Farley *et al* (1991) and used by Elmer *et al* (2012). Using the average resonant period (T, Figure 7.3) and body mass (M_b) leg stiffness was estimated using the following equations:

$$\omega = 2\pi/T$$

$$k = M_b\omega^2$$

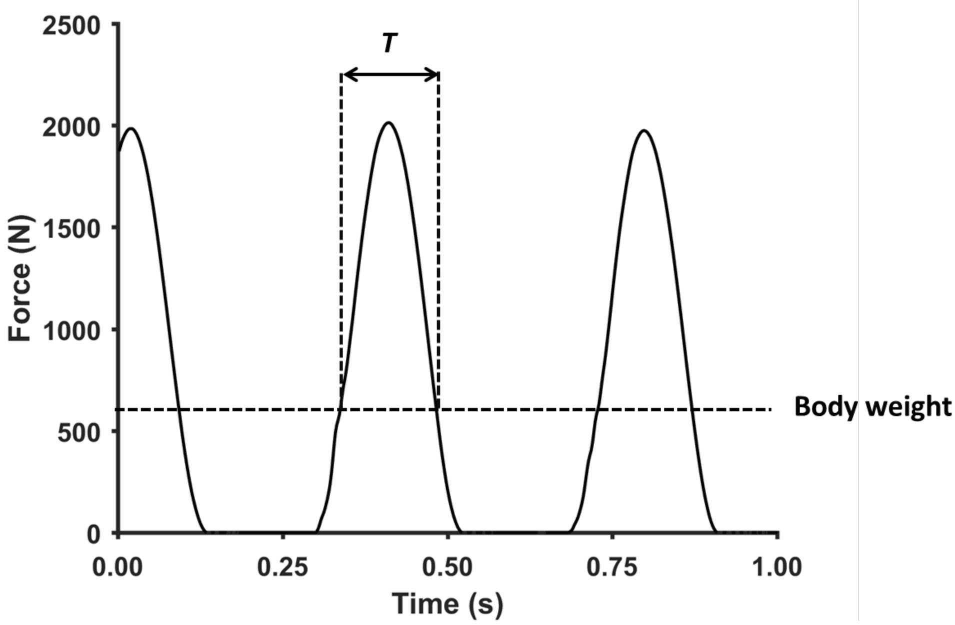


Figure 7.3. Force data acquired during the 10 s hopping test, a 1 s sample has been shown to demonstrate the method of analysis. The peak force of three hops is visible. T = resonant period i.e. time were force is greater than 1 BW.

Running kinematics assessment

Stride variables are influenced by absolute running speed, therefore the analysis of running kinematics was conducted at a standardised speed of first lactate threshold for each participant. Participants completed a self-selected 5 min warm-up followed by a 5 min continuous run at first lactate threshold on a treadmill at 0% gradient. Running kinematics were collected during the final 60 secs of this 10 min block. A photoelectric cell system (Optojump, Microgate, Bolzano, Italy) was used to measure ground contact time, flight time, stride length and stride frequency. The system consisted of two parallel units (a transmitter and a receiver), set on opposing sides of a 2 m section of the treadmill belt. The photoelectric system was positioned 0.3 cm above the plane of the treadmill belt and each transmitter contained 96 equidistant LEDs per meter, recording at 1 kHz. All variables were quantified using the Optojump Next software (v 1.9.9.0). Data were filtered to remove erroneous values >2 standard deviations away from the mean.

Training protocol

The eccentric cycling ergometer and the setup procedure for each participant were kept consistent throughout the thesis and are described in detail in Chapter 3. A schematic of the 8-week training protocol can be seen in in Figure 7.2. Each participant in the intervention group performed three familiarisation sessions at a pre-determined target power output; 1) 3 × 2 min at 3.5 $W \cdot kg^{-1}$, 1 min rest, 2) 4 × 2 min at 4.5 $W \cdot kg^{-1}$, 1 min rest, and 3) 10 × 2 min at 3.5 $W \cdot kg^{-1}$, 1 min rest. The objective of this familiarisation was to elicit the repeated bout effect and minimise muscle damage in the early stages of training. The intensity of this familiarisation was based upon the body mass and damage response of participants recruited in Chapter 6. In order to achieve progressive mechanical overload throughout the 8-week training period target power output was adjusted on a session-by-session basis in response to each participant's rate of perceived exertion for the legs (RPE_{legs}) during the final interval of the previous session (Table 7.1). Participants self-managed incorporating eccentric cycling sessions and habitual training throughout the 8-week period.

Training monitoring and perceived soreness

Participants recorded all training throughout the 8-week period by means of a self-report training diary. Total training load per week in minutes was used for analysis. On a daily basis participants were asked to assess waking perceived muscle soreness of the lower limbs. This was done using a 0 – 20 scale where zero represents no pain at all and twenty represents the worst pain imaginable. Average weekly muscle soreness values were used for analysis.

Table 7.1. Scale representing the change in target power output for a subsequent eccentric cycling session based upon the rate of perceived exertion in the legs experienced by the participant during the final interval of the previous training session.

RPE legs (last repetition)	Change in target W/kg for next session
10	+0.5
11	+0.4
12	+0.3
13	+0.2
14	+0.1
15	0
16	-0.1
17	-0.2
18	-0.3
19	-0.4
20	-0.5

Statistical analyses

Statistical testing was performed using SPSS 24 (IBM, New York, USA). All baseline measures were compared between groups with an independent measures t-test. To examine the responses of each group to the 8-week training period within group paired t-tests were performed on all pre and post measures. Between group comparisons were conducted using a 2 × 2 mixed-model ANOVA (Time: PRE and POST and group: intervention and control) and effect sizes (Cohen's D) were also calculated. Weekly muscle soreness and training load data were examined using an 8 × 2 mixed-model ANOVA (Time: weeks 1 – 8, and group: intervention and control). Significance was set at an alpha level of 0.05. Greenhouse-Geisser corrections were applied to significant F-ratios that did not meet Mauchly's assumption of sphericity. All results are presented as mean ± standard deviation.

7.3 Results

No differences were observed in baseline measures of stature (184 ± 10 vs. 182 ± 8 cm), age (28.7 ± 4 vs. 35.1 ± 8.8), mass (75.4 ± 9.3 vs. 70.0 ± 8.9) or 5 km seasons best (17.7 ± 1.6 vs. 18.1 ± 0.9 min) between the eccentric cycling and control groups respectively. Over the 8-week training period there was no change in average weekly muscle soreness within the eccentric cycling ($p = 0.57$) or control group ($p = 0.65$), with no group × time interaction effect ($p = 0.64$) (Figure 7.4). There was no overall effect of time on total training volume across the 8-week training period ($p = 0.66$). Nor was there any group × time interaction effect on total training volume ($p = 0.17$) (Figure 7.5). After the initial three familiarisation sessions the average target power per session increased from 271 ± 21 W to 523 ± 53 W (sessions 4 - 21).

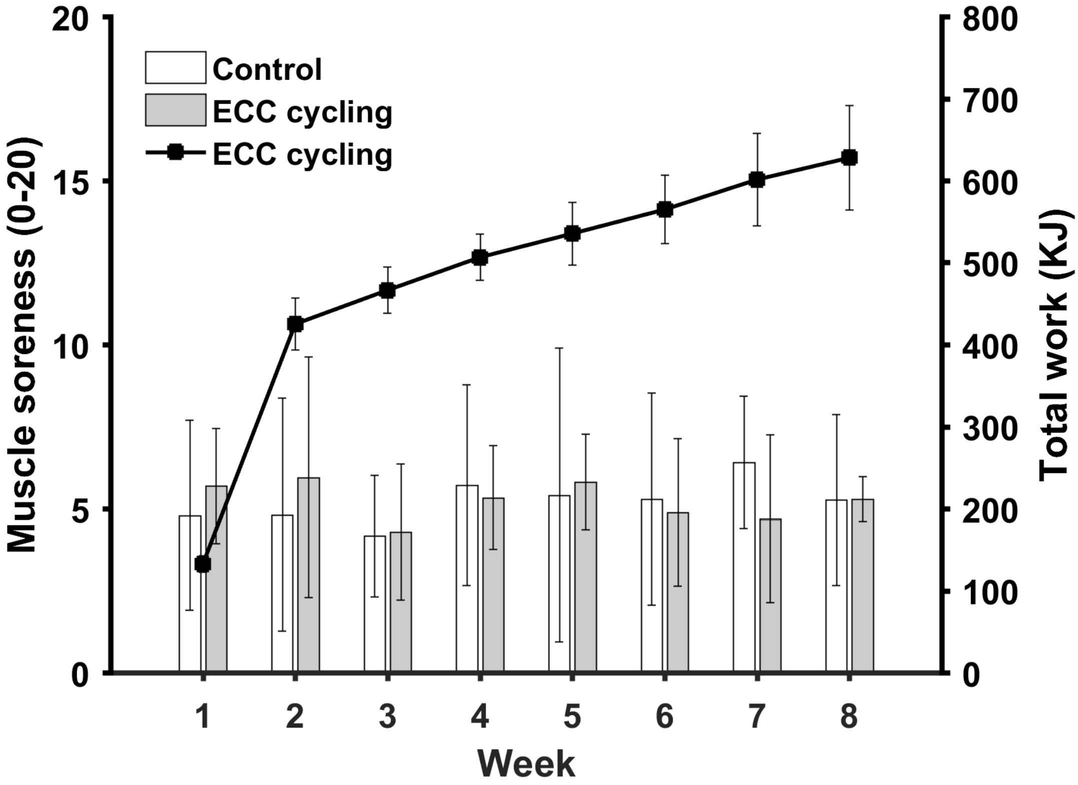


Figure 7.4. Total work performed as a result of eccentric cycling during each week of the 8 week intervention (■). Average weekly muscle soreness associated with the eccentric cycling group (filled bars) and control group (open bars).

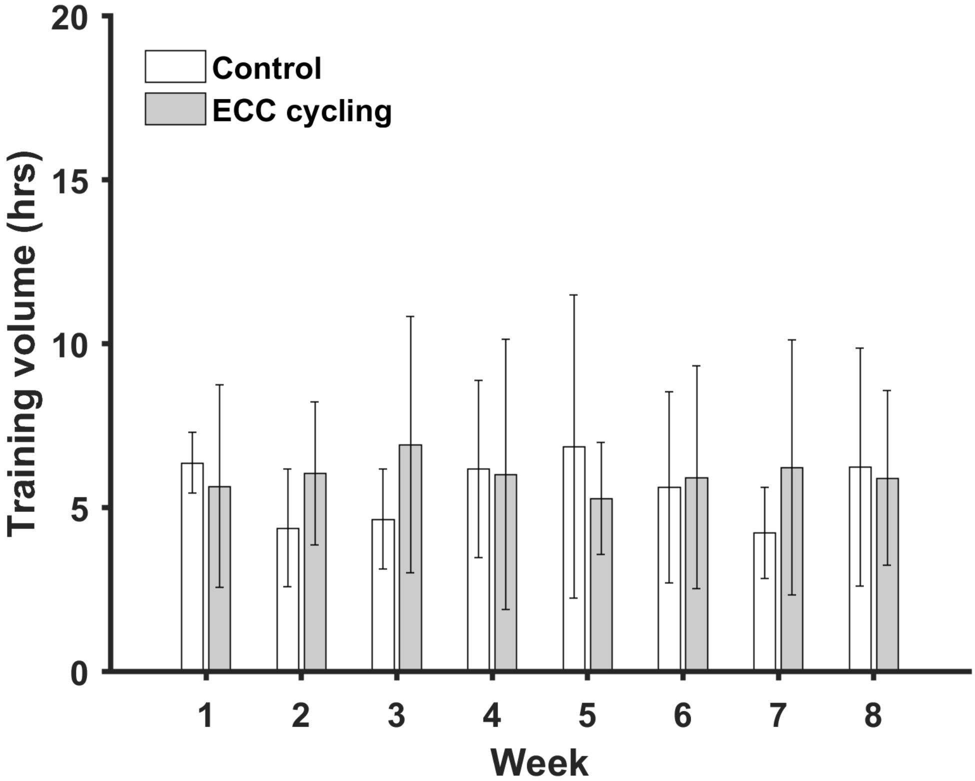


Figure 7.5. Average total weekly training volume of the eccentric cycling group (filled bars) and control group (open bars).

Strength, jump, and running assessments

At baseline, concentric quadriceps strength, CMJ power, SJ power and DJ height were greater in INT compared CON ($p < 0.05$, Table 7.2). All other biomechanical, strength, jump, and physiological parameters were consistent between groups at baseline ($p > 0.05$, Table 7.2). There was a significant interaction effect of group and time on stride length ($F_{(1, 12)} = 6.98$, $p < 0.05$), with average stride length increasing after CON ($p < 0.05$). Furthermore, CMJ power was significantly reduced after CON ($p < 0.05$). All other pre and post strength, jump, and running parameters remained unchanged after INT and CON ($p > 0.05$, Table 7.2). There were no other significant group × time interaction effects across any of the assessment parameters ($p > 0.05$, Table 7.2). Individual responses within each group for eccentric quadriceps force and SJ power can be seen in figures 7.6 and 7.7 respectively. These variables displayed the greatest trend for a post-intervention increase.

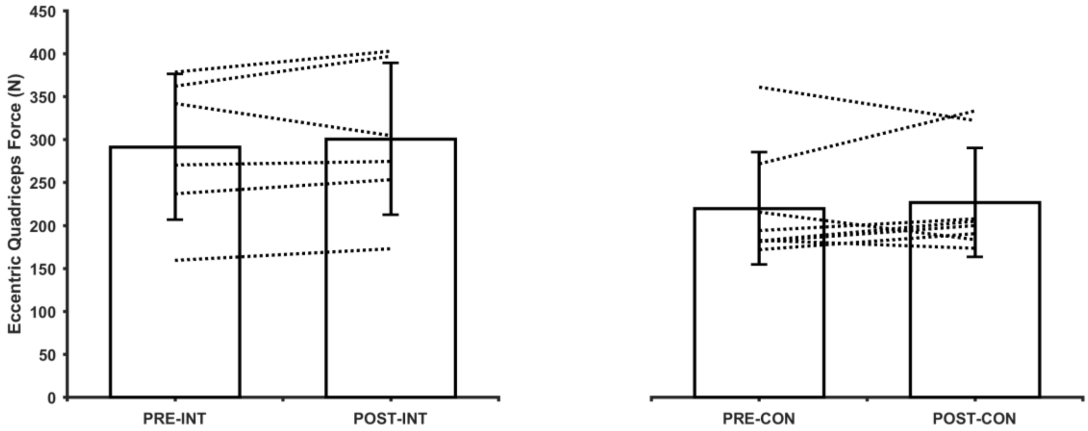


Figure 7.6. Group responses (bars) and individual responses (dashed line) of the intervention group (left panel) and control group (right panel) for peak eccentric quadriceps force production.

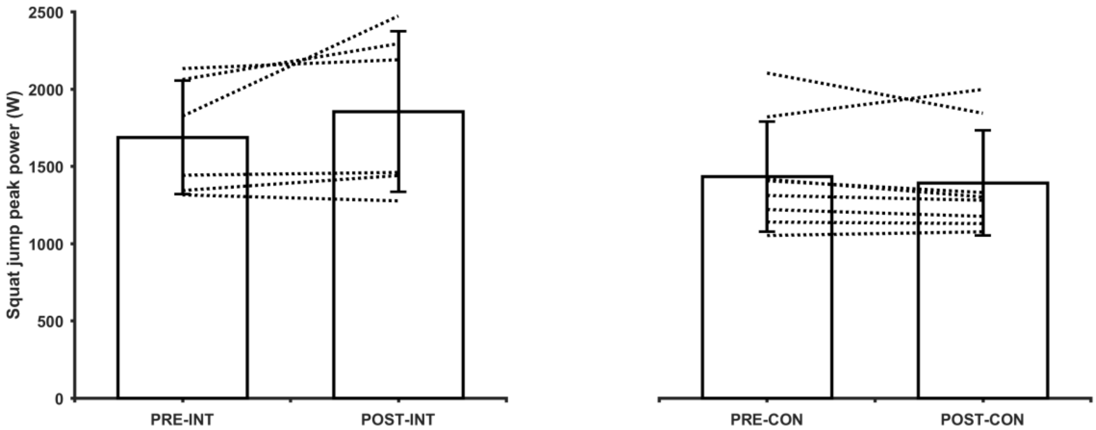


Figure 7.7. Group responses (bars) and individual responses (dashed line) of the intervention group (left panel) and control group (right panel) for peak squat jump power.

Table 7.2. Physiological and biomechanical variables assessed pre and post 8 weeks of interval eccentric cycling or habitual training (control). * denotes significant difference from baseline value ($p < 0.05$). ** denotes significant difference from control group baseline. † denotes significant group × time interaction effect ($p < 0.05$).

	Intervention group		Control group		ANOVA (group x time; P=)	Effect Size
	Pre	*Post*	*Pre*	*Post*		
Running assessment						
$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	62.3 ± 5.2	63.4 ± 7.1	63.0 ± 3.7	62.5 ± 2.6	0.348	0.66
Running economy ($Kcal \cdot kg^{-1} \cdot km^{-1}$)	1.31 ± 0.08	1.30 ± 0.09	1.31 ± 0.12	1.27 ± 0.1	0.197	0.78
Stride length (cm)	272 ± 31	265 ± 36	266 ± 24	275 ± 18 *	0.021 †	-1.41
Flight time (s)	0.11 ± 0.03	0.11 ± 0.03	0.11 ± 0.02	0.13 ± 0.03	0.067	-1.09
Contact time (s)	0.25 ± 0.04	0.25 ± 0.05	0.27 ± 0.1	0.23 ± 0.02	0.306	0.62
Jump assessment						
CMJ power (W)	2132 ± 438 **	2118 ± 473	1649 ± 370	1580 ± 386 *	0.212	0.70
SJ power (W)	1686 ± 367 **	1855 ± 519	1433 ± 357	1392 ± 340	0.061	1.06
DJ contact (s)	0.28 ± 0.12	0.28 ± 0.09	0.30 ± 0.06	0.29 ± 0.09	0.777	0.08
DJ jump height (cm)	36.4 ± 8.9 **	37.1 ± 9.5	26.8 ± 3.2	26.9 ± 3.7	0.660	0.24
Leg stiffness (kN/m)	38.7 ± 3.6	39.9 ± 5.5	36.3 ± 5.6	36.6 ± 6.2	0.699	0.21
Strength assessment						
ECC hamstrings (N)	189 ± 61	181 ± 62	130 ± 32	130 ± 32	0.283	-0.59
ECC quadriceps (N)	291 ± 85	301 ± 88	220 ± 65	206 ± 54	0.520	0.08
CON quadriceps (N)	236 ± 66 **	233 ± 48	182 ± 31	189 ± 36	0.486	-0.37
CON hamstrings (N)	138 ± 34	137 ± 33	107 ± 23	105 ± 25	0.839	0.11

7.4 Discussion

The aim of this study was to assess the effectiveness of an 8-week interval based eccentric cycling programme on running economy, running kinematics, jump performance, and lower limb anisometric strength in a cohort of well-trained male distance runners. Based on the preliminary results of this pilot study, a short training period of interval based eccentric cycling does not improve running mechanics or economy in well trained distance runners. However, the data did display a trend for increased eccentric quadriceps strength and SJ power which is worthy of further investigation. Additionally, a notable finding was the absence of increased muscle soreness when eccentric interval cycling was added to an existing training programme. With a suitable familiarisation period eccentric interval cycling can be introduced to a training programme with negligible impact on habitual muscle soreness. Such data reinforces the notion that the greater mechanical stimulus offered by eccentric cycling eccentric training can be prescribed without significant increases in muscle soreness. However, the practical relevance of this finding can only be assessed in conjunction with greater evidence of any potential performance benefits of this intervention.

It is important to acknowledge the pilot nature of this work. The low statistical power does not minimise the possibility of a type II error and makes drawing firm conclusions difficult. Although, previous studies have recruited 6 – 8 participants and observed significant increases in concentric cycling power (Leong *et al*., 2013), jump power, and leg stiffness (Elmer *et al*., 2012) after 6 - 7 weeks of eccentric cycling. Drawing such comparisons does not conclusively indicate a reduced effect of eccentric cycling in the current study, however, of note is that both previous studies recruited healthy adults rather than well trained runners. The average $\dot{V}O_{2peak}$ of participants in previous work (Elmer *et al*., 2012) was 47.5 ± 12 $mL \cdot kg^{-1} \cdot min^{-1}$ compared to 64.2 ± 6.0 $mL \cdot kg^{-1} \cdot min^{-1}$ in the current study. Given the similar sample sizes, training intervention and outcome measures it is possible that the absence of any observed changes in the current study is, in part, due to the greater training status of the participants. Other interventions that have targeted stretch shortening cycle function such as downhill running (Shaw *et al*., 2018) have also observed no effect in well trained runners.

Eccentric cycling is a quadriceps dominant activity (as highlighted in Chapter 5) and the absence of any significant change in eccentric quadriceps strength after 8-weeks of eccentric cycling was unexpected. An obvious conclusion to draw is a lack of statistical power, however, this rationale cannot be selectively applied without supporting evidence. Overall, 5 out of 6 participants that performed eccentric cycling displayed increased eccentric quadriceps strength compared to 5 out of 8 individuals in the control group. The only individual to display reduced eccentric quadriceps strength after eccentric cycling also exhibited reduced eccentric and concentric hamstring strength and reduced concentric quadriceps strength. This was unique insofar as they were the only participant across either group to display reductions across all four strength tests. Closer examination of their training data indicates a 123% rise in training volume during week 8 compared to the previous 7-week average. It is possible that although participants were asked to refrain for strenuous exercise on the 24 hrs prior to testing this sudden and large increase in training volume could have suppressed performance in the strength tests during the post testing period. The exclusion of this individual's data results in a significant PRE – POST change in eccentric quadriceps strength within the eccentric cycling group but the concomitant decrease in statistical power makes this conclusion somewhat difficult to make with any assertion. Whilst these arguments do not provide definitive proof for an effect of eccentric cycling on eccentric quadriceps strength in trained distance runners they do provide reasonable evidence to suggest an effect might exist and that further data collection is warranted to determine if a true effect is present.

Increases in jump height have previously been observed after a period of eccentric cycling with well-trained athletes (Gross *et al*., 2010). In Swiss national junior skiers 6 weeks of substituting 1 – 2 sets of lower limb resistance training with 20 mins of eccentric cycling, three times per week, increased SJ height compared to a control group. In agreement, a large effect size in the current study indicated a trend for increased SJ power after eccentric cycling. Combined, these studies provide evidence that a non-specific eccentric cycling stimulus might elicit performance improvements in functional movements such as SJ. Although, it does not appear that this non-specific eccentric stimulus also improves running specific mechanics. When examining isometric strength, Gross *et al.* (2010) saw no effect of eccentric cycling in national level skiers. The current study did not measure isometric strength but there was a trend for increased eccentric quadriceps strength after eccentric cycling. This discrepancy is likely due to the high propensity for eccentric training to induce modality specific adaptations (Roig *et al*., 2009). This modality-specific increase in strength is only evident in the quadriceps, most likely due to the higher levels of muscle activation compared to the hamstrings as observed in Chapter 5.

Target power output in the current study was lower than that previously prescribed to national level athletes (up to 850 ± 50 W, Gross *et al*., 2010). The likely explanation is that the national level skiers in the aforementioned study possess greater levels of quadriceps strength compared to distance runners. However, it does also raise the possibility that target power output in the current study was not great enough to elicit a measureable improvement in performance. Recent work has suggested that during eccentric cycling participants perceive greater levels of effort for a given degree of perceived exertion in comparison to concentric cycling (Peñailillo *et al*., 2018). This corresponds to the high levels of mechanical tension that eccentric cycling can elicit (effort) for a relatively low metabolic cost (exertion). To determine changes in intensity from session to session we asked participants for ratings of perceived leg exertion. Given that exertion should be lower than perceived effort for any given intensity we are confident that target power output was not under estimated. The continual increases in target power output throughout the 8-week training period for the same level of RPE_{legs} corroborates the idea that eccentric cycling ability was improving throughout and that target power output was not underestimated.

It should be noted that no intervention was prescribed to the control group in this study. The intervention group completed 8 weeks of eccentric cycling and the control group completed 8 weeks of their own habitual training. Therefore, it is possible that any differences between groups were a result of an increased training load in the intervention group rather than an effect of eccentric cycling. Total weekly training load was similar between groups, although it is possible that moderate variation in training load and low participant numbers resulted in a failure to detect an increased training load in the intervention group. When developing the protocol, consideration was given to the control group performing a matched concentric cycling or plyometric training programme. The former is an obvious control to eccentric cycling and the latter is the current best practice at improving SSC function and running economy. However, in a group of trained distance runners concentric cycling might have had a negative effect on SSC function which would have misrepresented the effectiveness of eccentric cycling and potentially led to false conclusions. A more appropriate comparison for eccentric cycling would have been plyometric training. However, an accurate method of matching eccentric cycling and plyometric training for total work could not be determined. Furthermore, if plyometric training had been used as a control intervention an additional control group would have been required to determine the effect of simply participating in the research (i.e. being tested). Given the scarcity of trained runners and the difficulty recruiting large numbers it was considered more important to have a control group completing their habitual training so an accurate determination of whether eccentric cycling was effective could be made.

As previously mentioned, one participant withdrew from the study after sustaining an injury whilst completing a familiarisation session on the eccentric ergometer. The participant sustained an avulsion fracture of the ankle due to dorsiflexion beyond the normal range of motion. The injury occurred during the third and final two minute interval of the first familiarisation session. The target power output was set at 247 W (3.5 $W \cdot kg^{-1}$) and anecdotally the participant found the exercise intensity, and associated technique, “very easy” prior to the injury. There was no injury to the knee joint which is likely a result ensuring each participant could not achieve a knee angle of 180° at any point of the pedal cycle. Furthermore, additional safety features of the ergometer such as the safety release buttons on each handlebar functioned correctly by stopping the ergometer immediately and likely preventing further injury. This highlights the importance of appropriate ergometer safety features when performing eccentric cycling. Although the exact series of events that led to the injury are unknown it is believed that there were two contributing factors; 1) post-injury, the participant believed that raising themselves out of the seat and thus altering the ankle-ergometer angle contributed to the accident, this was despite instructions to remain seated; and 2) following the injury the participant revealed a pre-existing hyper-mobility of the ankle joint which was not declared on the PAR-Q form prior to testing. As a result of this incident all participants were asked additional questions regarding ankle mobility prior to taking part in the study. Ankle hyper-mobility should be considered a possible contraindication for eccentric cycling.

In conclusion, 8-weeks of supplementary interval eccentric cycling does not appear to improve running economy or concentric lower limb strength in well-trained distance runners. There was, however, a trend for increased eccentric quadriceps strength and SJ power which warrants further investigation to determine if a true effect is present. The aim of this thesis was to systematically investigate the neuromuscular responses and application to performance of a bespoke eccentric cycling instrument. The purpose of this chapter was to examine the efficacy of eccentric cycling as a method to improve the determinants of performance in trained athletes. When combined with previous research it appears that eccentric cycling does not have the same positive effect on trained athletes as has been observed in un-trained individuals. Possible performance improvements might be seen in non-running specific movements e.g. SJ, however, eccentric cycling appears to have no effect on running kinematics or economy in trained distance runners. Caution should be exercised when prescribing eccentric cycling to well-trained athletes as the performance improvements might be limited to non-sport specific skills and more than 8-weeks might be required to elicit them. Lastly, these findings re-enforce the notion that with appropriate familiarisation interval eccentric cycling can be added to an existing training programme in well-trained runners with minimal impact on perceived muscle soreness.

CHAPTER 8

GENERAL DISCUSSION AND CONCLUSIONS

8.1 Summary

Eccentric cycling is an emerging exercise modality with promising applications in health, rehabilitation, and sport (Gerber *et al*., 2009; Gross *et al*., 2010; Lastayo *et al*., 2000; Vieira *et al*., 2011). Access to eccentric ergometers is still not widely available and as a consequence, research in this area is still in its infancy. The majority of this work has used continuous sub-maximal eccentric cycling in untrained individuals, despite a key characteristic of eccentric cycling being the high mechanical tension it can offer for a low metabolic cost, which might be advantageous to trained athletes seeking a novel stimulus that can repeatedly stress the lower limb musculoskeletal system. Using eccentric cycling, this thesis has examined the utility and applicability of the mechanical stimulus eccentric cycling can afford, specifically, how individuals familiarise to this novel stimulus, the consequences of interval and continuous training sessions, and the adaptations to a short-term period of training in trained distance runners. The primary findings from this thesis are as follows:

Chapter 4 – Familiarisation to maximal recumbent eccentric cycling

Peak instantaneous power, average power, and lower limb muscle activation required one familiarisation session to account for significant learning effects after initial exposure to 6 × 10 s of maximal eccentric cycling. After a single familiarisation session, between session reliability for peak and average power output at 60 rpm was moderate (95% CI; 6.5 – 16.2%) and good (95% CI; 2.6 – 7.2%) respectively. At all other cadences (20, 40, 80, 100, 120 rpm) only moderate (>10%) to poor (>15%) reliability was observed for peak and average power output. Surface electromyography displayed poor reliability (>15%) across all cadences. These results indicate that peak instantaneous power, average 10 s power, and lower limb muscle activation are not sensitive enough measures of eccentric cycling ability to effectively benchmark individuals or prescribe training from.

Chapter 5 – Torque, power and muscle activation of eccentric and concentric isokinetic cycling

During maximal eccentric cycling torque and power was significantly greater compared to concentric cycling over a range of cadences from 20 – 120 rpm (torque; mean +129 N·m, range 111–143 N·m, power; mean +871 W, range 181–1406 W). This underlines the attractiveness of eccentric cycling as a training modality in that it can elicit high levels of mechanical stress in a repetitive, low impact, manner. Markers of technique, such as pedal angle at peak torque and pedal angle at peak sEMG, were significantly different between eccentric and concentric cycling, a difference modulated by cadence. These observations clearly indicate that the technique required for eccentric and concentric cycling is different, which might result in differing adaptations between modalities after a period of chronic training.

Chapter 6 – Metabolic and mechanical consequences of interval and continuous eccentric cycling

Fatigue after 30 minutes of eccentric cycling is comprised of both central and peripheral factors. Completing a set work load of eccentric cycling in an interval manner, versus a continuous manner, exacerbates peripheral fatigue and muscle soreness after exercise. This difference is likely caused by the greater absolute torque generated during interval eccentric cycling compared to continuous eccentric cycling in which time under tension was greater but absolute levels of tension were lower. Additionally, metabolic strain was trivial across both session structures highlighting its specificity as a mechanical stimulus.

Chapter 7 – The effect of 8-weeks eccentric cycling interval training on lower limb strength and running economy in trained distance runners.

Eight weeks of interval based eccentric cycling does not appear to improve running economy in well trained distance runners. Although, there is a tendency for increased jump performance and enhanced eccentric quadriceps strength. Training was performed with negligible increases in muscle soreness throughout the 8-week period which indicates it can be successfully implemented into an existing training regime with minimal impact. This pilot work indicates that more data should be collected to increase statistical power and determine the meaningfulness of these trends.

8.2 Practical implications

This thesis demonstrates that eccentric cycling provides a greater mechanical stimulus than concentric cycling between 20 – 120 rpm. This mechanical stimulus was greatest at faster cadences, which indicates a potential for greater adaptation. However, greater variability in power output and sEMG at higher cadences indicates a greater technical competence is required. Anecdotally participants reported that 60 rpm was the most comfortable cadence to perform eccentric cycling. It was also the cadence that displayed the best between session reliability for measures of torque, power and sEMG. Therefore, although faster cadences provide a greater mechanical stimulus it might be wise to prescribe eccentric cycling at ~60 rpm, where the mechanical stimulus is still large, but the level of technical expertise (skill) required is minimised. These findings provide quantifiable data to support the selection of 60 rpm during eccentric cycling which has been commonplace in previous research (Elmer *et al*., 2012; Leong *et al*., 2013; Peñailillo *et al*., 2017b). Although, the prescription of other cadences could be recommended as a training stimulus provided that care was taken during the familiarisation to account for the greater technical difficulty.

Despite less technical proficiency being required at 60 rpm, the low level of between-session reliability for measures of torque and power make accurate determination of changes in these parameters difficult. During a 10 s maximal effort neither measures of torque nor power are reliable enough to detect meaningful changes in eccentric cycling performance. The capability to detect small changes in eccentric cycling performance would be advantageous for prescribing training intensity and assessing changes in performance. Care should be taken when inferring changes in torque, power, and sEMG from 10 s bouts of maximal eccentric cycling and if required to do so a cadence of 60 rpm should be used.

Eccentric exercise is inherently associated with EIMD and DOMS (Proske and Morgan, 2001). In the current thesis this association was a significant barrier to participant recruitment. Both participants and coaches were cautious about participation due to their perception that debilitating muscle damage would follow any form of eccentric exercise. Chapter 6 demonstrated that after only two short familiarisations interval and continuous eccentric cycling sessions could be performed with only moderate levels of subsequent muscle soreness. Additionally, Chapter 7 showed that with a structured familiarisation program eccentric cycling could be introduced into a training program with negligible increases in muscle soreness. Also in Chapter 7, we present evidence that eccentric cycling can be added to the training program of a well-trained athlete with minimal impact on existing training load. Participants in the eccentric cycling group did not have a significantly different training load to the control group and anecdotally were pleased at not having to remove training sessions to accommodate the eccentric cycling. The observation that eccentric training does not always induce high levels of muscle damage and soreness is not new. It has been seen previously in eccentric cycling (Lastayo *et al*., 2000) and the repeated bout effect is a well-researched phenomenon (Hyldahl *et al*., 2017). However, research replicating these observations is critical in communicating to a wide-ranging audience that eccentric exercise can be easily implemented without significant EIMD or DOMS. Coaches and athletes can be less cautious of implementing eccentric training regimes, but instead see this potentially powerful training modality as an opportunity to explore a novel stimulus to support long-term athlete development and performance improvements.

This thesis investigated eccentric cycling prescribed as a series of intervals and as a continuous bout of exercise (Chapter 6). The data collected will help researchers and practitioners make a more informed decision regarding what distribution of work load might best suit their needs. Interval training allows participants to produce greater levels of absolute torque (56 ± 13 vs 40 ± 9 N·m), whereas continuous training affords a greater time under tension (983 ± 142 vs 664 ± 131 s). Different work to rest ratios during the interval session will likely alter the exact ratio of these two mechanical stimuli. This mechanical stimulus was experienced for a low metabolic cost (< 35% $\dot{V}O_{2peak}$), highlighting its mechanical specificity and providing evidence that it would have minimal metabolic impact if incorporated into an existing training plan. Whilst mechanical stimulus might be the primary characteristic to consider when prescribing eccentric cycling, fatigue and recovery could also impact on choice of session structure. Interval eccentric cycling caused greater post-exercise peripheral fatigue (–32 vs –21% pre- to post-training reduction in knee extensor MVC) and soreness (8.4 ± 4.5 vs 3.9 ± 2.0 cm, VAS scale) compared to a continuous bout. These data indicate that fatigue after eccentric cycling is modulated by changes in absolute intensity rather than total time under tension. Although, muscle soreness should be considered moderate as values did not rise above 50% of the VAS scale used.

When planning training regimes for athletes, the available time for eccentric cycling and its proximity to other priority sessions might influence the decision to use interval or continuous sessions. Recovery after interval eccentric cycling in Chapter 6 was observed within 48 hrs, but it is likely that changes in session intensity will change the recovery timescale. Certainly, evidence of the repeated bout effect in eccentric cycling suggests that muscle damage and soreness may be reduced to an even greater extent (compared to observations in Chapter 6) after multiple training sessions (Peñailillo *et al*., 2013). The greater peripheral fatigue observed after interval based eccentric cycling could indicate a larger potential for subsequent peripheral adaption, however, more work would be required to substantiate this hypothesis. Overall, eccentric interval cycling sessions should be considered a feasible alternative to the continuous sessions that currently dominate the literature (Elmer *et al*., 2012; Gerber *et al*., 2007a; Lastayo *et al*., 2000; Mueller *et al*., 2009; Peñailillo *et al*., 2014, 2013). This adds to recent work which had shown perceived enjoyment to be similar between interval and continuous eccentric cycling sessions (Lipski *et al*., 2018).

In agreement with previous work in national level skiers (Gross *et al*., 2010), evidence from Chapter 7 indicates a non-specific eccentric stimulus might improve a functional movement such as SJ in trained athletes. This pilot work provides rationale that the performance improvements seen in un-trained individuals after a period of eccentric cycling might also occur in trained athletes (Elmer *et al*., 2012; Lastayo *et al*., 2000; Leong *et al*., 2013). However, the magnitude of these functional performance improvements appears reduced in trained distance runners compared to un-trained individuals, and even more pertinently to distance runners, there is no evidence that eccentric cycling impacts upon running specific variables. Chapter 7 also provided evidence of a likely trend for increased ECC quadriceps strength after 8-weeks of eccentric cycling. Whilst this did not appear to translate to an increase in concentric strength it could perhaps increase an athlete's tolerance to an increased training load. It is known that increased eccentric strength of the hamstrings has a protective effect on injury risk (Croisier *et al*., 2002). Eccentric cycling might confer a similar protective effect in the quadriceps muscle group (n.b. no quadriceps tears or injuries were observed amongst the injured participants). Eccentric cycling could be used as a non-specific training stimulus after which a period of sports specific training is employed in order to translate the conferred adaptations to an increase in performance. For example, previous research has shown that eccentric training augmented with over speed exercises can improve sprinting performance to a greater extent than eccentric only training (Cook *et al*., 2013). However, if increases in concentric lower limb strength are sought it may be more beneficial to explore existing concentric methods of strength gain as opposed to eccentric cycling.

8.3 Limitations

In Chapter 6 eccentric cycling intensity was prescribed as a set percentage of maximal aerobic power, as determined by a concentric cycling protocol. Although similar methods have been used previously (Peñailillo *et al*., 2013), the strength of the relationship between eccentric and concentric cycling ability is unclear. Therefore, it is possible that not all participants were exercising at the same intensity relative to their eccentric cycling ability during the interval and continuous sessions. Data from Chapter 5 showed that the correlation between eccentric and concentric power output varies with changes in cadence, albeit during 10 s maximal efforts as opposed to a longer duration bout. At cadences between 100 – 120 rpm eccentric and concentric power output were poorly correlated with each other. The cadence used for the interval and continuous eccentric sessions in Chapter 6 was 60 rpm, which displayed a moderate correlation between eccentric and concentric cycling ability. Therefore, whilst eccentric and concentric peak power production may not be perfectly correlated at all cadences, 60 rpm represents a cadence where performance between the two modalities is similar. It is, however, important to note that these findings are based upon recreationally active individuals. It is possible that individuals with a training history in conventional concentric cycling might exhibit different pedalling characteristics.

The use of two familiarisation sessions prior to the interval and continuous sessions in Chapter 6 is likely to have diminished the fatigue and muscle damage response to eccentric cycling. Eliciting a RBE by using two familiarisation sessions might have reduced the sensitivity of the experimental design to detect differences in fatigue and muscle damage between interval and continuous eccentric cycling sessions. An experimental protocol with no familiarisation sessions is likely to have elicited greater levels of fatigue and muscle damage which might have increased the likelihood of detecting differences between session structures. However, data from Chapter 4 showed that at least one familiarisation is required to achieve a consistent level of technique during eccentric cycling. Therefore, although fewer familiarisation sessions may have elicited greater muscle damage and fatigue it is likely that the technique of participants would not have reflected the technique used if training was to be repeated over a period of weeks or months. Furthermore, the use of two familiarisation sessions before the experimental sessions better replicates the fatigue and muscle damage that could be expected if eccentric cycling was to be implemented on a regular basis over a prolonged period of time.

In Chapter 8 trained distance runners were recruited for the eccentric cycling intervention despite the exercise modality appearing to be more specific to trained cyclists. Eccentric cycling is an unfamiliar modality to cyclists and runners and although the cycling action is similar between concentric and eccentric modalities the contraction type is opposite. Given the propensity for eccentric contractions to elicit adaptation in a mode specific manner the benefits of eccentric cycling is more likely beneficial to a stretch shortening dominant activity such as running. Furthermore, elite runners are a population that would benefit from high force exercise and typically have a high propensity not to engage in such work, therefore, a modality such as eccentric cycling could have large practical impact on this population.

8.4 Future direction

It is clear that greater investigation is required into methods of assessing eccentric cycling ability. This would facilitate training prescription relative to a mode-specific capability or capacity. Greater confidence that each individual is performing eccentric cycling at the same intensity relative to their eccentric cycling ability would enhance the quality of such research. Furthermore, a reliable method of assessment in eccentric cycling would help identify changes in ability over a period of training instead of relying on indirect or estimated markers of improvement. Given the mechanical nature of the eccentric cycling stimulus (as opposed to metabolic) it seems prudent to explore performance tests that prioritise assessing mechanical output during eccentric cycling.

Eccentric cycling is one of many eccentric training modalities. A comparison of the adaptations following eccentric cycling with other eccentric training methods would elucidate the key benefits of this modality. For example, during eccentric cycling large parts of the pedal cycle do not provide an eccentric stimulus, therefore, eccentric stepping might provide a similar stimulus without the technical proficiency required during eccentric cycling. However, comparisons between modalities could prove difficult as many eccentric bikes, steppers, or ergometers are similar yet subtlety different. Separating which adaptations are a result of slight differences in pedal movement pattern, i.e. cyclical or elliptical, may prove difficult. Further investigation into the consequences of cadence on the adaptation following eccentric cycling would better guide prescription. Lastly, exploring the efficacy of eccentric cycling to increase performance across a wider range of elite sporting populations would be beneficial to practitioners, researchers, and athletes.

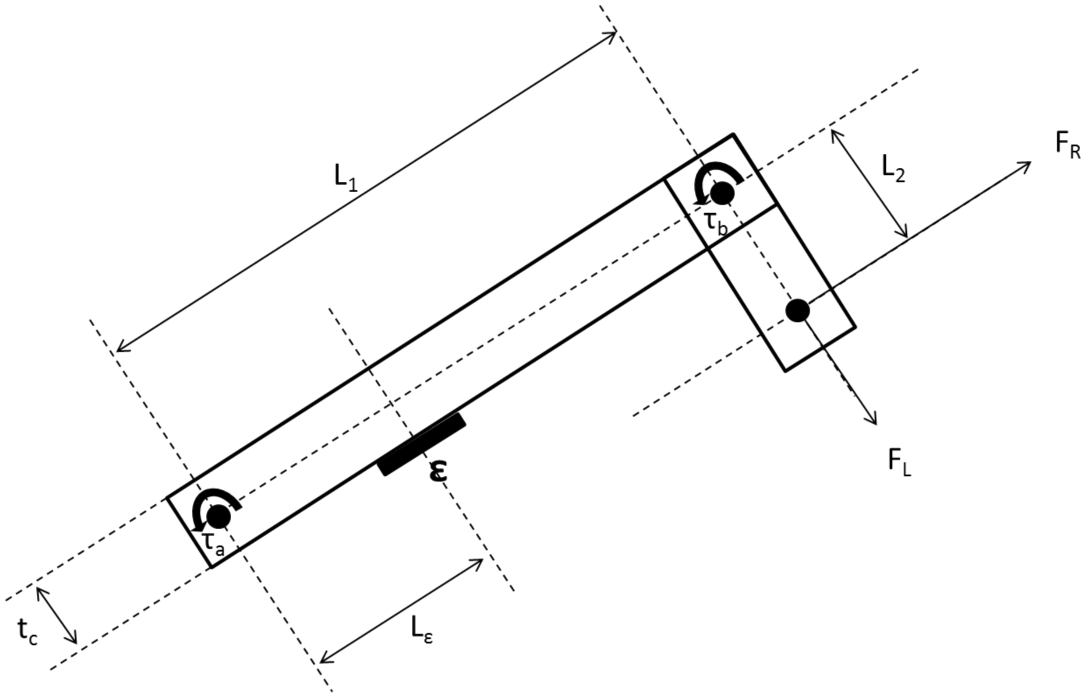
8.5 Conclusion

This thesis has demonstrated that eccentric cycling can provide a far greater mechanical stimulus than concentric cycling over a range of cadences. Differences in technique between eccentric and concentric recumbent cycling have also been described, differences that were modulated by cadence. Data has been presented showing that at least one familiarisation session should be employed to account for a learning effect when first exposed to eccentric cycling. However, despite familiarisation, a 10 s bout of maximal eccentric cycling is not a reliable protocol to determine peak power, average power, or sEMG output. Structuring eccentric cycling sessions in an interval manner results in greater peripheral fatigue, muscle soreness, and absolute mechanical stress compared to a work matched continuous session. However, this does not prevent interval eccentric cycling being implemented into the training program of well-trained distance runners with minimal disruption to existing training. When studied chronically, there is evidence to suggest that the eccentric-specific modality of eccentric cycling can improve eccentric quadriceps strength and SJ performance in trained distance runners, but with no discernible impact on running economy. Future research should focus on the efficacy of eccentric cycling to improve performance across a range of elite sporting populations and on developing a reliable method of assessing eccentric cycling ability.

APPENDICIES

Appendix 1 – Crank model calculations

Bike frame of reference dimensions.



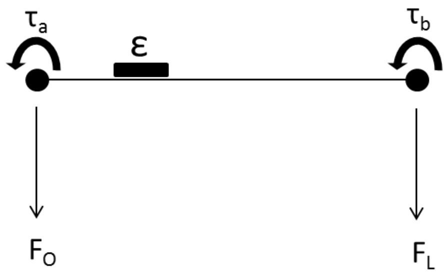
τ => torque

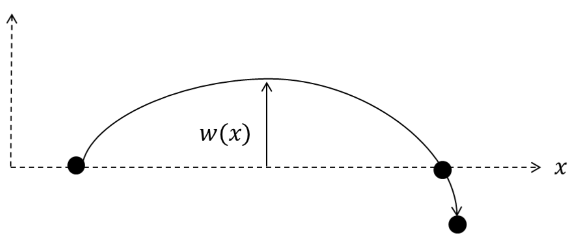
t, L => length

F => force

<u>Rotating crank frame of reference</u>

Main crank arm: Exaggerated beam shape: ★A





Beam shape:

Use Euler-Bernoulli: beam equation for a static (i.e. non-vibrating) beam:

E = Youngs modulus of crank

I = Second moment at area of crank cross section

$$EI\ \frac{d^4\omega}{dx^4} = 0$$

=> $\frac{d^4w}{dx^4} = 0$ ★B

The boundary conditions are:

$x = 0$

$w(0) = 0$ → by definition fixed end ★A

$w```\ (L_\varepsilon) = F_L$ → sheer force at pedal end

$w(0) = \tau_A$ → Torque at left end

$w``\ (L_\varepsilon) = \tau_b$ → Torque at pedal end

By direct integration of ★B we find a solution to ★B is:

$$w(x) = ax^3 + bx^2 + cx + d$$

Where a, b, c & d are constants to be determined from the boundary conditions.

To determine a, b, c & d we use the boundary conditions:

$w(0) = 0$ => $d = 0$

$w``(0) = \tau_A$ => $2b = \tau_A$ => $b = \frac{\tau_A}{2}$

$w```(L_1) = F_L$ => $6a = F_L$ => $a = \frac{F_L}{6}$

$w``(L_1) = \tau_b$ => $6aL_1 + 2b = \tau_b$ => $2b = \tau_b - 6al_1$ and $2b = \tau_b - F_L L_1$

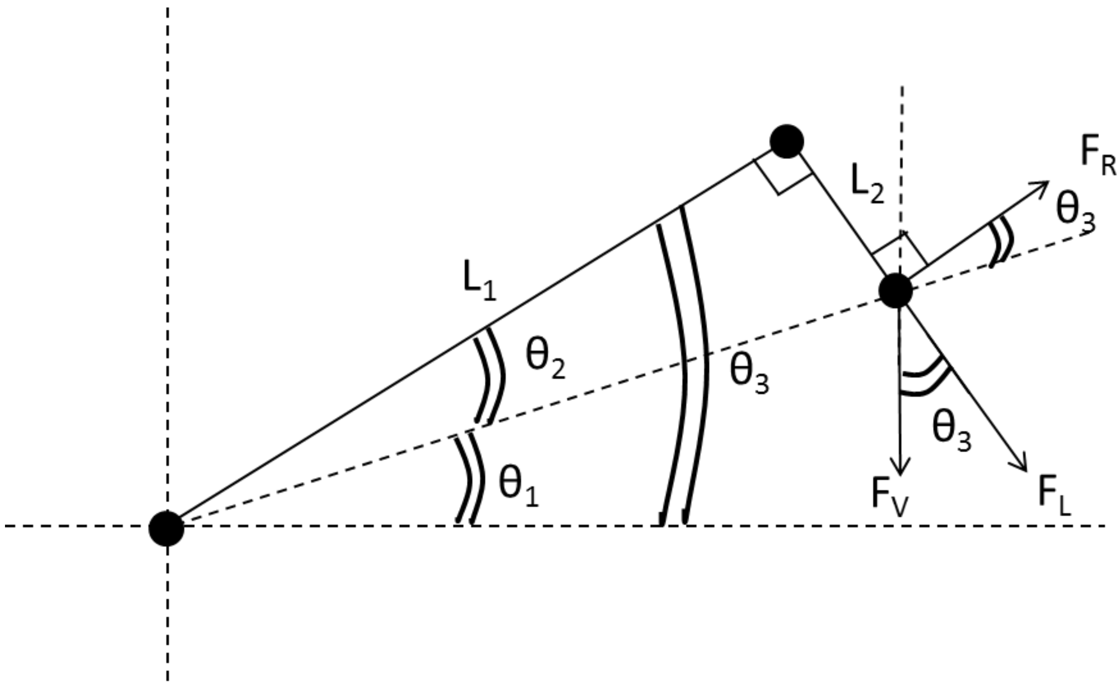
So we have:

$$w(x) = \frac{F_L}{6}x^3 + \frac{1}{2}(\tau_b - F_L L_1)x^2 + cx$$

The strain on the upper side of the crank at distance (x) is given by:

$$\varepsilon(x) \approx \frac{-t_c}{2}(L_\varepsilon F_L + \tau_A) \qquad \bigstar C$$

Calibration with weights experiment



In this case:

$$F_r = -F_v sin\theta_3$$

$$F_L = -F_V cos\theta_3$$

$$\tau_b = F_R L_2 = -F_V L_2 sin\theta_3$$

So

$$\varepsilon = \frac{t_c}{2}\left(F_V \cos\theta_3 (L_1 - L_\varepsilon) + F_V L_2 \sin\theta_3\right)$$

$$\varepsilon = \frac{F_V}{2}\left[\cos\theta_3 (L_1 - L_\varepsilon) + L_2 sin\theta_3\right]$$

Appendix 2 – Examples of participant information and consent forms

Force, velocity and power characteristics of eccentric cycling

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What is the purpose of this study?

Our primary objective is to gain a greater understanding of the force and power generated during contractions where the muscle is actively lengthening under tension (eccentric contractions). The rationale for studying eccentric muscle contractions lies in their ability to produce greater force than more traditional concentric muscular contractions. This greater force stimulates a greater adaptation which in turn could have a greater benefit to sporting performance.

Who is doing the research and why?

Dr Glyn Howatson is the senior investigator leading the project. David Green is a PhD student who will be responsible for the day-to-day running of the project. This study is part of a research project supported by the English Institute of Sport and Northumbria University.

Why have I been selected to take part?

You have been asked to consider taking part in this research project as you are male and potentially fulfil the other criteria required to take part.

Are there any exclusion criteria?

You will be one of twelve healthy adult males (BMI; 18.5-24.9 kg/m^2) between the ages of 18 – 40 currently exercising at least 5 hours per week. Prior to any experiments you will complete a health and physical activity questionnaire to ensure you are able to take part. You must be healthy, non-smoking, with no history of cardiovascular, metabolic or haematological disorders.

Once I take part can I change my mind?

Yes! After you have read this information and asked any questions you may have we will ask you to complete an informed consent form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact either investigator named at the top of this sheet. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing. If you do withdraw all data will be destroyed.

Will I be required to attend any sessions and where will they be?

Should you wish to take part in the study you will be required to attend the laboratory on five separate occasions; four times for 2 hours and once for three hours. Each session will take place in the English Institute of Sport Physiology Lab on campus at Loughborough University.

How long will it take?

Participants will be required to complete five laboratory sessions spaced out over five weeks. There are two weeks between the first and second visit and thereafter one week between visits. The total time commitment to this research project is 11 hours.

Is there anything I need to do before the sessions?

You are required to refrain from strenuous physical activity, alcohol and tobacco 24 hours prior to the experimental trials. You will also be asked to monitor your food and drink intake in the 24 hours prior to the first lab session to enable replication for subsequent sessions.

Is there anything I need to bring with me?

Nothing other than the clothes mentioned below, however you are welcome to bring a drink/snack to consume after the testing has finished.

What type of clothing should I wear?

On each visit you should bring shorts (not lycra), t-shirt and socks appropriate for exercise. There will be a private changing room made available for you. You do not need to bring cycling shoes as these will be provided in your size for each visit to the lab.

What will I be asked to do?

Visits 1-3: Eccentric force profiling

Initially you will be fitted with electromyography (EMG) electrodes (see below for details) followed by a 10 min recumbent cycling warm up. You will then perform six maximal 10 second cycling efforts at 20, 40, 60, 80, 100 and 120 RPM during which you will resist the pedals rather than pushing them. These efforts will have at least 5 minutes recovery between them.

Visit 4: Eccentric force profiling and concentric familiarisation

This visit is identical to visits 1 – 3 with the addition of six more maximal efforts on the bike at 20, 40, 60, 80, 100 and 120 RPM where you will push the pedals.

Visit 5: Concentric force profiling

The final visit will be a repeat of the final section of visit 4. You will be required to perform six maximal efforts at 20, 40, 60, 80, 100 and 120 RPM where you will push the pedals.

Experimental procedures: Electromyography (EMG):

EMG electrodes will be attached to various lower limb muscle groups to ascertain muscle activation patterns as you exercise. These are small (2cm diameter) circular sticky pads that attached directly onto the skin. The site for attachment will be prepared by shaving the site with shaving gel and a razor. This minimises stinging and pain when the electrode is removed.

Will my participation involve any psychological discomfort or embarrassment?

No

Will I have to provide any bodily samples (i.e. blood, saliva)?

No

What personal information will be required form me?

Apart from the information required from the health screening questionnaire, your height, weight and date of birth will also be required on your first visit to the laboratory.

Are there any risks in participating?

High-intensity 'all out' exercise will results in local muscle fatigue. All responses are transient and the investigators involved are vigilant in ensuring the participant's safety at all times. The participant is in complete control of the cycling ergometer at all times and can immediately cease exercise if necessary. Eccentric exercise can cause muscle soreness and stiffness which will peak approximately two days post exercise and can last up to a week. There are no negative long term consequences of this type of exercise.

Will my taking part in this study be kept confidential?

All data will be dealt with under the strictest of guidelines and according to the Data Protection Acts of 1984 and 1998. All data will remain anonymous other than to the researcher and supervisor. All data collected will be kept on a secure password protected computer system. All data will be kept until three years after the final publication when it will be destroyed. Participants are able to access any data on themselves on request.

What will happen to the results of this study?

The results of the study will be used to formulate relevant conclusions. After completion it may be used in further publication, however confidentiality will be preserved.

What do I get for participating?

Participants will receive feedback relating to their physiology as a result of the tests conducted during the study.

I have some more questions who should I contact?

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Faculty of Health and Life Sciences

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07860 783003

What if I am not happy with how the research was conducted?

If you are not happy with how the research was conducted, please contact the Northumbria University Faculty director of Ethics, Nick Neave, who will investigate your complaint.

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Force, velocity and power characteristics of eccentric cycling

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07976 632221

Name:

Gender: Date of Birth:

Participant Deceleration:

I have read the participant information sheet and fully understand what is involved in taking part in this study. Any questions I have about the study, or my participation in it, have been answered to my satisfaction. I have been informed that I am free to withdraw my consent and discontinue participation at any time. If I decide to withdraw I understand that it will not have any undesirable consequences. I have had my attention drawn to the following guidelines for research involving human subjects:

I would like to receive feedback on the overall results of the study at the email address given below:

Email address:____

I have had my attention drawn to the following guidelines for research involving human subjects:

World Medical Association Declaration of Helsinki

It has been made clear to me that, should I feel that these regulations are being infringed or that my interests are otherwise being ignored, neglected, or denied, I should inform the Northumbria University Faculty director of Ethics who will undertake to investigate my complaint.

Faculty Director of Ethics
Dr Nick Neave nick.neave@northumbria.ac.uk

Participant
Name (print) ______________________Signed:_______________ Date:

Reseracher
Name (print) ______________________Signed:_______________ Date:

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

All sections of this form must be completed

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Confidential Physical Activity Readiness Questionnaire

Full Name: ______ Date of Birth: ______

Height (cm): ______ Weight (kg): ______

Have you ever suffered from any of the following medical conditions? If yes please give details:

	Yes	No	Details
Heart Disease or attack	☐	☐	______
High or low blood pressure	☐	☐	______
Stroke	☐	☐	______
Cancer	☐	☐	______
Diabetes	☐	☐	______
Asthma	☐	☐	______
High cholesterol	☐	☐	______
Epilepsy	☐	☐	______
Other, please give details	☐	☐	______

Do you suffer from any blood borne diseases? If yes please give details; ______

Please give details of any medication you are currently taking or have taken regularly within the last year:

Please give details of any musculoskeletal injuries you have had in the past 6 months which have affected your capacity to exercise or caused you to take time off work or seek medical advice:

Other Important Information

During a typical week approximately how many hours would you spend exercising?

If you smoke please indicate how many per day:

If you drink please indicate how many units per week:

Are you currently taking any supplements or medication? Please give details:

Are you currently taking part in any other research trials? Please give details:

Signature (Participant): ______ **Date:** ______

Signature (*Test Coordinator): ______ **Date:** ______

**Test coordinator: The individual responsible for administering the test(s) and subsequent data collection.*

Response to chronic eccentric cycling

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I agree that the following tissue or other bodily material may be taken and used for the study:

Tissue/Bodily material	Purpose	Removal Method
Blood	To analyse the levels of blood lactate	Capillary sampling

I understand that if the material is required for use in any other way than that explained to me then my consent to this will be specifically sought. I understand that I will not receive specific feedback from any assessment conducted on my samples, but should any kind of abnormality be discovered then the investigator will contact me.

I understand that the University may store this tissue in a Licensed Tissue Bank only for the duration of the study, it will then be destroyed.

Method of disposal:

Clinical Waste [x]

Participant:
Name (print) _________________________Signed:_______________ Date:

Researcher:
Name (print) _________________________Signed:_______________ Date:

Appendix 3 – Rating or perceived exertion scale

RATING OF PERCEIVED EXERTION

6	
7	**VERY, VERY LIGHT**
8	
9	**VERY LIGHT**
10	
11	**FAIRLY LIGHT**
12	
13	**SOMEWHAT HARD**
14	
15	**HARD**
16	
17	**VERY HARD**
18	
19	**VERY, VERY HARD**
20	**MAXIMUM**

Appendix 4 – Visual analogue scale

How severe is your muscular soreness today? Stand in front of this scale, squat to 90 degrees and return to standing. Place a vertical mark on the line below to indicate how bad you feel your muscle soreness is today.

Take a picture of this mark including both ends of the scale and text/email it to 07729381703 or david.green@eis2win.co.uk

No soreness Unbearably sore

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