The effect of eccentric cycle training on physiological and performance parameters in cycling.

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Abstract

Prior research has demonstrated the benefits of 3 to 8 weeks of eccentric cycle training in athletes, the elderly, and in suffers of various pathophysiological conditions. Eccentric cycling requires participants to absorb force generated by an electric motor that drives a traditional cycle crank in a reverse fashion. Relative to traditional concentric cycle training, eccentric cycling is lower in metabolic cost and facilitates greater force production through multi-joint leg actions.

Chapter 2 reports on an investigation that utilises an eccentric cycling ergometer to evaluate and observe the influence of eccentric cycle training on a range of key performance parameters, and physiological measures on a well-trained cycling population. Specifically, in this novel study we assessed the physiological performance measures of leg spring stiffness, 4 s mean maximal sprint power, 4-km time-trial performance, and economy prior to, during, and following periodised eccentric cycle training. The investigation recruited eight healthy well-trained male participants (mean ± SD; age: 33 ± 12 yr; mass: 80 ± 11 kg; VO_2peak: 64 ± 8 ml.kg^{-1}.min^{-1}) to take part in a 6 week, 12 session eccentric cycling study. Utilising a commercially available eccentric ergometer (Cyclus2, Leipzig, Germany), the participants replaced two hours of their weekly cycle training, with eccentric cycling. Initial training loads were prescribed based on 25% of participant 4 s mean maximal sprint power (MM4SP). Stepwise increases of training load occurred every 3rd training session. Assessments of submaximal hopping to evaluate leg spring stiffness, 4 s mean maximal sprint power and 4-km time-trial performance were conducted, prior-to, during the 3rd week (Mid), and 1 and 4 weeks following the eccentric cycling intervention. Over a 6 week period, this stepwise approach led

to an increase in workload from 25% to 50% of participant MM4SP. Overall participants achieved 97 ± 4% of their individual prescribed training load during the 6 week eccentric cycling training intervention.

Relative to baseline measures, muscle stiffness effects were *very likely positive* (35.8 ± 30.4%) at week 3 (Mid), and at 1 week post (57.7 ± 22.3 and 46.6 ± 26.0%) week 4 post intervention. Effects for 4 s mean maximal sprint power were *likely beneficial* at 60 rpm at week 11 relative to both baseline, and week 7. Similarly, *likely beneficial* effects were reported at 120 (week 7 – pre), and 135 rpm (week 11 – pre). 4-km time-trial performance, at Mid (mean ± SD %: 0.2 ± 2.8%), and 1 week (0.7 ± 2.3%) post-training produced *unclear* alterations, while *likely beneficial* improvements were seen at week 4 (2.3 ± 3.6%) post-training. The findings of the current study suggest that 12 sessions of eccentric training over a 6 week period improved 4-km time-trial performance, and muscle stiffness within a well-trained population. Outcomes for the remaining endurance and sprint performance related measures however predominantly resulted as unaltered or *unclear* over the participant population.

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Abbreviations

CL – Confidence limits

CMJ – Counter movement jump

CON – Concentric cycling

CTRL – Control

CV – Coefficient of variation

DOMS – Delayed onset of muscle soreness

EMG – Electromyographic

ES – Effect size

HR – Heart rate

hr – Hour

$hr.wk^{-1}$ – Hours per week

IPPO – Incremental peak power output

ISAK – International society for the advancement of kinanthropometry

kg – Kilogram

kJ – Kilojoules

km – Kilometre

$_{K}N/m$ – Kilonewton metre

$L.min^{-1}$ – Litres per minute

MHCs – Myosin heavy chains

Mid – Week 3 assessment

Min – Minute

$ml.kg^{-1}.min^{-1}$ – Millilitres of oxygen consumed per kilogram per minute

MM4SP – Mean maximal 4s sprint performance

MMP – Mean maximal power

MPO – Mean power output

MS – Muscle stiffness

P1 – Post week 1 assessment

P4 – Post week 4 assessment

Pmax – Maximal power output

Pre – Baseline assessment

RPE – Rate of perceived exertion

rpm – Revolutions per minute

s – Second

SD – Standard deviation

SRM – Schoberer rad messtechnik

SSC – Stretch shortening cycle

TT – Time-trial

VO_2 – Volume of oxygen consumption

VO_2peak – Peak volume of oxygen consumption

W – Watt

$W.kg^{-1}$ – Watt's per kilogram

$W.min^{-1}$ – Watts per minute

yr – Year

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Thesis Overview

The format of this thesis includes a chapter that is presented in the style of individual journal article, and consequently, some information may be repeated. The thesis is comprised of three chapters; Chapter 1 contains a review of the literature available and introduces the reader to eccentric exercise as well as the concept of eccentric cycle training. Chapter 2 focuses on the effects eccentric cycle training has on cycling performance in well-trained cyclists, presented in the style of an individual journal article. The final chapter (chapter 3) summarises the overall findings from the previous chapters included in this thesis and provides both practical applications and suggested areas for further research.

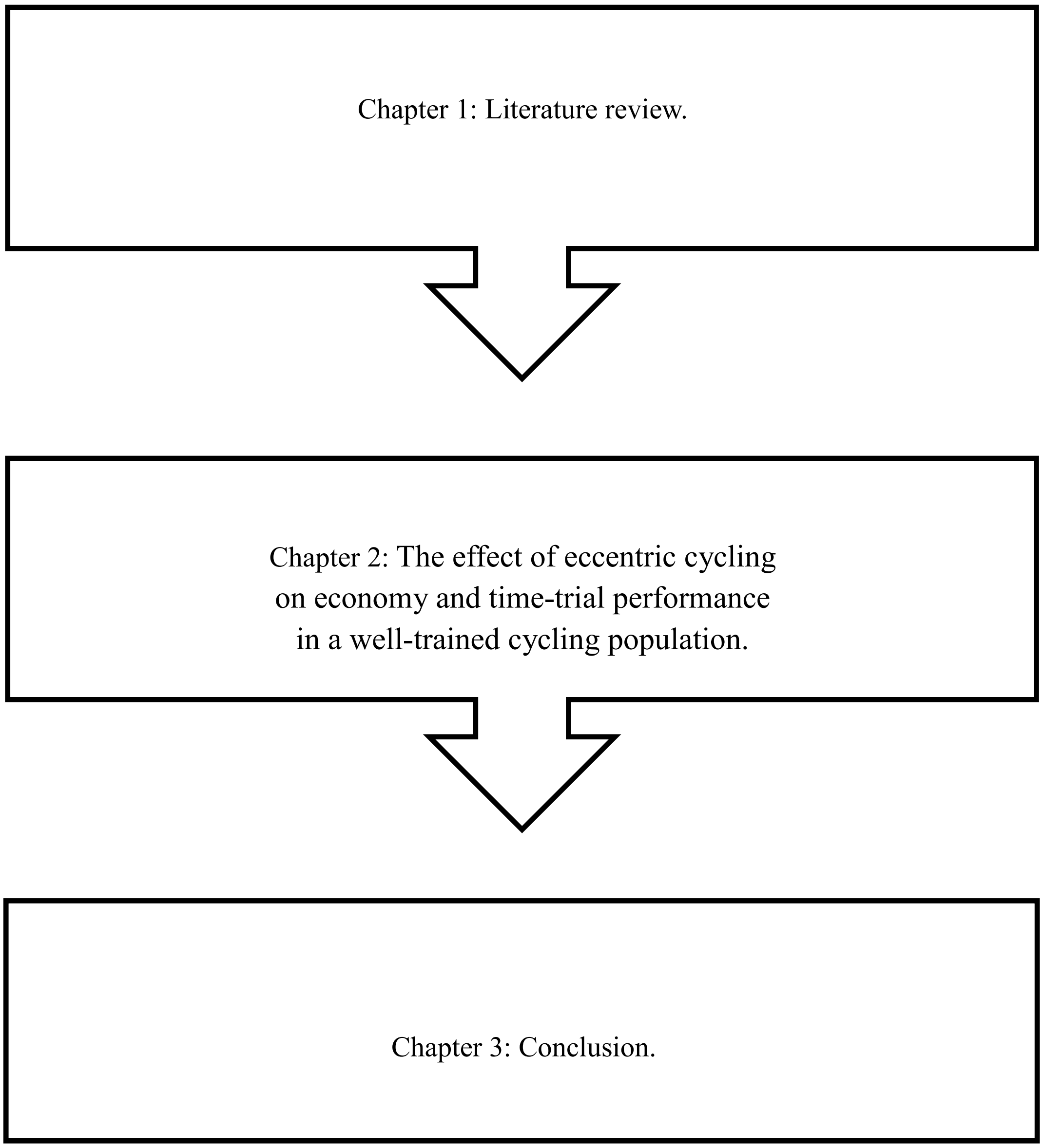

Figure 1: Schematic of the thesis structure

Chapter 1:

Literature Review

Introduction

Eccentric work is essential to our daily activities (Dickinson et al., 2000; Lindstedt, LaStayo, & Reich, 2001), it is characterised by a low metabolic energy demand, and an ability to produce high power outputs, relative to a singular concentric movement (Hortobágyi, Devita, Money, & Barrier, 2001; LaStayo, Pierotti, Pifer, Hoppeler, & Lindstedt, 2000). Traditional training of eccentric movements are generally performed with the use of free weights (barbells), dynamometers or cycle ergometers (Vogt & Hoppeler, 2014) resulting in research concluding with augmentations in eccentric strength enhancing stretch shortening cycle (SSC) dependent multi-joint actions (e.g. countermovement jump) (Elmer, Hahn, McAllister, Leong, & Martin, 2012). Improvements witnessed in multi-joint actions suggests that eccentric training may be vital in improving locomotive tasks, through the coupling of dominant locomotion eccentric and concentric muscle actions (Lindstedt et al., 2001).

Locomotion is accomplished by three types of muscle action: muscle shortening (concentric), muscle lengthening (eccentric), and isometric actions, muscle contraction without any visible movement of the joint (Fang, Siemionow, Sahgal, Xiong, & Yue, 2001; Linnamo, Moritani, Nicol, & Komi, 2003). Concentric and eccentric muscle contractions are dominant in locomotion, concentric pushes against the effects of gravity and eccentric contractions are seen during deceleration or braking, resisting the effects of gravity while absorbing mechanical energy. This can be observed when walking, as uphill walking is primarily concentric work, downhill walking is predominantly eccentric work, and level walking is a combination of both (Pimental, Shapiro, & Pandolf, 1982) (Figure 2). Mechanical energy absorbed through such actions (e.g. walking) may add additional force to the subsequent concentric action or be dissipated as heat when used in a dampening manner (Douglas, Pearson, Ross, & McGuigan, 2016) (Figure 4).

Traditional training interventions to improve physiological parameters and performance ability in regards to cycling have typically focused on a high volume and moderate intensity approach (Lucia, Hoyos, Margarita, & Chicharro, 2000; Schumacher & Mueller, 2002), with cyclists completing on excess of ~35,000 km per year. As such, an exploration of alternate training modalities have allowed for more off bike training approaches. Often these have been undertaken utilising movements of an explosive nature, in frequent high intensity intervals (Hansen, Rønnestad, Vegge, & Raastad, 2012). However, off bike training approaches typically overlook the enhancement eccentric training modalities may provide, as research is typically conducted over concentric based interventions. A recent eccentric training intervention (Elmer et al., 2012), reported that when match for work load participants of an eccentric training group had greater leg spring stiffness and maximum jumping power compared to participants in a concentric training group following work-matched training. This demonstrates eccentric work to be greater for the improvement in recovering of mechanical energy within active muscle. Furthermore, enhanced leg spring stiffness would be a key physiological factor in the enhancement endurance economy (Elmer et al., 2012).

Within the first section of this thesis, numerous theories and mechanisms associated with eccentric cycle training are introduced; these include neural alterations, metabolic load, force production and reduced training time alongside the available literature conducted around Eccentric training interventions.

Resistance training for cycling performance

Success in competitive road cycling relies on a combination of physiological (Quod, Martin, Martin, & Laursen, 2010), aerodynamic/biomechanical (Fintelman, Sterling, Hemida, & Li, 2016), tactical (Abbiss, Menaspà, Villerius, & Martin, 2013), and environmental (Peiffer & Abbiss, 2011) factors. At the elite level, cyclists have a designated role within their professional team based on their physiological make-up. For instance, riders can be classified into a hill-climbing specialist, time-trialist or a domestique depending on their innate physiological characteristics (Alejandro Lucia, Hoyos, Santalla, Earnest, & Chicharro, 2003). Regardless of their team responsibilities, it is acknowledged that elite cyclists not only possess some of the highest physiological related measures in the human population (Zapico et al., 2007), but these performance indicators also contribute to the differences in competition outcomes relative to lesser-trained cyclists (Lucía, Pardo, Durántez, Hoyos, & Chicharro, 1998). As such, there is no doubt that the physiological abilities of elite cyclists allows the application of substantial power output over a sustained period of time for cyclists during key races, such as time-trial events (Lucia, 2004), or in the mountain stages of a race (Vogt et al., 2007;Vogt et al., 2006).

Competitive road cycling often requires cyclists to compete in single or multiday races, with stages often lasting between 3 to 6 hrs (Alejandro Lucia et al., 2003; Rehrer, Hellemans, Rolleston, Rush, & Miller, 2010). Additionally, cyclists are required to frequently sprint for short to moderate durations (Abbiss, Straker, Quod, Martin, & Laursen, 2010) such as when attempting to establish a breakaway from the peloton (Abbiss et al., 2013). In this instance, cyclists are required to perform short duration surges of 5 to 15 s at, or above 900 to 1000 W, equating to 9.5 to 14 $W.kg^{-1}$, with maintenance of power output remaining at ~500 W for up to a 5 min interval, once the breakaway from the peloton is established (Abbiss et al., 2013). The intermittent and polarised nature of road racing places a range of demands across both the anaerobic, and aerobic energy systems, which collectively contributes to rider fatigue (Abbiss et al., 2010). Traditionally, in order to improve these key physiological parameters, and therefor performance ability, cyclists have focused on a high volume, moderate intensity training approach (Schumacher & Mueller, 2002). This training approach, which often requires the cyclists to complete ~35,000-km in a calendar year, is undertaken despite the previously identified stochastic demands of competitive road cycling (Abbiss et al., 2010; Ebert et al., 2005; Vogt et al., 2006). While the longer duration, moderate intensity training approach has proven beneficial for competition in steady-state events of 4 min at ~VO_2peak intensity (Schumacher & Mueller, 2002), it is obvious that a substantial and dedicated investment of time is required from the athlete in order to achieve such high training volumes.

In order to improve training efficiency, cycling coaches and team sports science practitioners have explored a range of alternate training methods to enhance cycling physiology and key performance parameters. Notably, a number of these methods have focused on the use of short-duration, high- to maximal-intensity exercise regimes employing both cycling and non-cycling exercises. Cycling related training programs have included the manipulation of cadence (Rønnestad, Hansen, Hollan, & Ellefsen, 2015), or the incorporation of high-intensity interval training (Stepto, Hawley, Dennis, & Hopkins, 1999; Sylta et al., 2016) into traditional moderate intensity training. Off the bike training programs have previously typically incorporated the use of traditional resistance training (Hansen, Rønnestad, Vegge, & Raastad, 2012), or explosive resistance training in combination with high-intensity intervals (Beattie, Carson, Lyons, & Kenny, 2017; Paton & Hopkins, 2005). Notably, the majority of these approaches have demonstrated beneficial effects for cycling performance in competitive cyclists with improvements as great as ~9% for 1-km time-trial performance (Paton & Hopkins, 2005), and between 7 to 8% for events of ~5 min (Hansen et al., 2012; Paton & Hopkins, 2005). Given that the margin between winning, and losing road cycling races can be as little as just 1% (Paton & Hopkins, 2006), improvements as large as those from the aforementioned training methods are then worthy of consideration.

Of particular interest to coaches and sports scientists is the role that strength training appears to play. Numerous authors have reported improvements in sprint performance (Beattie et al., 2017), neuromuscular function (Hausswirth et al., 2010), economy and endurance performance (Hansen et al., 2012; Paton & Hopkins, 2005). However, due to the possibility of gains in body mass due to the effects of hypertrophy of muscle, the role of resistance training in road cycling can be somewhat contentious (Mujika, Rønnestad, & Martin, 2016). Increases in body mass are likely to have a negative performance effect, particularly in events involving regular and long durations of substantial aerobic demand (e.g. hill climbing). Nevertheless, numerous authors have demonstrated positive outcomes in both well-trained cyclists without the further addition of body mass (Beattie et al., 2017; Hansen et al., 2012), suggesting that the concurrent training of endurance and strength can compliment each other without gains in body mass, in addition to added performance gains.

The beneficial findings reported as a result of resistance training are not unique to cycling, as previous research into the effects of strength training in runners reported that 9 weeks of resistance training including plyometric exercise led to improvements in anaerobic capacity, running economy, and 5-km performance in trained endurance runners (Paavolainen, Häkkinen, Hämäläinen, Nummela, & Rusko, 1999). The authors of this study suggested that the beneficial effects were as a result of improvements in the neuromuscular system, and occurred without an increase in body mass (Paavolainen et al., 1999). Notably, despite a number of key performance measures improving, Paavolainen et al., (1999) noted that neither VO_2peak or lactate threshold improved as a result of training. The authors then left to suggest that anaerobic capacity improvements were likely due to an enhanced neuromuscular function potentially via increased muscle stiffness (Paavolainen et al., 1999).

Recently, in recreational sporting populations, eccentric cycling sessions over a 6 to 8 week period have demonstrated improvements in maximum jumping power, maximum cycling power output and leg spring stiffness (Elmer et al., 2012; Leong, McDermott, Elmer, & Martin, 2013) to that of a concentric cycling training group when match for workload (Elmer et al., 2012). This could in part be due to eccentric groups being able to sustain higher working forces than concentric groups (Elmer, Madigan, LaStayo, & Martin, 2010) at a lower metabolic rate (Abbott & Bigland, 1953; Abbott, Bigland, & Ritchie, 1952) resulting in greater increases in strength in sprint performance over ascending rpm in 4s intervals, reported to increase 9% (Leong et al., 2013). This improvement in sprint performance corresponds with an increase in thigh girth specifically the vastus lateralis and rectus femoris by 24% and 13% (Leong et al., 2013) respectively. In addition to an improvement in strength, an ~80% difference in lowered metabolic demand (Abbott & Bigland, 1953; Abbott et al., 1952; Elmer et al., 2012) associated with bouts of eccentric cycle training is also been reported. Additionally, and importantly for athletes regularly undertaking concurrent training sessions, eccentric cycle training has enabled populations to complete the same training load (volume x intensity) in a shorter period of time (Elmer et al., 2012), to that of traditional resistance training.

Summary

Given the energetic demands road cycling places on well-trained cyclists, it would appear beneficial to incorporate forms of eccentric training into traditional road training interventions, as participants are able to complete the same training load in a more time effective manner. Notably, eccentric cycle training appears to improve single-joint, as well as multi-joint leg function in comparison to traditional resistance training witnessed through the improvement of sprint performance. Such improvements will allow for better recycling of mechanical energy and overall improved effects in economy during multi-joint tasks (i.e. cycling, running). Therefore, the current review of available literature will discuss aspects of eccentric cycle training on a range of physiological and performance measures in healthy participants.

Definition of concentric and eccentric exercise

A concentric movement occurs when muscular activity exceeds the external force applied to the muscle. Conversely, eccentric movement occurs because of the external force applied overcomes the muscle activity. The combination of these two movements can be seen in human locomotion where concentric (muscle shortening) push against the effects of gravity, and eccentric (muscle lengthening) contractions are used during deceleration or braking, resisting the effects of gravity while absorbing mechanical energy (Figure 2). Additionally, an eccentric movement results in energy being absorbed by the muscle (Moritani, Muramatsu, & Muro, 1988). During any subsequent concentric movement, the contribution of this stored energy assists concentric movement by as much as 20% (Lindstedt et al., 2001). This contribution action is more commonly known as the stretch shortening cycle (SSC). If action is unsuccessful and a concentric movement does not follow an immediate eccentric action heat will be displaced through the active muscle (Moritani et al., 1988).

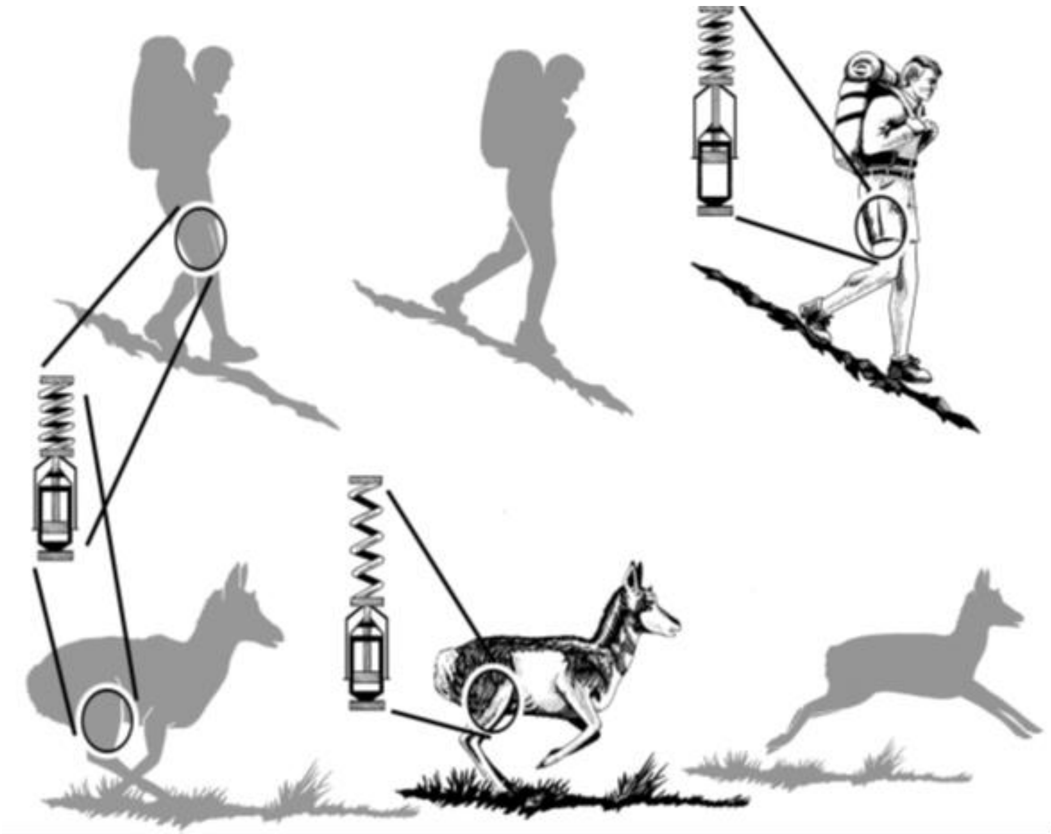

Figure 2: Eccentric muscle action. During active muscle lengthening, an eccentric contraction behaves like a shock absorber or spring. When hiking downhill, energy that stretches the active muscle is lost as heat in a dampening fashion (shown as an extension of the dampening shock). When running the energy required to stretch the muscle is stored as elastic recoil energy in a spring like fashion (shown as an extension of the spring), this recoil energy can be recovered during the subsequent concentric contraction. Recovery of elastic recoil energy is dependent on both the forces involved as well as the spring property of the active muscle. Retrieved from Lindstedt et al, (2001).

Modalities of eccentric training

The majority of eccentric training interventions have typically been carried out using a range of traditional weight training equipment such as barbells, dumb-bells and pulleys (Vogt & Hoppeler, 2014). This form of eccentric exercise training will frequently use either isotonic or isokinetic training modalities (Isner-Horobeti et al., 2013). Isotonic modalities apply constant mass to the active muscle, such as body mass or, an additional external load, in conjunction with gravity to lengthen the active muscles. By comparison, isokinetic eccentric based modalities typically utilise mechanical devices that maintain a constant force at an angular movement, or speed, resulting in active muscle lengthening (Isner-Horobeti et al., 2013). In eccentric research, isokinetic interventions have typically been investigated with results demonstrating improvements in overall strength of the active muscle (Miller et al., 2006). Indeed, over a 6 to 8 week period, eccentric movements utilising iso-kinetic movements, have resulted in strength increases of between 10 and 77% in the lower body (Blazevich, Cannavan, Coleman, & Horne, 2007; Miller et al., 2006). Meanwhile, similar training durations utilising an isokinetic eccentric device have resulted in improvements in sprint performance of between 5 to 9% (Leong et al., 2013). Similarly, jump height has been shown to improve by 7% after 7 weeks eccentric training using a similar isokinetic device (Elmer et al., 2012).

The first eccentric cycle ergometer reported in peer-reviewed literature was de-signed by Abbott, Bigland, & Ritchie in 1952, the ergometer was constructed with the use of two standard bicycles coupled together facing in opposite position. This enabled one participant to pedal conventionally, and the second participant to resist (Abbott et al., 1952), thus eliciting eccentric loading (Figure 3). Subsequent ad-vances in 1953 and in 1969 saw the addition of motor power, initially via a 2.5

horse-power motor (Abbott & Bigland, 1953) (Figure 6), and subsequently a 6.0 horse-power motor (Bonde Petersen, 1969). More recent literature, newly developed eccentric cycle ergometers have been successfully implemented as a novel resistance training stimulus in a range of populations (Elmer et al., 2012), including highly-trained athletes (Gross et al., 2010). Due to the positive physiological results seen by authors these initial eccentric ergometers have been refined and superseded, and are now offered on a commercial basis (Cyclus2, Leipzig, Germany, Figure 8).

Biomechanical results demonstrate participants utilising eccentric ergometers absorb force through the knees and hips (Elmer et al., 2012). This has resulted in eccentric exercise now being used for evaluating muscle strength, muscle stiffness (Elmer et al., 2012; Leong, McDermott, Elmer, & Martin, 2013), and for rehabilitation purposes (Kellis & Baltzopoulos, 1995) of muscle in the knee and hip joints. The use of eccentric ergometers has resulted in the enhancement of hypertrophy, and strength relative to more conventional mixed concentric/eccentric training methods (Hortobágyi et al., 2001; Vikne et al., 2006). Additionally, eccentric contractions have an ~80% lower metabolic demand than that of concentric only training (Abbott et al., 1952; Elmer et al., 2012) indicating that cardiovascular load is far lower for the same power output that would be produced concentrically. This suggests that, eccentric training populations are able to complete the same training load (volume x intensity), over a shorter time period, at lower metabolic cost, relative to a concentric training group (Elmer et al., 2012).

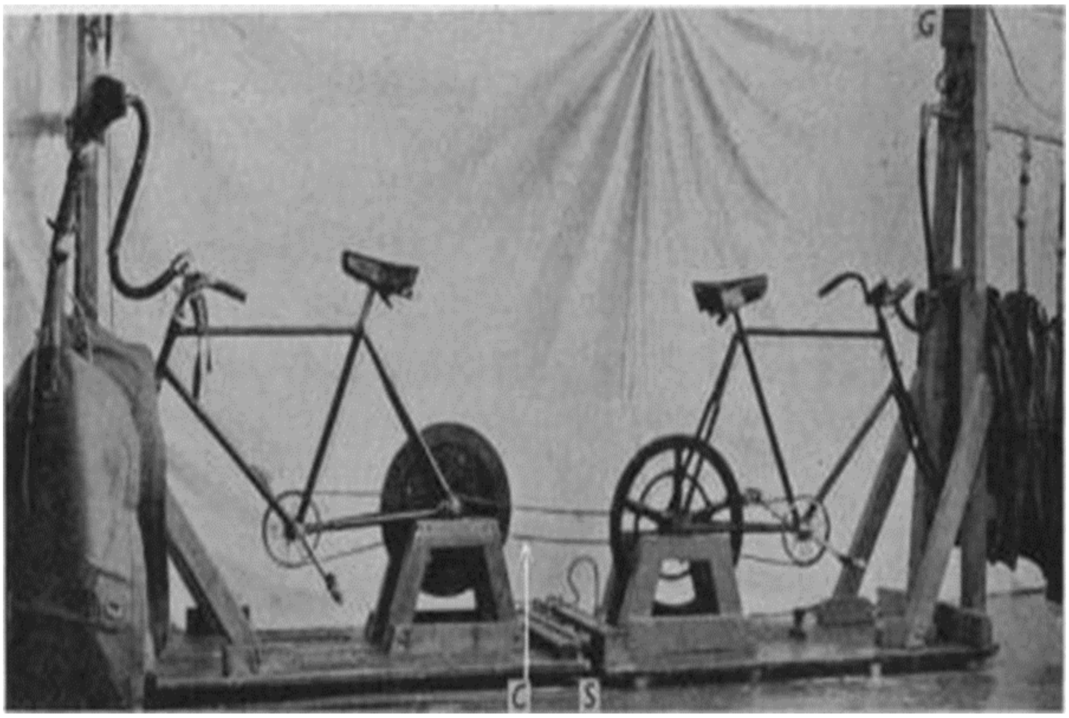

Figure 3: First eccentric cycle ergometer. Reproduced from Abbott, Bigland, & Ritchie, (1952), comprised of two standard bicycles coupled together facing in opposite position allowing for one participant to pedal conventionally and a second to resist, using an eccentric contraction.

Summary

An isokinetic/eccentric high intensity-low volume approach, often leads participants to complete high workloads resulting in improvements in strength, sprint performance, and jump height. Physiological adaptions made through an eccentric training intervention are due to an enhancement of hypertrophy and strength completed at a lower metabolic demand compared to that of traditional concentric training. Therefore, eccentric training modalities appear far more beneficial in completing a training load (volume x intensity), relative to a traditional concentric training intervention.

Characteristics, attributes and neural alterations of eccentric work

Adaptive responses made through eccentric work are thought to be due to the recruitment of satellite cells and other transcriptional pathways, with an appropriate stimulus (e.g. muscle damage through exercise) activating satellite cells to migrate to the active area, fusing too and surrounding the muscle (Cermak et al., 2013; Toigo & Boutellier, 2006). Following eccentric training, satellite cell recruitment has shown to increase from 30 to 150% (Cermak et al., 2013; Dreyer, Blanco, Sattler, Schroeder, & Wiswell, 2006; Leong et al., 2013). Once recruited to the active area, satellite cells will then go on to produce daughter cells and subsequently new myonuclei will form, this in turn will increase the capacity for protein synthesis (Dreyer et al., 2006). Following eccentric training (300 eccentric actions of the knee extensors on an isokinetic dynamometer) Cermak et al., (2013) demonstrated the significant increase in satellite cell recruitment within the adaptation of type II fibers; this is in contrast to that of no apparent change witnessed within type I fibers. This can be demonstrated in recent eccentric training reports (Elmer et al., 2012; Leong et al., 2013) as the explosive component, jump performance, which utilises type II fibers has been a dominant reporting after eccentric cycle training. The differences noted between that of satellite cell recruitment in eccentric, and concentric movement under maximal conditions have been investigated using three applications: surface electromyography (EMG), twitch interpolation and single motor unit assessment (Duchateau & Baudry, 2014). This has led to several unique attributes and characteristic observations being reported on healthy participants following an eccentric cycle training intervention.

Activation strategies

In order to report on the physiological adaptations made through an eccentric training intervention, it is common practice to provide participants with a familiarisation period. This is to allow familiarisation to any of novel movement patterns involved. Previous literature focusing on eccentric work has reported that as little as a single familiarisation session is sufficient to allow for muscular adaption that would in turn limit further muscle soreness, a consequence to the physiological stresses of eccentric movement training (Dufour et al., 2004). Focusing on literature utilizing eccentric training modalities, 3 to 4 familiarisation sessions are often incorporated to ensure that the muscle soreness response is minimal and will allow participants to accustom themselves with the specific coordination patterns of an eccentric cycling ergometer (Dufour et al., 2006; Perrey, Betik, Candau, Rouillon, & Hughson, 2001). Although, there is a need for a familiarisation period, no data has been published on what the average workload or variation over initial eccentric cycle trials should be. A need for a familiarisation period is to reduce passive tension, swelling, and any increases in muscle hardness (Murayama, Nosaka, Yoneda, & Minamitani, 2000) that may contribute to a reduction in the range of joint movement following eccentric training (Clarkson, Nosaka, & Braun, 1992). Initial adaptions can also be meet with a negative effect to the sense of force needed to be produced within the active muscle (Douglas et al., 2016), impairments predominately seen in locomotion through sporting tasks and an impairment to higher intensity exercise.

Previous studies that focus on examination of eccentric training (Table 1) comprised interventions that where on average no longer than 12 weeks and involved 2 to 3 sessions/week with only few investigations opting to train 5 sessions per week.

Throughout, sets and repetitions where reported to increase in a stepwise fashion alongside the duration of the training modality. Strength gains produce on average an increase of up to 1.2% and 2.4% when measured eccentrically (Vogt & Hoppeler, 2014). Furthermore, eccentric modalities using a low intensity high volume approach on initially untrained participants has led to larger strength gains than that of concentric training (Dufour et al., 2004; Lindstedt et al., 2001). Alongside an initial improvement in strength, it has been demonstrated that both strength and improved cross-sectional area mass may take up to 3 months post eccentric movement training to return to initial pre intervention levels (Andersen, Magnusson, & Aagaard, 2005). This indicates that the results of eccentric training on force production will be maintained for a greater extent of time compared with that of concentric training on force production (Poulin, Vandervoort, Paterson, Kramer, & Cunningham, 1992). Leong et al., (2013) was able to demonstrate this indication within a typically untrained healthy population as strength reported to show improved effects of 9% after an 8 week intervention, such effects were also maintained after 8 weeks post intervention.

Exercise-induced muscle damage and increased force production

Eccentric training, specifically the physiological activation of such movements is associated with a greater delay of onset muscle soreness (DOMS) and acute strength losses within initial session (Cleak & Eston, 1992) particularly within the 24-hr period post-exercise, and peaking within the following days (Cleak & Eston, 1992). DOMS refers to the dull, aching pain felt during movement or upon palpation of the effected tissue and often accompanies exercise induced muscle damage (Clarkson et al., 1992). The loss in strength as a result of eccentric work has been reported to be as long as one week post initial eccentric training session (Douglas et al., 2016; Guilhem, Cornu, & Guével, 2010; Murayama et al., 2000). With strength loss creatine kinase has been reported to be elevated after bouts of eccentric work (Booth & Baldwin, 2011; Ebbeling & Clarkson, 1989). With this enzymes elevated presences within the blood it indicates that eccentric training has elicited a higher work load to caused sufficient damage to the muscle membrane eliciting physiological changes to its permeability, as under traditional concentric resistance training conditions creatine kinase will not leak from the myocyte (Lee et al., 2002). Exercise induced muscle damage as a result of eccentric training is characterised by the increase in creatine kinase and skeletal troponin I alongside myoglobin, and myosin heavy chains (MHCs) (Tee, Bosch, & Lambert, 2007), and is known to impair force and power production (Isner-Horobeti et al., 2013) of participants in everyday tasks after an initial training sessions.

Physiological adaptions observed within participants conducting an eccentric cycle training intervention can be best described with the aid of previous work produced by Paavolainen et al., (1999). In this instance eccentric cycle training (resistance training) will elicit large effects to a participants neuromuscular capacity and moderately large effects to systems of anaerobic power, which in turn regulate lactic acid production, having moderately large effects in increasing lactate threshold which will have overall large effects on endurance exercise performance of eccentric movement. Allowing participants to train an eccentric movement at a higher intensity and for a longer duration of time without the fear of DOMS.

Muscle damage produced by eccentric contractions is independent of intensity particularly during initial trials (Paschalis, Koutedakis, Jamurtas, Mougios, &

Baltzopoulos, 2005), and during equal volumes of high and low intensity eccentric contractions will elicit similar amounts of muscle damage. (Vallejo, 2006). Work by Paavolainen et al., (1999) reported, eccentric cycle training (resistance training) to elicit large effects to a participant's neuromuscular capacity, which in turn will have a large effect on movement efficiency and overall a large *positive* effect on endurance performance. This improvement in endurance performance is due to high force eccentric contractions causing mechanical actomyosin detachment (Flitney & Hirst, 1978). This detachment causes a high strain on muscle fibers and could explain the increased tissue damage associated with trials of high force eccentric contractions (Enoka, 1996). This high force production of eccentric contractions is due to activation/bonding of a second myosin head, whereas during isometric and concentric contractions only one myosin head is bound, twice the bonding, twice the number of active cross-bridges during active lengthening leading to increased force production (Linari et al., 2000) overall improving endurance exercise performance.

Reduced metabolic demand

Abbott et al., (1952) has demonstrated that oxygen consumption was 2.4 times greater at 25 rpm during concentric training compared to that of eccentric training when using a coupled bicycle ergometer of equal force production. Subsequently, Bigland-Ritchie, Graichen, & Woods, (1973) reported similar results during eccentric training due to muscle activation in the concentric group being 1.5 to 3 times greater at 30, and 100 rpm, respectively. This is supported by the findings of Abbott et al., (1952) who reported that oxygen consumption differences are partly due to less active muscle fibers during eccentric training related to an concentric training group (Abbott et al., 1952). Greater oxygen consumption during concentric work of the lower limbs is predominately due to increasing force production of the quadriceps at higher workloads, in turn eliciting core stabilisers to perform greater isometric contractions leading to a higher oxygen consumption during concentric contractions to that of eccentric contractions (Perrey et al., 2001). This has been demonstrated in reports of downhill running, an eccentric movement requiring a lower oxygen consumption when compared to level or incline running (Mueller & Maluf, 2002), and in reports of eccentric over concentric cycle training (Abbott et al., 1952; Dufour et al., 2004; Perrey et al., 2001). Lowered oxygen consumption during eccentric cycle training will lead to a decrease cardiac index responses compared to concentric work (Vallejo, 2006), this suggests that eccentric resistance training is metabolically more efficient in improving strength as it requires less oxygen consumption to produce greater force (Cowell, Cronin, & Brughelli, 2012; Guilhem et al., 2010). The lower metabolic cost is due to isolation of the active muscle alongside recycling of mechanical energy, this is known as SSC in human locomotion. The lower metabolic intensity associated with eccentric training will typically result in lower perceived exertion, blood lactate accumulation, energy expenditure, and carbohydrate oxidation as well as higher fat oxidation during exercise bouts than that of concentric training when matched for mechanical workload (Peñailillo, Blazevich, & Nosaka, 2014). As eccentric exercise has shown to be, a greater training intervention for improved metabolic efficiency when matched for workload it would therefore be possible to attain a higher workload for longer with eccentric training relative to concentric training.

Stretch shortening cycle

SSC is important in improving exercise locomotion in many sports, and everyday functions (Lindstedt et al., 2001). SSC is a short and fast eccentric phase followed by an immediate transition to the concentric phase on ground contact (Komi, 2000; Vogt & Hoppeler, 2014) this is when the muscle acts in a spring like manner (Lindstedt et al., 2001) recycling mechanical energy (Figure 2 & 4). Recycling of mechanical energy is demonstrated when a contracted muscle is lengthen by an external force, the mechanical energy of the active muscle is temporarily stored in a series of elastic components to be recovered during a subsequent concentric muscle action (Lindstedt et al., 2001). However, this mechanical energy is dissipated as heat if not alternatively recovered (Moritani et al., 1988). Slow SSC recoil is witnessed during sports where angular displacement and ground contact is high. Fast SSC movements such as sprinting are characterised with shorter angular displacement, and ground contact time. The faster the transition, the greater mechanical energy stored within a series of elastic components resulting in locomotion requiring very little metabolic energy for force production (Lindstedt et al., 2001). This spring like transition is referred to as tendomuscular or muscle stiffness. Enhancement of muscle stiffness is achieved through training methods that force the muscle to lengthen, i.e. eccentric cycle training. The end result being an improvement in recoil through recycling of mechanical energy to the concentric phase (Vikne et al., 2006). Paavolainen et al., (1999) (Figure 2, 4 & 5) demonstrates this with the improvement in neuromuscular capacity witnessed in reports of muscle elasticity having *positive* effects of movement efficiency during endurance performance. However, recycling of mechanical energy is time dependent on transition during SSC (Moritani et al., 1988). A loss of SSC transition efficiency results in a decrease in power output during the concentric phase (Vogt & Hoppeler, 2014).

Injury prevention

The majority of athletic injuries occur during the transition between the concentric and eccentric contraction of the muscle (SSC) due to the inadequate or unbalanced muscle strength applied to the active movement (Arnason, Andersen, Holme, Engebretsen, & Bahr, 2008). In sports such as sprinting, where there is a regular high force transition between concentric and eccentric contractions training through forms of active lengthening within this instance eccentric training can decrease the risk of injury (Brughelli & Van Leemputte, 2013). As active lengthening through eccentric muscle exercise is the only known form for muscle lengthening it would stand to reason that this would be an ideal training intervention for injury prevention (Stanton & Purdam, 1989). This is due to eccentric exercise training allowing for muscle that is highly malleable in structure and function to adapt to the demands placed upon it through active lengthening (Booth & Baldwin, 2011). Like all biological tissues, modifications to the relative level of physical stress to muscle produced via training modalities result in an appropriate muscle adaptation for a given movement pattern (Mueller & Maluf, 2002)

Summary

Adaptive responses made through high intensity-low volume eccentric cycle training are due to an increase in hypertrophy eliciting a larger increase of 30 to 150% in the recruitment of satellite cells, and other transcriptional pathways. This recruitment allows for the increase in the capacity of protein synthesis within the adaptation of type II muscle fibers, which is witnessed in the improvement of strength, sprint performance, and jump height post eccentric cycle training due to the activation/bonding of a second myosin head within active muscle. To report on improvements to physiological adaptation participants are required to go through 3 to 4 familiarisation sessions to limit further muscle soreness, passive tension, swelling, and increases in muscle hardness. Overall, this will have a negative response to the sense of force production seen in locomotion a negative result following an initial eccentric cycle training session. Alongside the positive physiological adaptations to strength, sprint performance, and jump height, an improvement in muscle elasticity will aid injury prevention while helping to improve the recycling of mechanical energy through the muscle of participants completing an eccentric cycle training intervention.

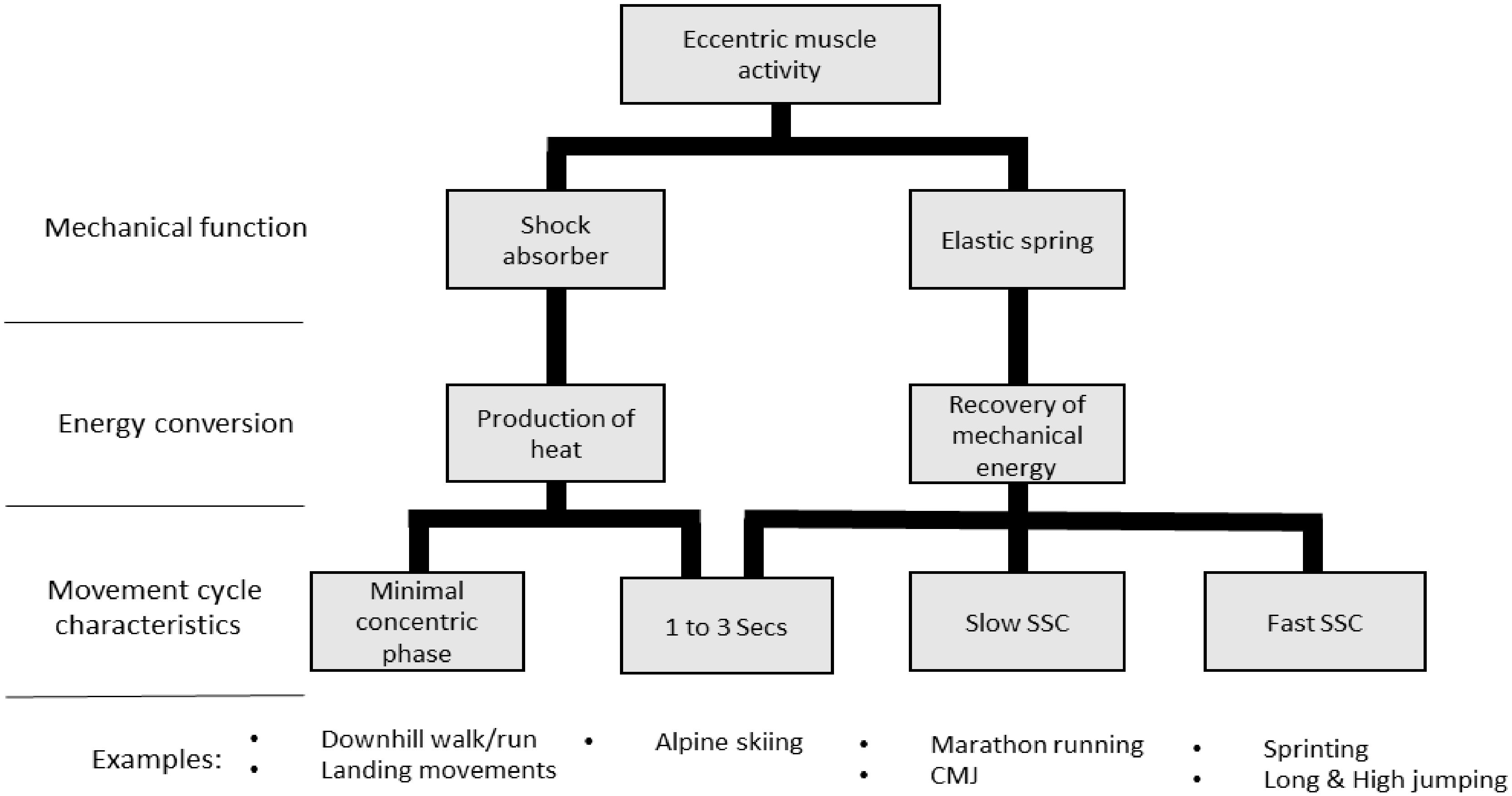

Figure 4: Eccentric muscle action during different locomotion movement; Retrieved and adapted from Vogt & Hoppeler, (2014).

Eccentric training modalities in healthy participants

Over the past decade, there have been many reports that have utilised eccentric cycle training intervention modalities and have achieved beneficial physiological adaptions with healthy participants (Table 1). Other eccentric training intervention populations include; the elderly (LaStayo et al., 2003; Mueller & Maluf, 2002); those suffering from; cardiovascular conditions (Meyer et al., 2003), chronic obstructive pulmonary diseases, Parkinson's disease, impaired glucose tolerance (Peñailillo et al., 2014), cancer survivors (LaStayo, Marcus, Dibble, Frajacomo, & Lindstedt, 2014), and those recovering from anterior cruciate ligament damage (Gerber et al., 2007). This section of the review will introduced the mechanisms associated with; eccentric cycle training by stepping through training interventions performed using only healthy participants to report on the specific mechanical stimulus generated by eccentric training to help determine a potential medium for future study.

Eccentric cycle training has demonstrated improvements in muscle strength, and hypertrophy within the active muscle of the lower limbs after 6 to 8 week training (Table 1). A factor to this is that eccentric cycle training allows for training work rate to be higher compared to that of a concentric cycle training group without muscle damage or pain (Isner-Horobeti et al., 2013; Lastayo et al., 1999). A meta analysis and systematic review of 20 studies revealed eccentric training is a superior method for improving total strength and it appears to be a more potent stimulus for producing hypertrophy relative to concentric cycle training (Roig et al., 2009). Reviews profiling the effects of eccentric training on muscle architecture have reported a typical mean increase of 52% in cross-sectional area of the quadriceps, while the capillary-to-fiber ratio will typically increase 47% (Isner-Horobeti et al., 2013). Furthermore, basketball players (Lindstedt, Reich, Keim, & LaStayo, 2002), and untrained participants (Elmer et al., 2012; Leong et al., 2013) who trained on an eccentric cycle ergometer, reported that maximal jumping power, and muscle stiffness improved following eccentric cycle training. This improvement is in comparison of a concentric cycle training, demonstrating that eccentric cycle training further improves the storage and recovery of elastic strain energy (Elmer et al., 2012) within the muscle, than that of concentric training. Due to the distinct characteristics of eccentric cycle training, integration of this as a training intervention has led to additional improvements by as much as 50% in the ability to modulate muscle force during variable eccentric training in comparison to concentric training (Isner-Horobeti et al., 2013). This occurs specifically, via the knee and hip flexors with an increase in quadriceps size, and strength alongside gluteal size within the active muscle (Elmer et al., 2012; LaStayo et al., 2003; Leong et al., 2013).

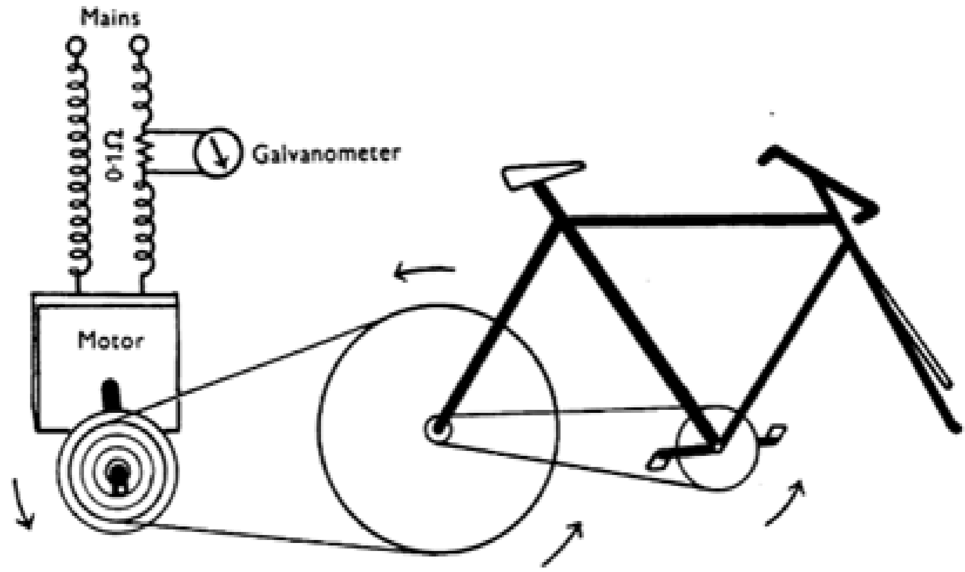

Figure 5: The first motorised ergometer utilised a 2.5 horse-power electric motor. Retrieved from Abbott & Bigland, (1953)

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Eccentric cycling studies

Investigations reporting on the effects eccentric cycle training may have on untrained healthy participants have typically employed a range of training durations in order to assess the physiological effects eccentric cycle training will elicit (Table 1). With eccentric contractions producing greater force than that of concentric contractions (Styf et al., 1995; Westing & Seger, 1989), and the addition of this exercise being performed at a lower metabolic demand compared to concentric contractions (Abbott & Bigland, 1953; Abbott et al., 1952). Eccentric cycle training intervention would prove to be a more effective method to improving muscular function. Indeed, a conclusion drawn from a recent systematic review on eccentric training by Roig et al., (2009), supported the notion that chronic eccentric contractions were more effective than concentric contractions in improving muscular structure and function.

The literature review (Table 1) can demonstrate the range of training and physiological effects eccentric cycle training elicit in healthy participants. An intervention utilising VO_2 (Lastayo et al., 1999) reported on a 6 week (2 to 5 x/wk; 10 to 30 min; 54 to 65%VO2) training intervention. During the 6 week training intervention, training duration increased from 10 to 30 min per session, while frequency increased from (1 to 5 x/wk). This equated to 25 eccentric training sessions with a combined time of 570 min. Interventions utilising HR response to guide training and workload (Elmer et al., 2012; LaStayo et al., 2000) have reported on the effect a 7 to 8 week stepwise training intervention at varied frequency and time can elicit. LaStayo et al., (2000) reported over an extended period of 8 weeks, the intervention is of a stepwise modality monitoring HR response, and rpm (30 to 70 rpm) during training (2 to 5 x/wk; 15 to 30 min; HR 54), HR increased from 54 to 65% within the final eccentric cycle training sessions. Whereas, Elmer et al., (2012) reported on an intervention (3 x/wk; 10 to 30 min; 54 to 66% HR) consisting of 21 eccentric training sessions over a 7 week period. Leong et al., (2013) utilised rpm modifying training intensity and duration from that of Elmer et al., (2012), running for an 8 week duration. This investigation (2 x/wk; 5 to 10.5 min; 20 to 55% of Pmax) had participants complete a total of 435 min eccentric training initially starting at 30 min within the first week progressing to 90 min within the final (week 7). A stepwise progression modality in time and resistance from 20 to 55% Pmax over the 8 week intervention period.

Lindstedt et al., (2001) and Gross et al., (2010) utilised 20 min and 30 min continuous eccentric training intervention respectively. Lindstedt et al., (2001) reported on eccentric cycle training bouts (5 x/wk; 30 min) over an 8 week period completing a high volume 1,200 mins eccentric cycle training. Gross et al., (2010) varied cadence (60 to 80 revs) while continually cycling (3 x/wk; 20 min; 60 to 80 rev.m^{-1}) completing 360 mins eccentric cycle training. Therefore, a standard for eccentric training is consists of 22 eccentric training sessions over a 7 week period, with increasing frequency and duration of training in a stepwise fashion, typically progressing from 11 to 25 min resulting in a total of 460 min completed eccentric cycle training over the training period. Eccentric cycle training intensity would progress in a stepwise fashion from 20 to 55% Pmax (where Pmax is the peak concentric power over a 4s period (Martin, Wagner, & Coyle, 1997)), or while participant HR is maintained at 54% within initial sessions (week 1 to 2) progressing to 66% of individual peak HR during the final training sessions (week 7 to 8).

The eccentric interventions in this review reported on key physiological performance parameters, namely, maximum concentric cycling power (Pmax), jump height, and eccentric force production through multi-joint actions (Elmer et al., 2012; Leong et al., 2013; Lindstedt et al., 2001). Elmer et al., (2012) and Leong et al., (2013) both reported on an increase in Pmax (7% to 9%) respectively, over a 4 s sprint assessments over varied rpm (60-80 rpm) and watts (50-125W). Jump height and bouts of submaximal hopping reported an increase of 8% (Lindstedt et al., 2001), 6.5% (Gross et al., 2010) and 10% (Elmer et al., 2012) respectively, whereas, pennation angle reported to increase 31% (Leong et al., 2013). Such reports alone show the benefits to functional actions due to eccentric cycle training. Alongside the functional benefits reported following eccentric cycle training isometric strength has increased 26% (LaStayo et al., 2000) and 33% (Lastayo et al., 1999) respectively. The positive reporting on strength however, are unsurprisingly met with increases in anthropometric measures of the active muscle, in this instance the lower limbs. Leong et al., (2013) reported the largest increase of 24% for anthropometric measures of the rectus-femoris and vastus lateralis. Gross et al., (2010) reported minimal effects of 2% in regards to anthropometric measures of lean thigh mass. The wide reporting represented by Gross et al., (2010) and Leong et al., (2013) may in part be due to participant selection. To date, Gross et al., (2010) is the only intervention to date that has assessed the effects of an eccentric cycle training intervention on trained athletic populations (well-trained alpine skiers). Participants did not report significant changes to performance measures of isometric flexion force and squat jump height compared to untrained participants reported on, but witnessed a 2.1 ± 1.6% and 1.5 ± 1.4% increase in both right and left leg lean thigh mass. Due to the nature of alpine skiing and the high amount of eccentric loading that these athletes get from their sport, eccentric cycle training may have had a muted effect, than athletes in sports in which eccentric activity is negligible.

The literature discussed has demonstrated strength to be assessed while maintaining a low oxygen demand (Lastayo et al., 1999), furthermore, eccentric cycling strength effects are reported even when matched with a low oxygen dependent concentric group that would typically report no physiological improvement to training (LaStayo et al., 2000). While limited, other investigations have reported on the alterations in muscular structure, thickness and pennation angles of the rectus-femoris and vastus lateralis. and lean body mass (Gross et al., 2010; Leong et al., 2013). Altogether reports allow the conclusion that supramaximal eccentric cycle training is well suited to improve maximal strength and muscle mass whereas submaximal training modalities are adaptable for enhancing power and muscle stiffness (Elmer et al., 2012). Due to the promising effects and characteristics of eccentric cycling it would seem wise for it to be implemented into the majority of sporting disciplines that utilise multi-joint leg actions. However, from the literature reviewed it is apparent that well controlled eccentric training studies into cycling populations are non-existent, and therefore, further research is required in order to broaden the understanding such applications will have on performance and physiological assessment within an well-trained cycling population.

Summary

Typically, an eccentric training intervention consisting of 22 high-intensity, low volume training sessions over a 6 to 8 week period, with increasing weekly frequency, and greater duration of training appears to be beneficial for key performance parameters. This includes sprint-cycling performance over a 4 s increment, jumping power and hopping frequency, muscle stiffness, isometric strength alongside the increase in cross sectional area of rectus-femoris and vastus lateralis. Reports from available literature suggest that effects of eccentric cycling on athletically trained participants will have little effect on key performance parameters, although may be beneficial as a training aid during the off-season to maintain eccentric strength. However, eccentric cycle training has shown to have beneficial effects for healthy participants that are not regularly taking part in eccentric, dominant activity. It would be possible to assume, that with limited literature available an eccentric cycle training intervention, there is a likelihood that it will benefit sprint performance, muscle stiffness and the recycling of mechanical energy in a well-trained population, competing within a concentric contraction based activity (e.g. running, sprinting cycling).

Table 1. Effect of eccentric cycle training on healthy participants

Study	Muscle group	population	Exercise intervention	Training modality	Results
Lastayo et al., 1999	Knee extensors	ECC training n = 4 CON training n = 5	ECC cycle ergometer CON cycle ergometer Intensity: same VO_2 between groups	Eccentric cycling @ 150-300 W power output, 30 min/session, 5 days/wk x 6-wks	+ ISO strength: ECC training +33%, no change after CON Work rate: ECC = 7 x CON, VO_2 ECC ≤ CON
LaStayo et al., 2000	Knee extensors	ECC training n = 6 CON training n = 7	ECC cycle ergometer CON cycle ergometer Intensity identical percentage of HRpeak	Eccentric cycling @ 54-65% HR, 30 min/session, 5 days/wk x 8 wks	+ work rate: ECC (489 W) Vs CON (128) + Quadriceps ISO strength: ECC + 36%, no change after CON Capillary to fiber ratio: ECC + 47%
Lindstedt et al., 2001	Knee and hip extensors	ECC training n = 6 CTRL N = 6	ECC cycle ergometer CTRL weight lifting	Eccentric cycling @500w 30min/session, 3 days/wk x 6-wks	Jump Height: ECC + 8%, no change after CON
Gross et al., 2010	Knee extensors	ECC training n = 8 CTRL n = 7 Alpine skiers n=15	ECC cycle ergometer Resistance training	Eccentric cycling: 3 x 30 reps for 4 leg exercises, followed by 20 min eccentric cycling. 4 leg exercises 3 days/wk x 6 wks	After ECC: +6.5% improvement in CMJ, + lean thigh mass, average work progress from 213 ± 23W to 850 ± 71W (mean ± SD)
Elmer et al., 2012	Lower limbs	ECC training n = 6 Con training n = 6	ECC cycle ergometer CON cycle ergometer	Eccentric cycling: @ 60 rpm, target HR set to 54-66% for 10-30 min (2 min/wk) increasing each wk, 3 days/wk x 7-wks	+ Leg spring stiffness: ECC + 10 ± 3% >Con -2 ± 4% + Pmax : ECC + 7 ± 2% vs CON -2 ± 3%
Leong et al., 2013	Lower limbs	ECC training n = 8	ECC cycle ergometer	Eccentric cycling: @ 60 rpm, 20-55% (5%/wk) of Pmax for 5-10.5 min (1 min/wk) increasing each wk.	After ECC: + 9% in Pmax, alongside a + 24% in muscle thickness and + 31% pennation angle.

ACL anterior cruciate ligamentoplasty, CMJ = countermovement-jump CON = concentric, CTRL = control, ECC = eccentric cycle, HR = heart rate, M = mean, Pmax = maximal power output, RPE = rate of perceived exhertion, rep = repetition, VO_2 = oxygen uptake, wk = week, + indicates increase.

Limitations and future directions

Research has demonstrated that eccentric cycle training may prove beneficial in completing a training load (volume x intensity), relative to a concentric training modality. Positive physiological adaptations to strength, sprint performance, jump height, and an improvement in muscle elasticity, which in turn will aid injury prevention and improve the recycling of mechanical energy through the muscle, have been witnessed following eccentric cycle intervention. Negative responses to locomotion from eccentric training is reported in the loss of the sense of force production, which can take up to weeks from the initial eccentric training session to regain. The muscle stiffness, and DOMS limiting locomotion from an initial eccentric cycle bout may deter well-trained individuals to conduct eccentric cycle training.

To date there has been very little research carried out on the effects eccentric cycle training may have on an athletic populations, and, despite the apparent benefits to healthy participants, there are limited reported effects of eccentric cycle training in well-trained athletic populations. As such, future research should address the effects of eccentric cycle training has on well-trained populations. A potential to this may be a well-trained cycling population, as eccentric training has proven to elicit changes in cycling power in healthy participants; alongside this, the unique activation patterns of an eccentric cycle ergometer may prove beneficial to neurological pathways of cyclists. Thus, reporting on an eccentric cycle training intervention, with particular focus on key parameters of cycling physiology and performance will give further insight in to the limited knowledge and help to identify if eccentric cycle training is a useful training adjunct to traditional cycling programs.

Conclusion

Eccentric cycle training intervention studies on non-athletic populations have collectively demonstrated significant improvements in key performance parameters as well as, muscular size, strength, and jump performance (hopping, CMJ) (Elmer et al., 2012; Leong et al., 2013). Current research on healthy participants suggests that eccentric cycle training facilitates various alterations, which in turn improve locomotor muscle function, and exercise capacity (Isner-Horobeti et al., 2013). For healthy participants and athletes looking to further performance a well-planned eccentric training periodization program could potentially be a major key for success (Issurin, 2008), not only for improving muscular power output but for aiding injury prevention due to improvements in ligament and muscular strength (Bastiaans, Diemen, Veneberg, & Jeukendrup, 2001). As the majority of sporting injuries occur, during the transition between the concentric and eccentric contraction of the muscle (SSC) due to the inadequate or unbalanced muscle strength applied to the active movement (Arnason et al., 2008). Additionally, eccentric cycle training has the potential to elicit such physiological adaptions at very low energy cost and induce distinct muscular activation patterns (Vogt & Hoppeler, 2014).

The effect of eccentric cycle training on key performance, and physiology measures would appear to support its use in traditional cycling training programs. Indeed, current research into the effects of eccentric cycle training has reported increases in strength, hypertrophy, muscle elasticity, and force production when cycling. Despite these findings, to date no studies have been published examining the effects of eccentric cycle training on well-trained cyclists. From the current literature review it can be concluded that eccentric cycle training intervention (2 to 3 x/wk;

10 to 24 min; 25 to 55% Pmax) would increase a number of measures thought important in cycling, namely; strength (Miller et al., 2006), and cycling sprint performance (Leong et al., 2013).

Chapter 2:

Study 1: The effect of eccentric cycling on economy and time-trial performance in a well-trained cycling population

Abstract

The purpose of this study was to determine the effect of eccentric training on cycling performance, and physiological measures in well-trained cyclists. Eight participants (mean ± SD; age: 33 ± 12 yr; body mass: 80 ± 11 kg; VO_2peak: 63 ± 9 ml.kg^{-1}.min^{-1}), performed 12 eccentric cycle training sessions, periodised by duration and intensity, over a 6 week period. Muscle stiffness (MS), 4s sprint (MM4SP), and 4-km time-trail performance (TT) were conducted at baseline, 1 week, and 4 week's following eccentric training. MS, MM4SP and TT were also conducted at week 3 (Mid) of the program. Whereas, incremental peak power output (IPPO) and VO_2peak, were conducted at baseline, 1 week, and 4 week's post eccentric training. Relative to baseline, eccentric training resulted in *unclear* improvement at Mid (mean ± SD%: 0.2 ± 2.8%), and 1 week post- (0.7 ± 2.3%) training, for time-trial performance, however *likely beneficial* (2.3 ± 3.6%) improvements were seen at 4 week post-training. Effects for MS were *very likely positive* (35.8 ± 30.4%) at Mid, and *most likely positive* at both 1 (57.7 ± 22.3%), and 4 (46.6 ± 26.0%), weeks post training. There were *likely beneficial* effects at 40% IPPO, and *likely trivial* or *unclear* outcomes for all other economy measures at moderate intensity cycling. Remaining measures were predominantly *unclear*, or *trivial*. It would appear that in trained endurance cyclists, replacing a component of traditional cycle training with 12 bouts of eccentric training improved 4-km cycling performance. Additionally, despite improved MS, sprint performance appeared to be unaltered following eccentric cycle training. Future research should investigate the effects of eccentric cycle training on sprint cyclists, to assess if improvements in MS flow onto improved sprint performance.

Introduction

Heavy and/or explosive resistance training has been shown to be a valuable adjunct to the training programs of endurance-trained athletes (Hamilton, Paton, & Hopkins, 2006; Paavolainen et al., 1999; Paton & Hopkins, 2005). Run concurrently with endurance training programs, recent investigations have included either traditional weight training (Hickson, Dvorak, Gorostiaga, Kurowski, & Foster, 1988), or explosive resistance training (Hamilton et al., 2006; Paavolainen et al., 1999) to assess performance outcomes. In well-trained endurance runners, 5 to 9 weeks of concurrent training has improved running performance by 2 to 3% (Hamilton et al., 2006; Paavolainen et al., 1999), relative to endurance training only. In well-trained cyclists, similar training techniques to that of Hamilton et al., (2006) resulted in enhancements in 1-km, and 4-km cycling time-trial performance by 8.0 to 9.0%, respectively (Paton & Hopkins, 2005). Resistance training, and more specifically eccentric training may lead to increases in muscle fibre hypertrophy, resulting in an improvement in cross-sectional area, motor unit recruitment and firing frequency (Elmer et al., 2012; Leong et al., 2013; Paavolainen et al., 1999). Despite numerous reports of improvements in endurance performance due to concurrent training, a number of studies have also reported negative performance outcomes (Bell, Petersen, Wessel, Bagnall, & Quinney, 1991). Therefore, the role of resistance training in combination with endurance training remains somewhat controversial (Leveritt, Abernethy, Barry, & Logan, 1999).

Recently, the novel development of eccentric cycle ergometer training has allowed researchers to apply a purely eccentric stimulus to both recreational (Elmer et al., 2012; Leong et al., 2013), and trained athletic (Gross et al., 2010) populations. Positive physiological adaptations witnessed as a result of eccentric cycle training include enhanced muscle stiffness, leading to reduced SSC time (Elmer et al., 2012), increased muscle thickness, and improved pennation angle (Elmer et al., 2012; Gross et al., 2010; Leong et al., 2013). Additionally, improved sprint cycling performance has been observed following eccentric cycle training (Leong et al., 2013). Notably, these improvements are a result of participants undertaking a high-intensity low-volume eccentric cycle training approach involving 5 to 30 min sessions, 2 x/wk, over a 6 to 8 week period (Elmer et al., 2012; Gross et al., 2010; Leong et al., 2013).

Although improvements in a range of cycling related measures have been reported as a result of eccentric cycle training, to date no studies have focused on the efficacy of eccentric training on performance measures in well-trained cyclists (Vogt & Hoppeler, 2014). Given that a high-intensity low-volume training approach appears to enhance a range of measures important to cycling performance (Leong et al., 2013), it would be interesting to assess the impact of such a training intervention on well-trained cyclists. Therefore, the aim of this study was to compare the effects of 6 weeks eccentric cycle training intervention on a range of cycling performance, and physiology measures in trained-cyclists.

Methods

Participants

Eight well-trained male endurance cyclists (mean ± SD; age: 33 ± 12 yr; body mass: 80 ± 11 kg; VO_2peak: 64 ± 8 $ml.kg^{-1}.min^{-1}$) participated in this study, which was approved by the Faculty of Education research ethics committee (EDU 118/14). All participants were injury free, had no prior illness and had been regularly training and competing in weekly local cycling competition preceding the study. The participants had no prior experience with the resistance training methods used and were instructed to continue their regular training schedule but replace 2 hr per week of regular cycle training with eccentric cycling training for a 6 week period. All participants provided written informed consent prior to engaging in any experimental procedures.

Experimental design

This single-subject controlled trial involved participants performing several physiological, and performance trials prior to, during and following the 6 week eccentric cycle training intervention (Table 2, Figure 6). Approximately two weeks prior to the start of the eccentric cycle training intervention participants reported to the laboratory for the first of several familiarisation trials of all performance and physiological assessments as outlined. Relative to the 6 week training intervention (week 1 to 7); Day 1 assessments were carried out at during weeks 1, 3, 7, and post training week 11, whereas day 2 assessments were carried out during weeks 1, 7, and post, week 11. All physiological assessments separated by a 24 hr period in a well-ventilated, temperature-controlled laboratory (18 to 20°C) on an electromagnetically braked cycle ergometer (Cyclus2, Leipzig, Germany) (Figure 8). The ergometer was fitted with the participant's own bicycle for all assessments. Gas-exchange and ventilatory measures were assessed using a mixing chamber metabolic system (TrueOne 2400, Parvo Medics, Sandy, UT). Calibration of the system took place prior to each test using alpha standard gases (BOC Gases, Auckland, NZ). Calibration of the turbine volume sensor was carried out using a 3 L syringe (Hans Ruldolph, Shawnee, USA) prior to all assessments. Participants within the investigation recorded dietary intake 24 hr prior to all initial trials and were asked to repeat this for all subsequent visits. Participants were required to abstain from caffeine, and alcohol in the 24 hr period prior to testing, and to perform no more than 2 hr of moderate intensity exercise the day prior to any assessments. Participants were asked to maintain a 2 hr decreased training load (12.1 ± 2.2 $hr.wk^{-1}$) during the time of the study and complete training time diaries on a weekly basis, which on completion, were given to the primary investigator.

Eccentric cycle training

The 6 week training intervention was undertaken on a commercially available eccentric cycling ergometer (Cyclus2, Leipzig, Germany) (Figure 8) 2 x/wk for 6 weeks. The initial workload (eccentrically absorbed) was based on 25% of individual participant's initial 4 s mean maximal sprint power (MM4SP). Workload increased by 5% after every third session, with target cadences of between 60, and 70 rpm depending on target workload (Table 5). Training was periodised based on previous research utilising the training methods of Leong et al., (2013) with suggested modifications from one of the co-authors of that paper (JCM). A calibrated crank-based power meter (Schoberer Rad Messtechnik, Julich, Germany) was fitted to the Cyclus2 eccentric ergometer for participants to target sessional workload. The power meter was also used to assess validity of the eccentric training ergometer. The power meter was offset prior to each training session as per manufacturer's instructions. During the final minute of each training session, economy was assessed using the methods and equipment described above. Heart rate (HR) was assessed during the final minute of each reputation using a Polar heart rate monitor (HR; RS800sd, Polar, Polar Electro, Kempele, Finland). Participants were asked to report ratings of perceived exertion of their total lower (RPE_{Legs}), and upper body (RPE_{Body}) using a Borg 6 to 20 scale (Borg, 1982). As eccentric cycling has been known to cause severe muscular soreness we employed a bilateral squat assessment prior to, and following, all training sessions to track participant severity of pain. Participant's indicated pain from zero (no pain at all) to 10 (worst pain imaginable) (Leong et al., 2013) with those scoring ≥5 (5 being moderate soreness) in the pre-session assessment being required to postpone the scheduled eccentric cycle training by a 24 hr period. We did this to ensure that participants were safely administrated with the appropriate eccentric cycling training intervention.

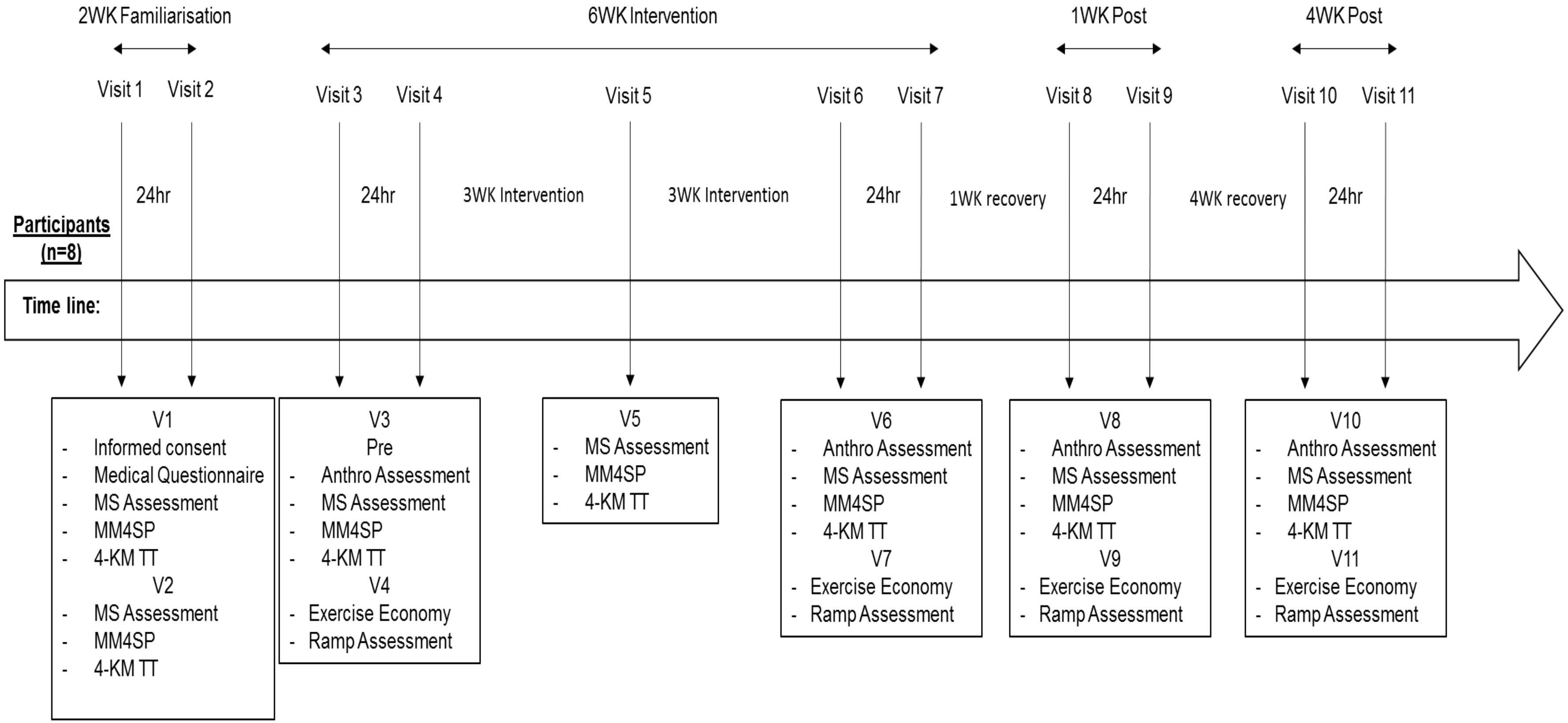


Figure 6: Schematic representation of 6 week eccentric cycle training intervention, in addition to post-intervention testing at weeks 7 and 11 of the investigation. N = number of participants; 24 hr = 24 hr rest period between assessment; MS Assessment = muscle stiffness assessment; MM4SP = 4 s mean maximal sprint power over ranging cadence; 4-km TT = 4-km time-trial performance; Exercise Economy = 5 minute exercises economy stages; Ramp Assessment = incremental ramp assessment.

Figure 7: Cyclus2 eccentric cycle ergometer that utilises participants own bicycle. Retrieved from Eccentric training- Cyclus2 - Performance diagnostics, and training on your own bike.

Table 2. Six week eccentric cycling training intervention. work: rest ratio was 1:1 durir all sessions.

Week	$\%P_{Max}$[1]	Cadence (rpm)	Sets	Rep Duration (min)	Session Duration[2] (min)
1	25	60	3	3	9
2	30	60	4	3	12
3	35	60	5	3	15
4	40	60	5	3	15
5	45	65	5	4	20
6	50	70	6	4	24

[1]%PMax = Percent of initial mean maximal 4s sprint cycling power relative to the individual participant.

[2] Duration of total time of eccentric training stimulus for one session.

Anthropometric measurement

Prior to warm-up procedures, sum of 8 skinfolds, and calf, quad and gluteal girth were assessed by an ISAK accredited anthropomotrist in order to track any changes in body composition as a result of the eccentric cycling training intervention. Body mass was measured in cycling bibs, without shoes using an electronic scale (Seca, Gmbh Hamburg, German) to the nearest 0.01 kg, and stature via stadiometer (Seca, Gmbh Hamburg, German) was measured barefoot to the nearest 0.01 cm both calibrate to the manufacturer's instructions.

Muscle stiffness

Following a 5 min cycling based moderate-intensity warm-up, participants proceeded to remove all footwear and commence straight leg hopping on a Bertec Aquire force plate (Bertec corporation, Columbus, Ohio), and to carry out three sets of 10 s jumps with each set separated by a 2 min passive rest period. Participant's stood on the force plate and were then asked to perform two-legged hopping while maintain leg stiffness by avoiding any knee bend focusing movement through the calf muscles. Muscle stiffness was calculated using the method of Dalleau, Belli, Viale, Lacour, & Bourdin, (2004) Stiffness ($_K$N/m) was subsequently calculated by modelling the ground reaction force as a sine wave, from this the peak reaction force, and vertical displacement during contact was determined, and vertical stiffness calculated.

4 s mean maximal sprint power output

Following a 5 min passive rest, participants mounted the Cyclus2 ergometer to perform 6 maximal sprints each of 4 s duration in ascending order of 60, 75, 90, 105, 120, 135 rpm. Participants were instructed to sprint in a seated position as fast as they could and given verbal encouragement throughout each trial. Each sprint was separated by a 2 min rest period were participants were free to cycle at low-intensity.

4-km Time-trial performance

After maximal concentric sprints, participants were given a 5 min rest period prior to the commencement of the 4-km time-trial. Participants were able to self-select gearing, and cadence to best reflect individual competition performance. Completion time, and mean power output (MPO) were recorded during each time-trial. Participants had previously been familiarised with these time-trials in the weeks prior to baseline assessments.

Exercise economy

Exercise economy was assessed using stepwise increases equating to 40, 50, and 60% of participants 4-km time-trial MPO. The final 30 s of each 5 min workload was used for subsequent analysis. Participant's heart rate (HR) (RS800sd, Polar, Polar Electro, Kempele, Finland), perceived exhaustion, and rpm were recorded in the final 30 s of each workload to assess individual perceptual, and physical responses.

Incremental ramp assessment

At the conclusion of the economy assessment participants commenced the incremental ramp assessment, starting at a workload equivalent to 60% of participant 4-km time-trial performance. The incremental ramp assessment increased by 20 W·min^{-1} until volitional exhaustion. Participant's VO_2peak was determined as the highest 30 s mean VO_2 prior to exhaustion.

Statistical analysis

Data is presented as mean ± SD unless otherwise reported. All performance, physiological, and RPE measures were analysed using a customised analysis spread sheet (Hopkins, 2006). Performance, and physiological data was log-transformed for analysis to reduce bias arising from non-uniformity of error, and subsequently back-transformed to obtain changes in means and variations as percentages, while RPE was analysed using the raw data. To make inferences about the population, values for the effect of eccentric cycle training on 4-km cycling performance was expressed as 90% confidence limits (CL), and as likelihoods that the true value of the effect represents substantial change to be harmful or beneficial. An effect was deemed *unclear* if its confidence interval overlapped the thresholds for substantiveness; that is, if the effect could be substantially positive and negative or beneficial and harmful (Hopkins, 2004). Smallest worthwhile change in performance was calculated as 1%, this being 0.3 of the coefficient of variation (CV) of typical error (TE) for power in performance reliability trials and is in agreement with studies investigation competitive time-trial variation (Hamilton et al., 2006). Physiological (mechanistic) measures were calculated as 0.2 of the between-subject SD (Hopkins, 2004). Clinical inference was based on threshold chances of harm and benefit on performance of 0.50%, and 25% respectively. The default values and qualitative terms were set at: <0.5%, *most unlikely*; 0.5-5%, *very unlikely*; 5% - 25%, *unlikely*; 25 to 75%, *possibly*; 75 – 95%, *likely*; 95 – 99.5%, *very likely*; >99.5%, *most likely*. Effect sizes (ES) were calculated using Cohens *d*, with an ES of <0.2 considered *trivial,* >0.2 *small,* >0.6 *moderate,* >1.2 *large* and >2.0 *very large.* Concurrent validity between the criterion SRM measure and Cyclus2 eccentric cycle ergometer was assessed using the mean of bi-weekly training power (W) absorbed for each of the 6 training weeks, via a customised spread sheet (Hopkins, 2015) at 90%CL. Weekly validity is reported using Pearson correlation score (± 90%CL), and percentage typical error of estimate (%TE×⁄÷90CL).

Results

Mean sessional power absorbed over the 6 week period ranged from 282 ± 42 W in week 1 to 496 ± 70 W in week 6 as recorded by the SRM power meter. Over the same time period mean work completed increased from 121 ± 32 kJ to 705 ± 44 kJ. This is alongside participants completing a mean workload (12.1 ± 2.2 $hr.wk^{-1}$) of cycle training each week.

Muscle stiffness

Relative to baseline measures, *likely positive* (mean ± SD 0.39 ± 0.22 $_{K}$N/m), *most likely positive* (0.63 ± 0.16 $_{K}$N/m), and *very likely positive* (0.51 ± 0.19 $_{K}$N/m) outcomes were observed at week 3, 7, and 11, respectively. There was a *likely trivial* reduction in muscle stiffness (-0.12 ± 0.18 $_{K}$N/m) between week 7, and 11.

Mean maximal sprint power

Likely beneficial effects for 4 s mean maximal sprint power were witnessed at 60 rpm at week 11 relative to both baseline, and week 7. Similarly, *likely beneficial* effects were reported at 120 (week 7 – Pre), and 135 rpm (week 11 – Pre). In contrast *possibly harmful* effects were reported at 60, and 75 rpm (week 3 – baseline) and 90, and 105 rpm (week 11 to 7). Regardless of cadence, the remainder of outcomes of eccentric cycle training on 4 s mean maximal sprint power were *unclear* (Table 7, Figure 9).

4-km Time-trial performance

Six weeks of eccentric cycle training had *unclear* effects on 4-km time-trial MPO at weeks 3, and 7, a 4 week cessation of eccentric training resulted in *likely beneficial* outcomes for MPO relative to both baseline (2.3;90%CL; ± 2.4%), and week 7 (1.6 ± 1.6%) outcomes (Table 6).

Economy

Relative to baseline 6 weeks of eccentric training resulted in *likely beneficial* improvements to economy at 40% IPPO at week 7, and 11. *Possibly beneficial* effects were reported at 50% IPPO at week 11 of the investigation period. The remainder of effects for economy were either *unclear* or *trivial* (Table 8).

Incremental ramp assessment

Outcomes for incremental peak power indicted a *likely harmful* (-2.1 ±90% CL; 2.5%) effect on incremental peak power output 1 week following 6 weeks of eccentric training. Six weeks of eccentric cycling led to a *likely beneficial* increase in incremental peak power at week 11 relative to week 7 (2.5 ± 2.6%), however this only resulted in an *unclear* (0.4 ± 2.5%) effect for week 11 relative to baseline (Table 6). Relative to baseline measures for VO_2peak, 6 weeks of eccentric cycle training resulted in *very likely trivial* effects at week 7, and *most likely trivial* effects at week 11, and week 11 relative to 7 (Table 8).

Validity of eccentric cycle ergometer

Pearsons correlation score for weekly raw mean power (W) absorbed (SRM vs Cyclus2) for week 1 to 4 was 1.00 ± 0.00, while scores for week 5, and 6 were 0.00 ± 0.01, and 0.99 ± 0.02, respectively. There appeared to be a trend for increased percent TE (1.0 ×/÷ 0.0%; 1.3 ×/÷ 0.6%; 1.2 ×/÷ 1.6%; 1.4 ×/÷ 1.6%; 1.6 ×/÷ 1.9%; and 2.2 ×/÷ 0.6%) over the same training period as weekly power absorption increased.

Anthropometry

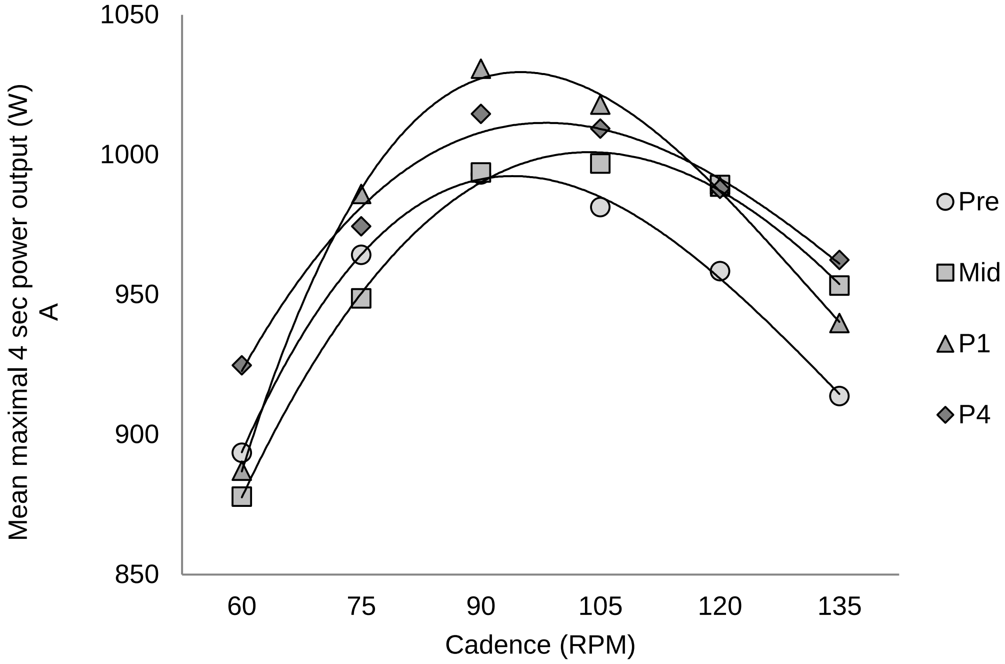
Anthropometric measures were assessed prior to, and at weeks 3, 7, and 11 of investigation. Eccentric cycle training had a *very likely trivial*, outcome at weeks 3 (0.05 ± 0.09 kg), 7 (0.04 ± 0.14 kg), and 11 (-0.04 ± 0.10 kg) of the investigation, relative to baseline. At these same time point, measures for sum of 8 skinfold was reported to be *likely trivial* (-3.5 ± 3.7 cm), *likely negative* (-10.9 ± 8.7 cm), at week

3, 7, and *possibly negative* (-7.6 ± 7.5) from week 7, to 11. Gluteal circumference was reported as *most likely trivial* (-0.01 ± 0.09 cm), *most likely trivial* (-0.05 ± 0.05 cm), at week 3, 7, and a *most likely trivial* reduction (-0.04 ± 0.07 cm), from week 7, to 11. Quad circumference was reported as *possibly positive* (0.20 ± 0.25 cm), *possibly positive* (0.23 ± 0.24 cm), at week 3, 7, and reported as *very likely trivial* (0.03 ± 0.13 cm) post investigation from week 7 to 11. Calf circumference *reported very likely trivial* (-0.02 ± 0.14 cm), *likely trivial* (0.13 ± 0.17 cm) at week 3 to 7, and reported as *possibly positive* (0.15 ± 0.22 cm), from week 7 to 11.

Table 3. Group mean cycling related measures at baseline, during and subsequent to eccentric cycle training. Data are mean ± SD

Measure	**Condition**			
	Baseline	**Week 3**	**Week 7**	**Week 11**
4-km TT MPO (W)	376 ± 22	379 ± 26	380 ± 25	385 ± 27
4-km TT time (MM4SP)	328.9 ± 5.6	327.9 ± 7.1	327.5 ± 5.8	325.8 ± 8.2
MS ($_K$N/m)	4.4 ± 2.8	5.8 ± 3.6	6.8 ± 4.0	6.1 ± 3.2
Economy 40% iPPO ($L.min^{-1}$)	2.1 ± 0.1		2.0 ± 0.1	2.1 ± 0.1
Economy 50% iPPO ($L.min^{-1}$)	2.5 ± 0.2		2.5 ± 0.1	2.5 ± 0.1
Economy 60% iPPO ($L.min^{-1}$)	3.0 ± 0.2		3.0 ± 0.2	3.0 ± 0.2
IPPO (W)	418 ± 17		410 ± 28	420 ± 25
VO_2peak ($ml.kg^{-1}.min^{-1}$)	63 ± 9		63 ± 9	63 ± 9

TT = time-trial; MPO = mean power output; MMP = mean maximal power; IPPO = incremental peak power output, MS = muscle stiffness



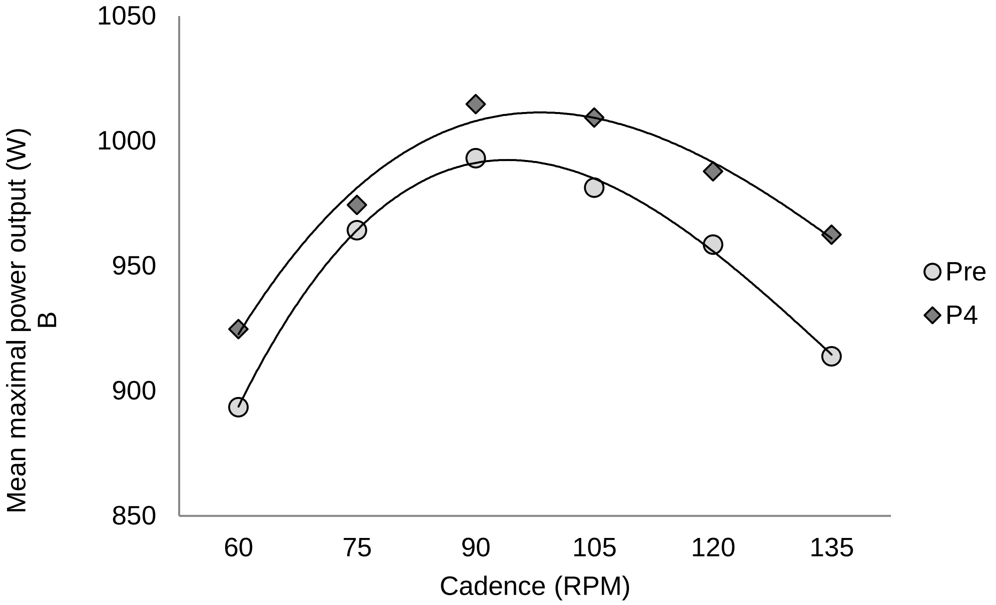


Figure 8 A & B: Comparison of pre-to-post changes in cycling power **A.** A complete comparison of all testing assessments, **B**. A comparison of pre, and post week 4 only. Values are presented as mean ± SD; with SD bars are removed for clarity.

Pre= Baseline assessment. **Mid**= week 3 assessment, **P1**= post week 1 assessment, **P4**= post week 4 assessment

Table 4. Pairwise comparisons quantifying magnitudes of eccentric cycle training on 4-km time-trial mean power output (W) and 4 s mean maximal sprint power output (W). Units of change are % for all measures

	Treatment Effect[a]		
	Mean ± SD; ±90%CL (%)	**% Magnitude (+/trivial/-)**	**Qualitative Inference**
4-km TT MPO (W)			
Wk 3 – Pre	0.2 ± 2.8; ± 1.8	55/8/37	Unclear
Wk 7 – Pre	0.7 ± 2.3; ± 1.5	77/6/17	Unclear
Wk 11 – Pre	2.3 ± 3.6; ± 2.4	94/1/5	Likely beneficial
Wk 11 – Wk 7	1.6 ± 2.5; ± 1.6	93/2/5	Likely beneficial
4 s MMSPO (W)			
60 rpm			
Wk 3 – Pre	-1.6 ± 4.1; ± 2.6	5/29/66	Possibly harmful
Wk 7 – Pre	0.3 ± 9.3; ± 6.0	42/24/34	Unclear
Wk 11 – Pre	4.7 ± 8.2; ± 5.5	88/8/4	Likely +ive
Wk 11 – Wk 7	4.3 ± 5.9; ± 4.0	92/6/2	Likely +ive
75 rpm			
Wk 3 – Pre	-1.4 ± 4.2; ± 2.7	7/32/61	Possibly harmful
Wk 7 – Pre	2.4 ± 7.6; ± 5.0	69/19/12	Unclear
Wk 11 – Pre	2.2 ± 6.1; ± 4.1	71/21/8	Unclear
Wk 11 – Wk 7	-0.2 ± 6.7; ± 4.4	31/32/36	Unclear
90 rpm			
Wk 3 – Pre	-0.6 ± 8.2; ± 5.2	30/27/44	Unclear
Wk 7 – Pre	3.6 ± 10.3; ± 6.8	76/13/11	Unclear
Wk 11 – Pre	2.0 ± 10.3; ± 6.7	61/18/21	Unclear
Wk 11 – Wk 7	-1.6 ± 6.0; ± 3.8	13/27/60	Possibly harmful
105 rpm			
Wk 3 – Pre	1.2 ± 6.4; ± 4.2	52/30/18	Unclear
Wk 7 – Pre	3.8 ± 9.2; ± 6.1	79/12/9	Unclear
Wk 11 – Pre	2.3 ± 7.5; ± 5.0	68/20/12	Unclear
Wk 11 – Wk 7	-1.5 ± 8.5; ± 5.4	21/23/56	Possibly harmful
120 rpm			
Wk 3 – Pre	2.9 ± 6.2; ± 4.2	79/15/6	Unclear
Wk 7 – Pre	3.3 ± 6.9; ± 4.6	81/13/6	Likely beneficial
Wk 11 – Pre	2.4 ± 8.0; ± 5.3	69/19/13	Unclear
Wk 11 – Wk 7	-0.9 ± 12; ± 7.5	32/19/49	Unclear
135 rpm			
Wk 3 – Pre	4.4 ± 11.3; ± 7.5	79/10/10	Unclear
Wk 7 – Pre	3.8 ± 11.3; ± 7.5	75/12/13	Unclear
Wk 11 – Pre	7.3 ± 9.7; ± 6.7	95/3/2	Likely beneficial
Wk 11 – Wk 7	3.4 ± 11.7; ± 7.6	71/13/15	Unclear

Table 5. Pairwise comparisons quantifying magnitudes of effect of eccentric cycle training on physiology, muscle stiffness, and incremental peak power output

	Treatment Effect[a]		
	Mean ± SD; ±90%CL (%)	% Magnitude (+/trivial/-)	Qualitative Inference
Muscle stiffness (K_n)			
Wk 3 - Pre	35.8 ± 30.4	99/0/1	Very likely +ive
Wk 7 – Pre	57.7 ± 22.3	100/0/0	Most likely +ive
Wk 11 – Pre	46.4 ± 26.0	100/0/0	Most likely +ive
Wk 11 – Wk 7	-7.1 ± 25.8	17/6/77	Unclear
VO_2 ($L{\cdot}min^{-1}$) 40% iPPO			
Wk 7 – Pre	-0.46 ± 0.32	0.3/8.5/91.2	Likely +ive
Wk 11 – Pre	-0.34 ± 0.28	0.4/17.9/81.7	Likely +ive
Wk 11 – Wk 7	0.11 ± 0.45	36/53/11	Unclear
VO_2 ($L{\cdot}min^{-1}$) 50% iPPO			
Wk 7 – Pre	-0.08 ± 0.25	3/76/20	Trivial
Wk 11 – Pre	-0.14 ± 0.23	1/67/31	Possibly +ive
Wk 11 – Wk 7	-0.06 ± 0.20	2/87/11	Trivial
VO_2 ($L{\cdot}min^{-1}$) 60%iPPO			
Wk 7 – Pre	-0.02 ± 0.16	2/94/4	Trivial
Wk 11 – Pre	-0.05 ± 0.18	2/90/9	Trivial
Wk 11 – Wk 7	-0.03 ± 0.16	1/94/4	Trivial
PPO (W)			
Wk 7 – Pre	-2.1 ± 3.9	3/19/78	Likely -ive
Wk 11 – Pre	0.4 ± 3.9	33/51/17	Unclear
Wk 11 – Wk 7	2.5 ± 3.8	85/13/2	Likely +ive
VO_2peak ($ml.kg^{-1}.min^{-1}$)			
Wk 7 – Pre	-0.02 ± 0.09	0.6/98.8/0.4	Trivial
Wk 11 – Pre	-005 ± 0.04	0.1/99.7/0.2	Trivial
Wk 11 – Wk 7	-0.03 ± 0.05	0.2/99.7/0.1	Trivial

Table 6. Pairwise comparisons quantifying magnitudes of eccentric cycle anthropometry measures. Units of change are % for all measures.

	Treatment Effect[a]		
	Mean ± SD; ±90%CL (%)[a]	**% Magnitude (+/trivial/-)**[b]	**Qualitative Inference**
Sum of 8			
Wk 7 – Pre	-0.10 ± -3.5; ± 0.11	0/94/6	Likely trivial
Wk 11 – Pre	-0.32 ± -10.9; ± 0.27	0/21/79	Likely negative
Wk 11 – Wk 7	-0.22 ± -7.6; ± 0.22	0/43/57	Possibly negative
Body mass			
Wk 7 – Pre	0.08 ± 2.5; ± 0.16	10/90/1	Likely trivial
Wk 11 – Pre	-0.08 ± 4.3; ± 0.28	5/73/22	Likely negative
Wk 11 – Wk 7	-0.16 ± 3.0; ± 0.19	0/64/35	Possibly negative
Glute			
Wk 7 – Pre	-0.01 ± 1.1; ± 0.09	0/100/0	Most likely trivial
Wk 11 – Pre	-0.05 ± 0.7; ± 0.05	0/100/0	Most likely trivial
Wk 11 – Wk 7	-0.04 ± 0.8; ± 0.07	0/100/0	Most likely trivial
Quad			
Wk 7 – Pre	0.20 ± 2.4; ± 0.25	49/50/1	Possibly positive
Wk 11 – Pre	0.23 ± 2.3; ± 0.24	58/41/1	Possibly positive
Wk 11 – Wk 7	0.03 ± 1.3; ± 0.13	2/97/1	Trivial
Calf			
Wk 7 – Pre	-0.02 ± 1.3; ± 0.14	1/97/2	Very likely trivial
Wk 11 – Pre	0.13 ± 1.5; ± 0.17	24/76/0	Likely trivial
Wk 11 – Wk 7	0.15 ± 2.0; ± 0.22	35/64/1	Possibly positive

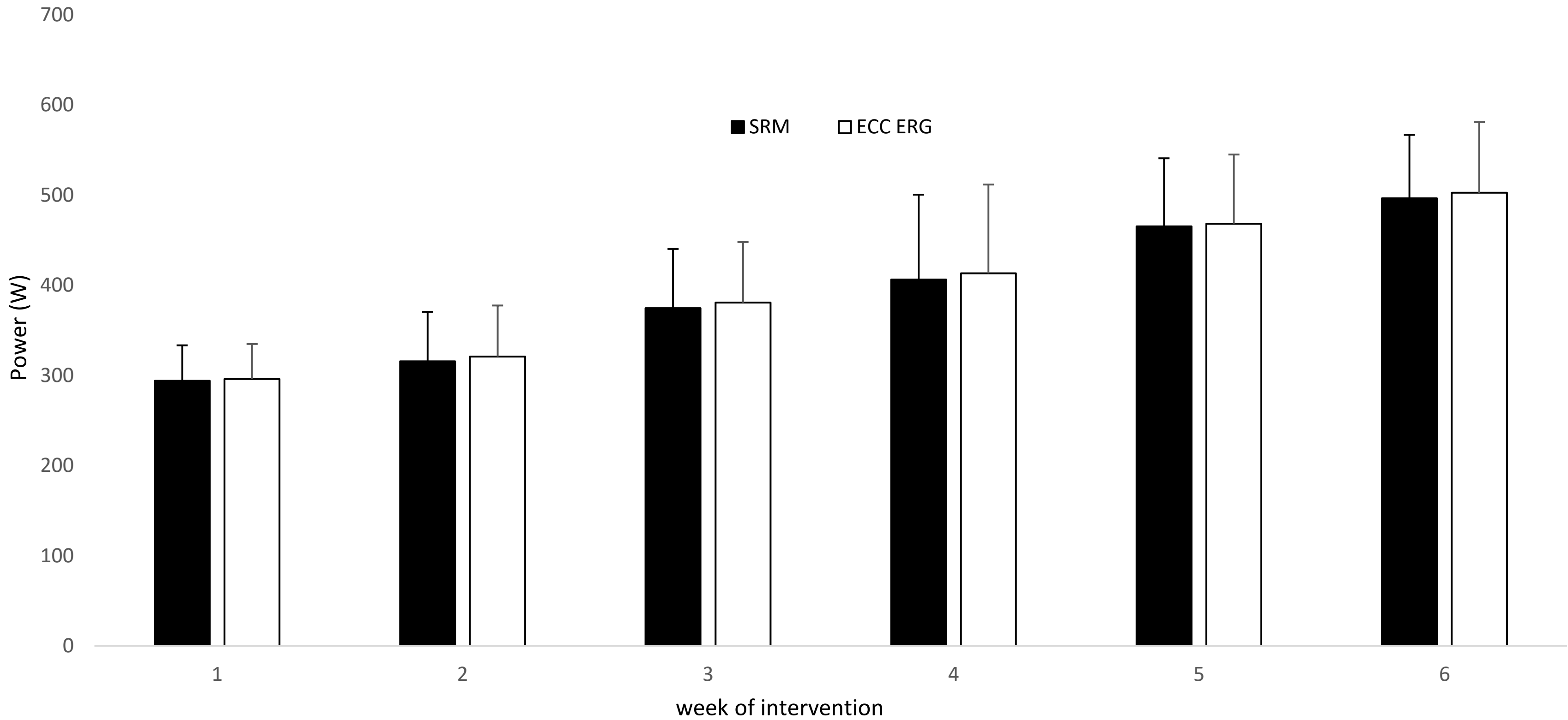


Figure 9: Mean power output obtained during each submaximal weekly training intervention from Cyclus2 eccentric ergometer (black columns) and SRM (white columns).

Discussion

To the best of our knowledge, this is the first investigation to evaluate the effects of eccentric cycle training on a range of performance, and key performance indicators/parameters in a well-trained cycling population. Over the 6 week training period, mean sessional power absorbed increased by 76%, resulting in an 483% increase in energy metabolism in agreement with previous findings (Elmer et al., 2012; Gross et al., 2010). Furthermore, the investigation reported on the validity of power for an eccentric cycle ergometer relative to what is considered the gold-standard in mobile ergometer power meter (Bertucci, Duc, Villerius, Pernin, & Grappe, 2005). Relative to the SRM mean power output (W), the eccentric cycling ergometer ranged from 0.7 to 1.9% lower across the 6 week training period (Fig 7). As this is, the first investigation to report on the effects of eccentric cycle training on time-trial performance direct comparisons with similar studies is limited. Findings of the current study show that 4-km time-trial time reduced by 1.0%, in addition to an increase in muscle stiffness by 58% as a result of 6 weeks eccentric cycle training.

Findings for incremental peak power output IPPO and VO_2peak were predominantly *trivial,* which is surprising given economy was shown to improve at 40% IPPO. Previous concurrent training methods have reported an 8% improvement in 4-km time-trial mean power output in a similarly trained population to the current study following a 6 week concentric resistance-training program (Paton & Hopkins, 2005). Similarly, Paavolainen et al., (1999) reported improvements in 5-km running performance in well trained runners witnessed this without an improvement in VO_2peak. Despite a number of key performance parameters reporting improvement, Paavolainen et al., (1999) noted that neither VO_2peak or lactate threshold improved as a result of training. Although not measured, anaerobic capacity improvements were likely due to an enhanced neuromuscular function potentially via increased muscle stiffness (Paavolainen et al., 1999). Therefore, findings, from the current study and that Paavolainen et al., (1999) suggest that the correlation witnessed in 4-km time-trial performance, and muscle stiffness is likely due to the neuromuscular component of the training intervention. The positive outcomes for 4-km time-trial performance is opposed to aerobically derived mechanisms, given that several aerobic measures (VO_2peak, peak incremental power output, and economy) were largely unchanged in the current study (Table 2). This could be due to the fact, that participants who undertook the current intervention were well-trained and would not show improvements in economy as a result of the current eccentric training intervention and/or that the efficiency by which our athletes transfer raw metabolic power to mechanical power has not been affected much like results seen from Paavolainen et al., (1999).

In the current study, there appeared to be no improvement in sprint performance during, and following 6 week eccentric cycle training (Table 3). This is despite previous research (Leong et al., (2013) reporting improvements in sprint performance following similar training modalities as the current study at 1 (Elmer et al., 2012), and 8 (Leong et al., 2013) weeks post cessation of training. When matched for timing of post-training assessment both the current investigation and Elmer et al., (2012) witnessed no significant effects as a result of eccentric training apart from the *likely beneficial* effects witnessed at a cadences 120 rpm. However, Leong et al., (2013) reported that 8 weeks of eccentric cycle training elicited a 5% increase in the sprint performance of untrained participants. Differences in results witnessed by Leong et al., (2013), and (Elmer et al., 2012) to that of the current study could be due to the employment of trained cyclists who regularly complete in events which require frequent supramaximal intensity bursts (Vogt et al., 2006). Thus, the non-significant findings report by Elmer et al., (2012) following eccentric training may be as a result of muscle remodelling following eccentric exercise as previous investigators have reported long lasting indicators of muscle remodelling with suppressed muscle force after eccentric exercise (Allen, 2001; Proske & Morgan, 2001). This in part is due to eccentric contractions facilitating within the activation/bonding of a second myosin head. As concentric contractions only activate one myosin head, twice the bonding would lead to twice the number of active cross-bridges during active lengthening increasing contraction velocity of alternative concentric contraction (Linari et al., 2000). This eccentric exercise muscle remodelling may be a time course event as findings of the current study and that of the previously mentioned allow us to speculate that satellite cell recruitment/elevation after eccentric exercise may be elevated longer than concentric exercise 60 days post exercise (Kadi et al., 2004).

The current investigation elicited improvements in mean leg muscle stiffness by 58% at week 7; whereas this reduced to 46% 4 weeks post intervention (Table 4). Leg muscle stiffness was measured through trials of submaximal hopping, a multi-joint activity that includes the stretch-shortening cycle offering a simple model for evaluating the elasticity properties of the leg (Blickhan, 1989; Elmer et al., 2012; Farley & Morgenroth, 1999). Adaptations witnessed in leg muscle stiffness are likely due to enhancement in neural activation, and enhanced stretch reflex mechanisms (Elmer et al., 2012; Paavolainen et al., 1999), although more direct measures through electromyography along with muscle biopsies is needed to confirm this. Additionally, without the aid of EMG biopsies it could be concluded that this is result from a modification to cytoskeletal protein titin, as previously suggested Elmer et al., (2012), and Lindstedt, Reich, Keim, & LaStayo, (2002) as it is a potential contributor to enhancement of muscle-tendon spring properties. However, this has not been observed following chronic eccentric training in well-trained athletes and would warrant further investigation. The improvements witnessed in multi-joint leg function expand upon previous eccentric training investigations that demonstrate increases in knee extensor strength (Elmer et al., 2012; Lastayo, Reich, Urquhart, Hoppeler, & Lindstedt, 1999). While also supporting previous work by Elmer et al., (2012), and Lindstedt, LaStayo, & Reich, (2001) which reported an increase in leg muscle stiffness, and maximum jumping power, through trials of hopping, a submaximal multi-joint activity that demonstrates muscle elasticity through the SSC (Elmer et al., 2012). Furthermore, relative to 1 week post training cessation, the decrease in muscle stiffness witnessed at week 4 post training suggests that unlike (Leong et al., 2013), and what we have discussed within the previous paragraph, the well-trained participants within the current investigation appear to be experiencing an increase in muscle elasticity rather than an increase in supramaximal intensity bursts.

The distinct characteristics of eccentric cycle training have allowed for integration of this training intervention too lead to, additional improvements, by as much as 50% in the ability to modulate muscle force during variable eccentric training, in comparison to concentric training (Isner-Horobeti et al., 2013). This has occurs specifically, via the knee and hip flexors with an increase in quadriceps size, and strength alongside gluteal size within the active muscle by previous authors (Elmer et al., 2012; LaStayo et al., 2003; Leong, McDermott, Elmer, & Martin., 2013).

Anthropometric measures from the current investigation have reported to be predominately *unchanged* (Table 6). However, sum of 8 reported to be *negative*, quad circumference was reported as *possibly positive* (0.20 ± 0.25 cm)*, possibly positive* (0.23 ± 0.24 cm), at week 3, 7, and reported as *very likely trivial* (0.03 ± 0.13 cm) post investigation from week 7 to 11. A previous report by Leong et al., (2013), supports such findings post a large eccentric stimulus leading to increases of 13, and 24% in muscle thickness of the rectus femoris and vastus lateralis, respectively.

The current investigation has allowed the observation of 12 eccentric cycle training sessions on well-trained cyclists. The main findings report an increase in 4-km time-trial performance alongside increases in muscle stiffness. Adaptations witnessed through eccentric cycle modalities have challenged several distinct physiological properties of the participants, such as different neurological patterns (Enoka, 1996), and faster cortical activity through movement execution (Fang et al., 2001). These in turn have improved functional activities that requiring multi-joint actions of the lower limbs, for example jumping, and cycling (Elmer, Madigan, LaStayo, & Martin, 2010). As traditional cycle training modalities are multi-joint tasks that include a mostly passive eccentric phase proceeded by a concentric phase, thus not relying heavily on movement enhancement through SSC by recovery of mechanical energy (Neptune & Kautz, 2001) it would be reasonable to assume that eccentric cycle training would not have an effect on highly trained cyclists. This notion is based on the none significant findings reported for peak power output within the trials of incremental assessments, which are usually a valid predictor for increased performance measures in cycling (Hopkins, Hawley, & Burke, 1999). Therefore, it is possible to assume that performance assessment, post eccentric cycle training is a reflection of well-trained cyclists showing no improved effects for supramaximal intensity bursts, rather than experiencing a cascade of events still taking place for complete muscle remodelling witnessed in reports of eccentric cycle training in untrained healthy participants (Elmer et al., 2012).

Limitations

We employed eight participants for the current study which is consistent with previously published eccentric papers (Lastayo et al., 1999; Leong et al., 2013). Obviously, a novel aspect of the current research was targeting well-trained cyclists to assess the influence of a bout of eccentric cycle training on a range of physiological, and performance measures. It is important to note that the inclusion criteria somewhat limited the pool of potential volunteers. However, the benefits of employing a regularly trained athlete population is that trained athletes have less variation in week-to-week performance, be more familiar with maximal performance than untrained participants, and be cognizant of the need to pace time-trial efforts.

Practical applications

The results of the present investigation show that 6 weeks of eccentric training is a highly effective method of improving muscle stiffness, and may improve time-trial performance of 5 to 6 min in trained cyclists (Martin et al., 2001). These appear to be due to an improvement of neuromuscular capacity as VO_2peak appeared to be unchanged as a result of the current investigation.

Conclusion

This is the first study to assess the effects of eccentric cycling on performance measures in trained cyclists. Over the 6 week training intervention, 12 sessions of short duration eccentric training resulted in improvements in 4-km time-trial performance, and neuromuscular activation, but minimal change in sprint performance or cycling economy. Future studies should explore the effect of eccentric cycle training on highly trained cyclists, well-trained athletes, in sports that involve multi-joint tasks through the SSC (e.g. basketball, volleyball) as we have reported changes in muscle stiffness.

Acknowledgments

We thank the participants for their time, enthusiasm and effort over the course of this research project.

Chapter 3:

Conclusion

Summary

The study in this thesis was intended to assess the efficacy of eccentric training to enhance a number of key performance parameters, and physiological measures in well-trained cyclists. The main findings of this 6 week training intervention demonstrated that, relative to baseline measures (4-km TT baseline times), periodised eccentric cycling had a *likely beneficial* improvement 4-km cycling time-trial performance 1 (327.5 ± 5.8 s), and 4 (325.8 ± 8.2 s) weeks after the cessation of training. Additionally, leg muscle stiffness was enhanced reporting very likely positive at week 3 (35.8 ± 30.4 KN/m), most likely positive at week 7 (57.7 ± 22.3 KN/m), and most likely positive at week 11 (46.4 ± 26.0 KN/m). Moderate positive effects were observed for economy at 40% (150 ± 50 W) peak power output suggesting an improved rate of oxygen cost during moderate intensity cycling. The reported enhancements in, 4-km time-trial performance, leg spring stiffness and cycling economy warrants the need for further investigation into the effects of eccentric training on cycling performance. Given the current findings the effects of eccentric cycling on time trials would be of interest, in particular those of ~6 min duration. Additionally, mass-start events in which race outcomes are often influenced by factors such as sprinting, economy and sustained aerobic power output, may well benefit from eccentric cycle training. Notably, the improvements in leg muscle stiffness did not lead to an enhanced sprint cycling performance, opposing previous research in this area. This may have been as a result of the previous untrained nature of participants in previous research, given the participants employed in Chapter 2 were trained and competed in cycling events on a regular basis, thereby exposing themselves to frequent accelerations and sprint based activity. Additionally, a ceiling effect might exist for endurance trained cyclists sprint ability, which, even increases in muscle stiffness are not able to positively influence.

Practical applications

Evidence from the current research project supports the use of eccentric cycling if well-trained cyclists are attempting to improve short-term, high-intensity performance of ~6 min. While the research demonstrated large improvements in leg muscle stiffness as a result of 12 sessions of eccentric, no improvement in sprint performance was observed, suggesting that, in trained cyclists, sprint cycling performance is unaltered by increased muscle stiffness. To the best of our knowledge, the research in this thesis is the first to assess the effects of eccentric cycling on 4-km time-trial cycling performance, sprint ability, economy, VO_2peak, and numerous other physiological measures. Therefore, it would appear that ~12 sessions of eccentric cycle training would provide a valuable adjunct to well-trained cyclists attempting to improve cycling performance. The following recommendations are made for further studies to employ:

Future research

- Eccentric cycle training improves 4-km time trial performance in trained cyclists, future research should address whether durations of greater distance are enhanced after bouts of eccentric cycle training.
- Regardless of frequency or number of training sessions, graduated, periodised eccentric cycling should be incorporated similar to that of the current study in order to safely progress skeletal- and neuro-muscular adaptations.

- Previous research has shown that the combination of cycle specific strength training in conjunction with high intensity cycle training has i8mproved cycling performance and markers of aerobic performance. Therefore, future research should assess whether the combination of eccentric cycle training and high intensity cycling improves cycling performance and aerobic ability.
- Eccentric cycle training enhanced both cycling performance and leg spring stiffness; therefore research into sports such as triathlon is warranted.

Limitations

Scientific study design for interventions tend to use a double blind randomised control model. This level of control best attributes bias on behalf of the participants, and scientific team. However, achieving such goals can be often difficult; the current project used a single subject design. It was possible to utilise an independent tester and it is further believed that any effects caused by the tester's knowledge of the participant groups was minimal. In terms of standard operating procedures, the tester used standardised procedures and dialogue to ensure consistency between participants. Secondly, the primary results of training workloads, training heart rates were all determined electronically via pre-written software scripts. This ensured that the tester could not bias any testing procedures to improve the results seen by the experimental group. Furthermore, participants would not be influenced by expectations associated with the experimental or control group. In relation to participants, all participants were given, and asked to fulfil a dietary, and training diary prior to any testing procedures and asked to replicate as best as possible the 48 hours prior to any further testing assessment. Within the participant information pack there was no implied bias towards alternative strength adaption processes. Therefore, all participants approached training with an intent to improve time-trial performance, and strength over 4-km performance.

Conclusion

The current thesis has clearly demonstrated that acute bouts of 9 to 24 min at a low load, eccentric cycling can achieve benefits to key performance parameters at a lower cardiovascular, and metabolic stress load, namely, 4-km time-trial performance. Furthermore, when utilised as a training intervention over a 6 week duration, significant improvements in muscle stiffness have been reported. This is very promising for athletes that require large effects in recycling of mechanical energy, clinical setting for individuals with exercise intolerance as benefits to locomotion can be achieved with significantly lower stress on the cardiovascular system.

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Appendices

Appendix 1 - Research consent form - The effect of eccentric cycling on economy and time-trial performance in a competitive cycling population.

Project Supervisor: Joe McQuillan

Project Title

The effect of eccentric cycling on economy and time-trial performance in a competitive cycling population.

I have read and understood the information provided about this research project (Information Sheet dated 1st May 2017)	Yes/No
I have had an opportunity to ask questions and to have them answered	Yes/No
I am not suffering from injury or illness which may impair my physical performance	Yes/No
If I withdraw, I understand that all relevant information will be destroyed	Yes/No
I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way	Yes/No
I understand that any data or answers will remain confidential in regard to my identity through a coding system. The data will be made publishable as group means and therefore participant confidentiality will be ensured.	Yes/No
I wish to receive a copy of the report from the research	Yes/No

I agree to take part in this research Yes/No

***Please note**: While every effort will be made to ensure confidentiality, this cannot be guaranteed.*

Participant signature:...

Participant name:……………………………………………………….

Date:…………………………………………………….

Participant’s contact details:

…………………………………………………………………………………
..

…………………………………………………………………………………
..

Research Student Contact Details:

Piers C Dillon

Te Oranga School of Human Development and Movement Studies

University of Waikato

Ph 027 359 6246

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Project Supervisor Contact Details:

Joe McQuillan

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Hamilton

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Appendix 2 - Participant information sheet - The effect of eccentric cycling on economy and time-trial performance in a competitive cycling population.

Participant information sheet

Date Information Sheet Produced:
1st May 2017
Project Title: The effect of eccentric cycling on economy and time-trial performance in a competitive cycling population.
An Invitation
Hi, my name is Piers Dillon and I am with Te Oranga School of Human Development and Movement Studies. I am inviting you to help with a project that looks at the role eccentric cycling might play in enhancing cycling performance. You should decide whether or not you would like to be involved. You don't have to be involved, and you can stop being involved in the study at any time.
What is the purpose of this research?
Traditional strength training involves the combination of sequential, concentric muscle shortening movements (pushing against gravity) and eccentric muscle lengthening (resisting the effect of gravity) movements. Both of these actions exist in everyday life. For instance, standing up from a seated position is a concentric movement where we oppose or push against the effect of gravity, whereas sitting down we subtly oppose or resist the effect of gravity in order to control how quickly we reach a seated position. Notably, in humans, eccentric strength (or the ability to resist the influence of gravity) is at least twice that of concentric strength. In an attempt to enhance cycling ability and reduce the likelihood of injury cyclists will often incorporate 'strength' training into their regular training plan. In support of this, frequent and progressive strength training utilising concentric and eccentric movements has been shown to increase cycling performance. However, gym-based weight lifting exercise routines, tend to be 1) bilateral, and 2) acyclic in nature whereby movement incorporate a repetitive start/stop pattern over a number of sets of a specific exercise. Conversely, lower limb cycling is unilateral and cyclical and has no apparent start or finish point.

Recently, the development of a commercialized 'eccentric cycling ergometer' has allowed researchers to investigate the effect of cyclical, eccentric training on cycling performance. An eccentric ergometer applies a controlled mechanically driven resistance in the opposite direction to a 'normal' pedal stroke, i.e. a backwards pedaling action. Eccentric cycle training involves having the rider resist the reversing pedaling action, the outcome of which is an increase in eccentric load through the legs. As with traditional strength training, participants are able to express superior power outputs eccentrically, thus providing greater stimulus to the musculoskeletal system. In sedentary populations research appears to support the use of eccentric cycling to increase muscle mass and improve cycling performance, however very few studies have been carried out on competitive cyclists. This study aims to measure the effect of 10 sessions of eccentric cycle training on cycling performance and related key physiology. The outcomes of this study will help with identifying the usefulness of this specific training modality on currently competitive athletes.

The purpose of this research study is to establish what, if any effect, eccentric cycle training has on several key physiological and performance parameters relating to cycling, namely peak aerobic power, cycling economy, time-trial ability and anthropometric measures.
How was I chosen for this invitation?
You have expressed verbal or written interest in the research and you meet the age and athletic criteria set for the study.
What will happen in this research?
To ensure you meet the minimum criteria of aerobic fitness (VO_2max of 55 ml/kg/min) we will carry out an incremental step test. The incremental step test is routinely employed as a means to measure aerobic ability and involves frequent, gradual step-wise increments of an even intensity (power) over time. Throughout the test your oxygen expenditure, heart rate response and perception of effort will be measured. In order to control the intensity (wattage) of each step, we will place your bike on the sport science lab cycling ergometer.

Physiological and Performance Assessments: In order to assess any changes in fitness and cycling ability over the duration of the study we will use both the incremental step test described above, and a 4-minute time-trial. The incremental step test will be carried out prior to and following the training intervention. The 4-minute time-trial will be carried out prior to, during and following the training intervention (refer to Tables 1 and 2). The 4-minute duration is representative of the time taken for elite male cycling team pursuit to complete 4 km. We are interested in the mean power output during the time-trial. The 4-minute time-trial will be performed on the same cycle ergometer as the incremental assessment. To ensure you are physically prepared for the 4-minute time-trial, the preceding warm up will consist of several stages of easy to moderate intensity cycling during which time we will measure oxygen expenditure to quantify any changes in cycling economy.
Skinfolds: During the study we will measure your body dimensions using skinfold callipers and a tape measure. These measurements are used as part of the standard monitoring procedures in athletic tracking and will take place at the University of Waikato Sports Science Laboratory, Avantidrome, Cambridge.
Training Intervention: After meeting the minimum aerobic fitness criteria outlined above you will be assigned to either a control or experimental group. Over a 5-week period the control group will maintain their current training and racing program whereas the experimental group will replace 2 hours of cycle training per week with 2 x 1 hour sessions of eccentric cycle training equating to 10 sessions. The experimental group will undertake this lab-based training on a commercially available eccentric cycling ergometer located at University of Waikato Sports Science Laboratory, Avantidrome, Cambridge. As part of the study, participants in both the control and experimental groups are expected to be racing competitively in local weekly club events. Tables 1 and 2 detail potential assessment and training scenarios for both groups.

Table 1. Potential Assessment Outline for Control Group

WEEK	MON	TUE	WED	THUR	FRI	SAT	SUN
1	INCR. Test Pre-intervention + 4-min TT FAM #1		4-min TT FAM #2				
2	4-min TT pre-intervention						
3							
4							
5	4-min TT mid-intervention						
6							
7	4-min TT post-intervention		INCR. Test Post-intervention		4-min TT post-intervention		

INCR. Test = Incremental VO_2max Assessment; TT FAM = Time-trial familiarisation.

Table 2. Potential Assessment and Eccentric Cycle Training Outline for Experimental Group

WEEK	MON	TUE	WED	THUR	FRI	SAT	SUN
1	INCR. Test Pre-intervention + 4-min TT FAM #1		4-min TT FAM #2				
2	4-min TT pre-intervention		ET 1		ET 2		
3			ET 3		ET 4		
4			ET 5		ET 6		
5	4-min TT mid-intervention		ET 7		ET 8		
6			ET 9		ET10		
7	4-min TT post-intervention 1		INCR. Test Post-intervention		4-min TT post-intervention 2		

INCR. Test = Incremental VO_2max Assessment; ET = Eccentric Training; TT FAM = Time-trial familiarization.

Recording of Training and Racing: The study will be performed whilst you are in a phase of medium to high volume training (≥8 hours/week) with weekly and on-going road and/or track competition. A training diary will be provided to all participants to fill out regardless of which group they are in. These training diaries will be recorded and analysed on a weekly basis by the research investigators. Prior to any training will be standardized for 24 h prior to each trial for each individual.

Dietary control: To minimise any effect that dietary influences might have on the test outcomes during the study, we will ask you to refrain from alcohol and caffeine for 48 and 24 hours prior to all assessments, respectively. To monitor this you will be asked to complete a two-day diet-diary to report dietary intake on the days prior, and the days of, the initial incremental cycling assessment and time-trial. You will be asked to repeat this diet on the day before, and the day of, all remaining physiological and performance assessments.

What are the discomforts and risks?
It is very likely you will experience some temporary discomfort (exertion) towards the end of the incremental exercise assessment and during the 4-minute time-trial. This will be similar to what you feel during hard training and racing (heavy breathing, tired muscles). If you are part of the experimental group it is likely that during training sessions you will experience tiredness towards the end of sessions. It is likely that this discomfort will be no different than a moderately hard interval training session and is a sign that we are applying an adequate training stimulus. Should you feel any excessive discomfort you will be able to stop the procedures at anytime.

How will these discomforts and risks be alleviated?
The lead researcher is a qualified first aid responder and a medical clinic is located within the building where the lab testing will take place. Cool water will be offered at the end of the training sessions and assessments. Adequate measures will be taken if you feel at all dizzy during any of these sessions. You will have sufficient time to warm-up prior to starting the training or the assessments.

What are the benefits?
You will establish markers of fitness and performance at this current period in your cycling career. We will provide heart rate based training zones based on the results of the initial incremental test.

What compensation is available for injury or negligence?
In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?
All information related to you will be coded in order to ensure that you cannot be identified. The information will remain in locked storage and will only be accessible to the people of the cycling assessment project. No-one will be able to identify you from any of the summary findings for the report of the project.

Please note*: While every effort will be made to ensure confidentiality, this can not be guaranteed.*

What are the costs of participating in this research?
The only cost to you is that of time. You should allow 45 minutes for the first incremental exercise assessment. The day of the initial 4-minute familarisation time-trial will also include an explanation of the warm-up procedures and a sum-of-eight skinfold assessment, therefore 60 minutes should be allowed for this session. For all subsequent 4-minute time-trials, 45 minutes should be allowed.

All assessments will take place at the University of Waikato Sports Science Laboratory, Avantidrome, Cambridge. You should maintain your usual training during this time.

What opportunity do I have to consider this invitation?

You may take the time you need and decide whether or not you would like to be involved
You can stop being involved in the project at any point

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to myself.

Will I receive feedback on the results of this research?

Yes, feedback will be provided to you, if you request it.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor: Joe McQuillan, Te Oranga School of Human Development and Movement Studies, Faculty of Education, University of Waikato, ph 027 429 5140.
Concerns regarding the conduct of the research should be notified to Sally Peters, Head of School, Te Oranga School of Human Development and Movement Studies.

Whom do I contact for further information about this research?

Researcher Contact Details:

Piers C Dillon, Research student of Sport, Health and Human Performance, University of Waikato, ph 0273596246. Piers.C.Dillon1@outlook.com
Joe McQuillan, Te Oranga School of Human Development and Movement Studies, Faculty of Education, University of Waikato, ph 027 429 5140.
joe.mcquillan@waikato.ac.nz

Approved by the University of Waikato Human Ethics Committee on DD/MM/YYYY.
Reference number EDU118/14

Appendix 3 - Pre-test medical questionnaire

First Name/s ________________________________ Surname ________________________________

Date of Birth _____/______/_____ Gender (circle) Male Female

Please answer the following questions by circling the appropriate response, or filling in the blank.

1. How would you describe your present level of activity?
   Sedentary Moderately Active Active Highly Active

2. How would you describe your present level of fitness?
   Unfit Moderately Fit Trained Highly Trained

3. How would you consider your present body weight?
   Underweight Ideal Slightly Over Very Overweight

4. Smoking habits:

Are you currently a smoker?	**Yes**	**No**
How many do you smoke?	……per day	
Are you a previous smoker?	**Yes**	**No**
How long is it since you stopped?	……..years	
Were you an occasional smoker?	**Yes**	**No**
	……per day	
Were you a regular smoker?	**Yes**	**No**
	……per day	

5. **Do you drink alcohol?** **Yes** **No**
   If you answered **Yes**, do you have?
   An occasional drink A drink everyday More than one drink a day

6. **Have you had to consult your doctor in the previous six months?**
   If you have answered **Yes**, please give details…………………………………………………………………….

………
…………………

7. **Are you presently taking any form of medication?**
If you have answered **Yes**, please give details………………………………………………………………………….
………
…………………

8. **As far as you are aware, do you suffer from or have you ever suffered from?(circle if yes to any)**

a. Diabetes	b. Asthma
c. Epilepsy	d. Bronchitis
d. Any form of heart complaint*	e. Raynaud's Disease
f. Marfans Syndrome*	h. Aneurysm/embolism*
i. Anaemia	j. Haemophilia*

9. ***Is there a history of heart disease in your family? Yes No**
10. ***Do you currently have any form of muscle or joint injury? Yes No**
11. **Have you had to suspend your normal training in the previous two weeks? Yes No**
12. **Please read and answer the following questions:**
    a. Are you suffering from any known serious infections? **Yes No**
    b. Have you had jaundice within the previous year? **Yes No**
    c. Have you ever had any form of hepatitis? **Yes No**
    d. Are you HIV antibody positive? **Yes No**
    e. Have you ever been involved in intravenous drug use? **Yes No**
    f. For females, are you currently, or in the previous 6 months, pregnant? **Yes No**

13. As far as you are aware, is there anything that might prevent you from successfully completing the tests that have been outlined to you?

If the answer to any of the above questions is yes then:

a. Discuss with the clinic personal the nature of the issue

Consent of Athlete/Participant

__________________________ _____/______/_____

Athlete/Participant Signature Date

____ ___________________________ ____/______/____

Guardian name (required if age less than 16 yr) Athlete/Participant Signature Date

____ ___________________________ ____/______/____

Witness name Signature Date

Appendix 4 - UOW Sports science laboratory informed consent

The effect of eccentric cycling on economy and time-trial performance in a competitive cycling population

I (print name) ___________________________ consent to participate in physiological assessment on the following terms:

1. I have read the Explanation of Physiological Assessment Procedures attached and have understood what I will be required to do. I have had the opportunity to ask questions and received satisfactory explanations about the assessment/s to be conducted.

2. I understand that I will be undertaking physical exercise at or near the extent of my physical capacity and there is possible risk in the physical exercise at that level, such as episodes of transient light-headedness, fainting, abnormal blood pressure, chest discomfort.

3. I understand that this may occur although the staff in this laboratory will take all proper care in the conduct of the assessment, and I fully assume that risk.

4. I understand that I can withdraw my consent, freely and without prejudice, at any time before, during or after testing.

5. I have told the person conducting the assessment of any illness or physical defect I have that may contribute to the level of that risk.

6. I understand that the information obtained from the test will be treated confidentially with my right to privacy assured. However, the information may be used for statistical or scientific purposes with privacy retained.

7. I release this laboratory and its employees from any liability for any injury or illness that I may experience during the assessment as well as any subsequent injury or illness that is connected to or to any extent influenced by the assessment.

8. I will indemnify this laboratory in respect to any liability it may incur in relation to any other person in connection with the assessment.

9. I hereby agree that I will present myself for testing in a suitable condition and have abided by any requirements for diet and activity prescribed to me by laboratory staff.

_________________________ _____/______/_____

Athlete/Participant Signature Date

____ __________________________ ____/______/____

Guardian name (required if age less than 16 yr) Athlete/Participant Signature Date

____ __________________________ ____/______/____

Witness name Signature Date

From Australian Institute of Sport, 2013, *Physiological tests for elite athletes,* 2nd ed. (Champaign, IL: Human Kinetics).

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Ethics number: EDU118/14

Appendix 5 - Rate of perceived exertion scale

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Rate of Perceived Exertion Scale

6.	**No Exertion at All**
7.	**Extremely Light**
8.	
9.	**Very Light**
10.	
11.	**Light**
12.	
13.	**Somewhat Hard**
14.	
15.	**Hard (Heavy)**
16.	
17.	**Very Hard**
18.	
19.	**Extremely Hard**
20.	**Maximal Exertion**

Borg, G.A., (1982). Physiological basis of physical exertion. *Medicine and Science in Sport and Exercise*, 14, p 377.

Appendix 6 - Ethics approval

Dean's Office
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THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

MEMORANDUM

To:	**Joe McQuillan**
cc:	Dr Nicola Daly
From:	Professor John Williams Chairperson, Research Ethics Committee
Date:	5 February 2015
Subject:	Research Ethics Application – Staff (EDU118/14)

Thank you for submitting the amendments to your application for ethical approval for the research project:

The effect of eccentric cycling on economy and time-trial performance in a competitive cycling population

I am pleased to advise that your application has received ethical approval.

Please note that researchers are asked to consult with the Faculty's Research Ethics Committee in the first instance if any changes to the approved research design are proposed.

The Committee wishes you all the best with your research.

Professor John Williams
Chairperson
Faculty of Education Research Ethics Committee

Appendix 7 – Directed study

Meta-analysis: Effects of eccentric and concentric cycle ergometer training on power output: A systematic review and meta-analysis of randomized controlled trials

Abstract

Aim: The aim of this systematic review was to determine if eccentric cycling training is superior to concentric cycle training for developing power output in healthy adult males and females.

Methods: Two reviewers performed electronic searches for studies investigating the effects of eccentric (ECC) and/or concentric (CON) cycle ergometer training on lower body power output in healthy adult male and female participants. In order to compare the magnitude of effects between ECC and CON training interventions meta-analyses were performed on the pooled data. Cohens *d* effect size and mean percentage differences (*MDiff)* were also calculated for the included studies to highlight the varying effects of ECC and CON training.

Results: Seven studies met the inclusion criteria (N = 77), comprised of 17 male and 5 female participants (age of 21.5 ± 3.7 yr) within the eccentric group; and 54 males participants and 1 female participant (25.1 ± 4.3 yr) within the concentric group. The meta-analysis revealed (Hedges *g* = -0.13) that eccentric cycle ergometer training (*Mdiff* = 1.59 ± 6.10%; *d* = 0.13 ± 0.5) elicited larger improvements in jump performance, while power output was revealed to (Hedges *g*= 0.49) improve during concentric cycle training comparison (*MDiff* = 7.18 ± 10.6%; *d* = -0.61 ± 0.81).

Conclusions: This systematic review demonstrates that ECC training is associated with greater improvements in countermovement jump performance and CON training is associated with greater improvements in cycling power.

Introduction

Eccentric and concentric contractions govern human locomotion, concentric contractions occur during muscle shortening to produce force; whereas eccentric contractions are active during deceleration, braking and absorbing energy. Eccentric contractions occur when the muscular-tendon unit is stretched, absorbing force and mechanical energy (Lindstedt et al., 2001). Eccentrically, the musculo-tendon unit works to absorb shock and temporarily store energy within the series elastic muscle fibres and subsequently transfer this energy during an concentric contraction (Lindstedt et al., 2001).

Concentric "positive" and eccentric "negative" resistance training is most commonly performed with free-weights e.g. bar-bells, dumb-bells and pulleys (Vogt & Hoppeler, 2014)· However, newly developed commercially available dynamometers and ergometers that utilise an electric motor have been successfully implemented as a novel resistance training stimulus across a range of populations (Elmer et al., 2013; Isner-Horobeti et al., 2013). Eccentric cycle ergometers built in the 1950s using modified cycle ergometers, required participants to resist the force of the pedal cranks generated by an electric motor, causing lengthening of the muscle (eccentric contraction), which allows for better control of known workloads from the motor to the ergometer, as workloads were adjusted via a brake under subject control. This design was further advanced several years later, which allowed pedal frequency to be determined by an electric motor and subjects were able to adjust the load by producing more or less effort against the pedals (Elmer et al., 2013). All subsequent studies using ECC protocols have used motorised eccentric cycle ergometers of a similar design.

Compared with concentric contractions, eccentric contractions have the potential to stimulate greater muscular force and power adaptations (Guilhem et al., 2010). Eccentric loading from electrical motor driven cycle ergometers also has the potential to overload the muscular system at half the metabolic cost (Isner-Horobeti et al., 2013), therefore athletes are able to train at a reduced metabolic expense and for an increased duration of time. Extensive reviews of eccentric exercise training have (Guilhem et al., 2010; Isner-Horobeti et al., 2013; Roig et al., 2009) resulted in the utilisation of two differing loadings parameters, “high-intensity low-volume” training characterized by high work load which can exceed one repetition maximum and “low-intensity high-volume” training characterized by high duration but submaximal exercise intensities. The effectiveness of such novel training modalities have reported improvements in strength and muscle size (Elmer et al., 2012; Leong et al., 2013); however, there is a lack of literature focussing the effects of eccentric cycle ergometer training on rate of force development and power output during stretch-shorten cycle movements, such as squatting and jumping. Therefore, the purpose of this systematic review and meta-analysis was to review the limited number of studies conducted on healthy adult participants and determine if ECC training is more beneficial than CON to improving force and power during jumping and cycling.

Methods

Search strategy

Two reviewers performed separate electronic searches on MEDLINE, PUBMED, PEDro, Google Scholar and the institutions online database. The initial search included the following key terms "concentric cycling", "concentric contraction", "cycle ergometer", "eccentric cycling" and "eccentric contraction" was performed. The search was restricted to articles published in English. The results of the primary search were than combined via a Boolean search with the following keys terms: "force", "power", and "jump height". The final electronic search was performed in January 2017. Additionally, reference lists from studies meeting the inclusion criteria were scanned using the same modality as applied to the initial citation search to conclude the search databases.

Selection

Studies were only included in the systematic review if they: were controlled trials (randomised and non-randomised) published in a peer-reviewed journal; utilised healthy adult participants (age: 18 to 50 yr) with no prior serious injuries within the last 6 months; had comparisons of ECC and CON cycling training; had training programmes lasting a minimum of 3-weeks (wks) with a minimum training frequency of 2 x wk; and included a jump or cycling performance measure (e.g. jump height, force or power) as one of the key outcome measured. Studies were excluded if they did not meet the minimum requirements outlined. Based on the inclusion criteria, two independent reviewers (PCD and DTM) screened citations of potentially relevant publications. If the study seemed to have potential relevance, screening at abstract level was carried out. Once screened at abstract level and the article indicated potential inclusion, full articles were reviewed for inclusion using a modified PEDro scale (Figure 4).

Study quality assessment

Two reviewers (PCD and DTM) independently performed quality assessments of the included studies; disagreements were resolved during a consensus meeting with a third reviewer (JM). Methodological quality was assessed using a modified PEDro scale, which is based on the following 11 items: eligibility criteria, random allocation, concealed allocation, follow-up, baseline comparability, blinded subjects, blinded therapists, blinded assessors, intention-to-treat, between-group analysis, and both point and variability measures. Inter-rater reliability was evaluated using intraclass correlation coefficient based on the total score.

Data analysis

When studies were similar in terms of loading parameters during training, measurements (e.g. cycling and jump performance) and output variables (e.g. jump height and power) meta-analyses were performed to determine the effectiveness and differences of ECC versus CON training on performance. Data were pooled into the following subgroups: CON-only training and ECC-only training.

Effect size (Cohens *d* = PostMean – PreMean / PreSD) and mean percentage differences (Mdiff%= [PostMean-PreMean] / {[PreMean+PostMean]/2} x 100) were calculated for each study to determine the magnitude of effects for a given training intervention. The mean percentage change per training session (MDiff% /

[duration x frequency]) and Hedges *g* (Hedges *g* = [(Post-PrePooledEccMean) – (Post-PrePooledConMean) / PooledSD] were also calculated to provide a normalised effect comparisons between the ECC and CON training interventions. If an article that was selected did not provide sufficient data for the analysis, authors were contacted to obtain data needed. Studies were excluded from the meta-analyses if the relevant data (means, SD and sample size) was not available.

Results

Figure 1 displays the flow chart, identifying different phases of the study selection process. The initial search of databases identified 13000 titles, of which 500 were suitable for abstract review. Screening the references of these articles yielded a further 120 citations eligible for abstract review. Following a review of titles and abstracts, 9 full text articles were reviewed. When exclusion criteria were applied, 7 studies satisfied the criteria to be included in the review. The primary reasons for exclusion were as follows: data presented without means and SD, no cycling of jumping performance measure, short intervention durations (< 3-wks) and ineligibility of participants due to age constraints and clinical conditions.

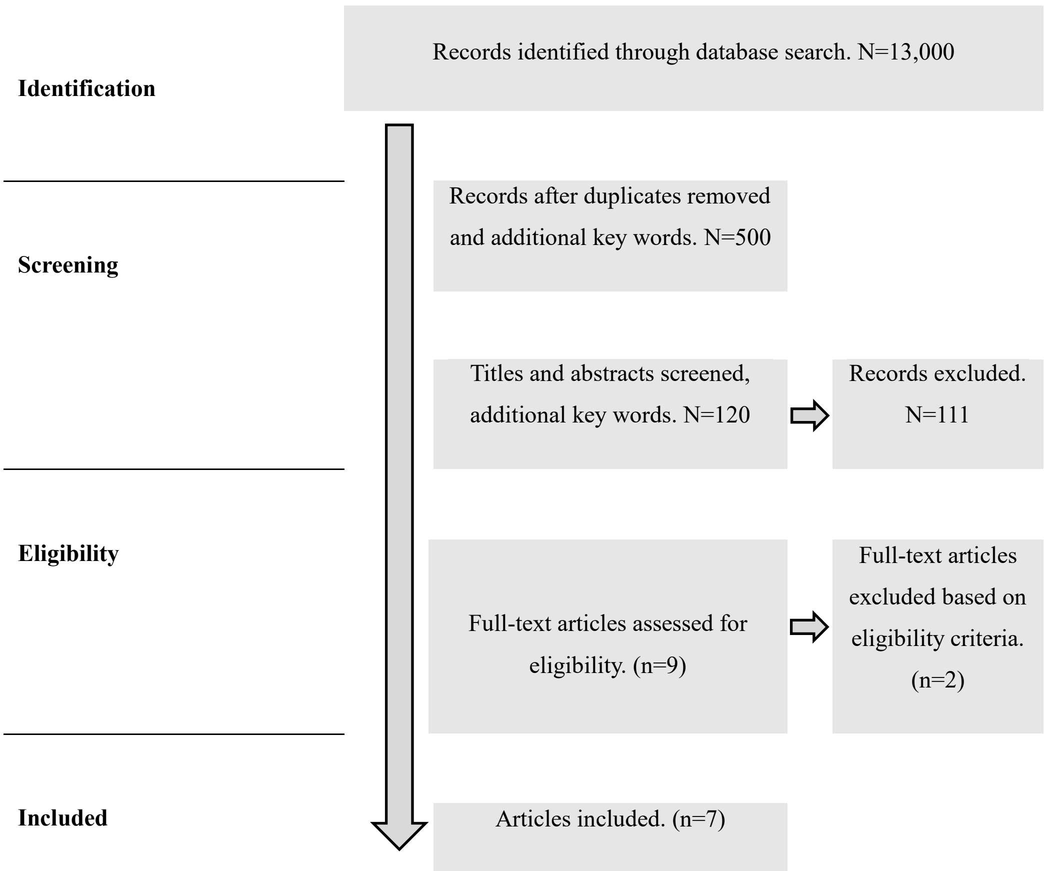

Figure 10: Flow chart of records deemed appropriate for review

Study quality

A detailed description of the PEDro scores for each study are shown in Table 1. The mean study quality was 5.1 (SD 0.38) out of 10. All studies were categorised as moderate quality and none categorized as having poor methodological quality. The most common flaws were blinding of the assessors and participants, which is nearly impossible when administering ECC-only and CON-only cycle training interventions. The study quality ratings herein produced perfect inter-rater reliability (ICC = 1.00).

Study characteristics

The total number of participants of the included studies was 77. The eccentric and concentric cycling training interventions included 22 and 55 participants, respectively; while 18 participants served as controls, and therefore were excluded from the analysis. The main characteristics of the included studies are presented in table 1. From the included studies those utilising an ECC training intervention, one study reported findings against CON group. Although some studies did not provide all demographic data, the age of the ECC and CON groups was 21.5 (3.7) and 25.1 (4.3), respectively. The distribution of sex among the included studies was unproportioned with 71 healthy male and 6 healthy female participants.

ECC and CON training interventions on average lasted 7.0 (1.0) and 5.7 (2.2) wks in duration with mean weekly training frequencies of 2.7 (0.6) and 2.6 (0.8), respectively. All eccentric and concentric studies included/utilized a cycling ergometer. All of the ECC training interventions varied greatly in terms of volume and intensity. Leong et al., (2013) prescribed continuous ECC for 5 to 10 min; Elmer et al., (2012) prescribed 10 to 30 min progressively increasing in volume each wk; and (Gross et al., 2010) prescribed 20 min of ECC following resistance training. Gross et al., (2010) implemented ECC coupled with resistance training, which consisted of 3 x 30 repetitions across 4 different lower body exercises separated by a 3 min rest period prior to commencing a 20 min of ECC at a pedalling cadence between 60-80 rev·m^{-1} 3$^{\times}$wk^{-1}. Whereas, Elmer et al., (2012) matched work rates of both the eccentric and concentric groups, conducting training 3$^{\times}$wk^{-1} for 7-wks. Work rate was initially set to 54% of maximum heart rate progressing to 66% by wk-7. Leong et al., (2013) Implemented a modified training intervention, where ECC training power was initially set to 20% of pre-training Pmax for 5 min progressively increasing to 55% of pre-training Pmax for 10.5 min over the 8-wk training period. All interventions and data collection were conducted outside of the competitive season.

The CON volume and intensity also varied greatly between the five included studies. As previously mentioned, Elmer et al., (2012) prescribed 10 to 30 min of CON progressively increasing in volume each week. Paton et al., (2009) utilised a high and low intensity mixed concentric modality consisting of sets of maximal effort single-leg jumps alternating with sets of maximal intensity cycling efforts. The jump phase of the training required participants to perform 20 explosive step-ups off a 40-cm box, while the cycle phase consisted of 5 × 30 maximal efforts through cadences of 60-120. Swart et al., (2009) had both experimental groups complete a high-intensity interval training session, consisting of 8 by 4 min intervals interspersed with 90 s self-paced recovery periods, with the exception of one group completing each interval at a fixed workload corresponding to 80% of mean maximal power output. Jenkins & Quigley, (1992) utilised an 8-wk training intervention consisting of 30 min of concentric cycling conducted 3.$^{\times}$wk^{-1} for the first 5-wks increasing by 5 min per wk thereafter with an initial training intensity set to each individuals mean exercise intensity based on a 40 min critical power test, gradually increasing over the intervention period. Linossier et al., (1997) implemented repeated sprint concentric cycling consisting of 2 sets of 15 x 5 s sprints with 55 s rest between each sprint and 15 min rest between sets. Interventions and data collection were conducted outside of the competitive season, with the exception of Paton et al., (2009) collecting data within the competitive season.

Meta-analyses

Due to the limited number of studies meeting the inclusion criteria, comparisons between CON and ECC training studies was applied for those that undertook an experimental and control group and pooled comparisons of jump and cycling performance outcomes were reported for all others. The pooled meta-analysis (Table 3) favoured the ECC training in comparison to CON training for improving jump performance (Hedges g = -0.16); whereas the CON training lead to larger improvements in concentric cycling power (Hedges g = 0.57). However, due to the range in magnitudes of the effects (Cohens d) elicited by the CON (d = -0.31 to 2.36) and ECC (d = 0.05 to 0.46) training interventions, interpretation of the Hedges g should be viewed with caution.

Cycling power

Cycling power output was measured as maximal power output (Pmax). Following continuous eccentric cycle ergometer training, Pmax resulted in a *small* increase of 5.1% in a group of healthy adult male and female participants (Leong et al., 2013); in contrast a *trivial* decrease of 0.5% was also observed in group of healthy adult male and female participants (Elmer et al., 2012). A *trivial* Pmax increase of 0.8% was also observed in continuous concentric cycling in health adult participants (Elmer et al., 2012). Whereas *very large* increases in Pmax (24.4%) and critical aerobic power (26.2%) were observed following repeated concentric sprint cycling in a group of healthy adult males. Of note, *Extremely Large* improvements in mean power absorption were observed in the ECC studies (d = 7.92, 11.88 and 27.70).

Jumping performance

Jumping performance was assessed via maximum concentric jump power. The meta-analysis revealed mixed training effects following continues ECC training; one group had a *small* increase (5.9%) in jump performance (Elmer et al., 2012) and another group had a *small* decrease (-0.57%) in jump performance (Gross et al., 2010). The continuous CON trained group of health adults reported a *small* decrease (-2.3%) in jump performance (Elmer et al., 2012).

Table 7. Study quality PEDro scores

Study	Eligibility criteria	Random allocation	Concealed allocation	Baseline compare	Assessors blinded	Participants blinded	Follow-up	Intention-to-treat analysis	Between group analysis	Points estimation variability	Total score
					Interventions						
Leong *et al*	*yes*	*no*	*no*	*yes*	*no*	*no*	*yes*	*yes*	*no*	*yes*	5
Elmer *et al*	*yes*	*no*	*no*	*yes*	*no*	*no*	*no*	*yes*	*yes*	*yes*	5
Gross *et al*	*yes*	*no*	*no*	*yes*	*no*	*no*	*no*	*yes*	*yes*	*yes*	5
Paton *et al*	*yes*	*no*	*no*	*yes*	*no*	*no*	*no*	*yes*	*yes*	*yes*	5
Swart *et al*	*yes*	*no*	*no*	*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*	5
Jenkins *et al*	*yes*	*no*	*no*	*yes*	*no*	*no*	*yes*	*yes*	*no*	*yes*	5
Linossier *et al*	*yes*	*yes*	*no*	*yes*	*no*	*no*	*no*	*yes*	*yes*	*yes*	6

Table 8. Effects of eccentric cycle ergometer training on jump performance and cycling power output

Study	Participants	Duration (weeks)	Frequency (days/wk)	Loading Parameters	Output	*d*	%Δ / session
Gross *et al*	Male skiers (n=8) Age 18±1	6	3	Eccentric cycling: 3x30 reps for 4 leg exercises, followed by 20-min eccentric cycling.	**Jump**		
					-Pmax	0.05	-0.03%
					-MPA	27.70	6.66%
Elmer *et al*	Healthy Male (n=5) Female (n=1) Age 25±6	7	3	Eccentric cycling: @ 60rpm, target HR set to 54%-66 for 10-30 (2 min/wk) increasing each week.	**Jump**		
					-Pmax	0.46	0.28%
					Cycle		
					-Pmax	-0.04	-0.02%
					-MPA	7.92	3.05%
Leong *et al*	Healthy Male (n=4) Female (4) Age 22±2	8	2	Eccentric cycling: @ 60 rpm, 20-55% (5%/wk) of Pmax for 5-10.5 min (1 min/wk) increasing each week.	**Cycle**		
					-Pmax	0.39	0.32%
					-MPA	11.88	5.95%

%Δ / session = percentage change per training session; CP = cycling critical power *d* = Cohen *d* effect size calculation; JH = jump height; N = total number of participants; n = number of participants per study; Pmax = maximal power produced; MPP = mean power production; MPA = cycling eccentric mean power absorption;

Table 9. Effects of concentric cycle ergometer training on jump performance and cycling power output

Study	Participants	Duration (weeks)	Frequency (days/wk)	Loading Parameters	Output	*d*	%Δ / session
Elmer *et al*	Healthy male (n=5) female (n=1) Age 25±2	7	3	Concentric cycling @ 60rpm, target HR set to 54%-66 for 10-30 (2 min/wk) increasing each week.	Jump Pmax	-0.31	-0.11%
					Cycle Pmax	0.09	0.04%
Paton *et al*	Healthy male (n=9) Age 27±7	4	2	Mixed jump and low cadence concentric cycling	Cycle Pmax	0.79	0.72%
	Healthy male (n=9) Age 25±6	4	2	Mixed jump and High cadence concentric cycling	Cycle Pmax	0.14	0.29%
Swart *et al*	Healthy male (n=6) Age 30±5	4	2	Gheart group completed a high intensity trainingt session, consisting of 8, 4min bouts at 80%Wmax.	Cycle Pmax	0.67	0.46%
	Healthy male (n=6) Age 30±8	4	2	Gpower group completed a high intensity trainingt session, consisting of 8, 4min bouts at own pace	Cycle Pmax	0.33	0.48%
Jenkins *et al*	Healthy male (n=12) Age 19±1	8	3	Concentric cycling: 30-45 min @ 40 min CP output increasing each week.	Cycle CP	1.44	1.09%
Linossier *et al*	Healthy male (n=7) Age 20±1	9	4	Concentric repeated sprint cycling: 2 sets of (15 x 5s sprints: 55 s rest) 15 min rest between sets	Cycle Pmax	2.36	0.68%

%Δ / session = percentage change per training session; CP = cycling critical power *d* = Cohen *d* effect size calculation; N = total number of participants; n = number of participants per study; Pmax = maximal power produced.

Table 10. Pooled effects of eccentric and concentric cycle ergometer training on jump and cycling performance

Measure	**Eccentric Training**	**Concentric Training**	**Cohens *d***	**Hedges *g***
	%Δ	%Δ		
Jump Performance	2.7%	-2.4%	-0.13	-0.16
Cycling Power	2.3%	9.6%	0.88	0.72

%Δ = percentage change

Discussion

This investigation has focused on the effects of ECC vs CON ergometer training in healthy adults. The meta-analysis indicates that ECC training is associated with greater improvements in countermovement jump performance and CON training is associated with greater improvements in cycling power.

Cycling power

Elmer et al., (2012) reported no change in concentric cycling power output against that of an ECC and CON trained group. Maximum power-output during concentric cycling did not differ significantly between groups (ECC 1035 ± 142 vs 1030 ± 133 W - CON 1072 ± 98 vs 1081 ± 85 W). While those that completed training interventions without comparison of a concentrically trained group as control (Gross et al., 2010; Leong et al., 2013) reported ECC training to improve concentric cycling power output 2.3%. Secondly, CON using varied modalities reported a mean improvement of 9.6%, with studies that investigated both a high and low intensity intervention favouring a low-intensity training modality based on the effects of 60-s power (Swart et al., 2009). The gains in performance with low-cadence training (6 to 11%) are twice that of a high-intensity training modality when performed at either a fixed heart rate or fixed power in well-trained cycling population (2.3 vs 5.7%) (Paton et al., 2009).

Power absorption within a eccentrically trained group (*MDiff* = 93%; *d* = 15.8) has shown to be twice that of the concentric trained group when matched on heart rate (Elmer et al., 2012), this has allowed for eccentric modalities to have a greater effect on muscle force altering neural control (Dartnall, Nordstrom, & Semmler, 2011). Mean power absorbed by the eccentric group increased 94% over the intervention period, whereas, this remained mostly stable within the concentric group. Gross et al., (2010) alternatively ran a mixed weight and eccentric cycle protocol where the average power absorption during eccentric cycle training progressed from 213 ± 23 to 850 ± 71 W, an aggressive protocol with participants increasing power absorption by 300%. This reporting minor increase in hypertrophy compared to 10-20% increases seen in high-resistance training (Campos et al., 2002) or the 40-50% seen in untrained participants after ECC training (LaStayo et al., 2000). Although ECC training elicits greater increases in hypotrophy CON training was reported to improve concentric cycle Pmax (2.3 vs 9.6%), furthermore this is seen in low-intensity modalities.

Jump performance

Elmer and Gross in which we compared jump performance against that of a concentric group (Elmer et al., 2012; Gross et al., 2010). Reported, an increase of 2.66% against that of the concentric group decrease of -2.3%. Participants who were eccentrically trained (5 to 20 min) showed greater improvements / higher power output than concentrically trained group in maximal jump power (2123 ± 279 to 2252 ± 275 W vs 2314 ± 173 to 2260 ± 166 W). Improvements in muscle stiffness, hypertrophy and power, specifically related to the knee and hip extensors (Elmer et al., 2012; Gross et al., 2010; Isner-Horobeti et al., 2013; Leong et al., 2013; Linossier et al., 1997) have been reported. Such adaptions relate to multi-joint tasks (e.g. jump height) (Elmer et al., 2012) and performance during SSC (Vogt & Hoppeler, 2014) likely due to a change in muscle architecture and/or neural adaptions. Findings of this nature links reports of Leong et al., (2013) with that previously mentioned by Elmer et al., (2012) and Gross et al., (2010). This would suggest that an ECC training modality, although showing great improvements in cycling performance is greater than that of a concentrically trained group for improving jumping performance. Although Gross et al., (2010) found eccentric cycling not to contribute significantly to isometric leg strength. Gross believed it to be an effective group ^{x} time effect for improving countermovement jump height relative to participants involved competing in alpine ski trials.

Traditional CON training modalities are multi-joint task that include a mostly passive eccentric phase that precedes the concentric phase, and thus likely does not rely heavily on the stretch-shortening cycle. Therefore, not eliciting improvements in jumping performance as seen in eccentric modalities (Elmer et al., 2012).

Conclusion

In summary, this systematic review suggests that ECC training leads to greater improvements in jumping performance, while CON training leads to greater improvements cycling Pmax.

What are the findings
➢ **Eccentric cycle training leads to greater improvements in jumping performance** ➢ **Concentric cycle training leads to greater improvements cycling Pmax** ➢ **Eccentric cycle training leads to *extremely large* improvements in cycling power absorption**

What are the applications of these findings
➢ **Continuous eccentric cycling training may enhance countermovement jump performance and cycling power absorption** ➢ **Enhanced leg spring stiffness would be important for improving activities that involve a substantial landing component.**