Greater decrements in neuromuscular function following interval compared to continuous eccentric cycling

David James Green[1,2], ORCID 0000-0002-0749-0087

Kevin Thomas[1], ORCID 0000-0003-2973-5337

Glyn Howatson[1,3] ORCID 0000-0001-8494-2043

[1] Faculty of Health and Life Sciences, Northumbria University, Newcastle-upon-Tyne, UK

[2] English Institute of Sport, Loughborough, UK

[3] Water Research Group, School of Environmental Sciences and Development, Northwest University, Potchefstroom, South Africa

Address for correspondence:

Email: david.green@eis2win.co.uk

Disclosures

This project was part of a collaborative PhD studentship between the English Institute of Sport and Northumbria University, UK. No potential conflict of interest was reported by the authors.

Key words:

Recovery, time under tension, electromyography, torque, muscle lengthening

Abstract

Our aim was to determine the demands and consequences of a single session of continuous (CONT) or interval (INT) eccentric cycling. Fourteen healthy males performed 'work-matched' CONT and INT eccentric cycling in a cross over design. Measures of maximal voluntary contraction (MVC), resting twitch force, voluntary activation (VA), muscle soreness, and creatine kinase (CK) were taken at baseline, immediately post, and 24, 48, and 72 h post the first exercise bout. The second bout was used to characterise within session demands. Decreases in MVC (INT 19%, CONT 13%), twitch force (INT 31%, CONT 18%), and VA (INT 10%, CONT 6%) were observed immediately post session ($p < 0.05$). Reductions in twitch force were greater after INT ($p < 0.05$) and lasted 48 h. Muscle soreness was greater following INT, versus CONT ($p < 0.05$), although no differences in CK were observed. Metabolic demands (% of $\dot{V}O_{2peak}$ and [BLa]) were greater during INT vs. CONT (32 ± 6% 28 ± 6%; $p < 0.001$), [BLa] (1.0 ± 0.4 vs. 0.8 ± 0.2 $mmol \cdot L^{-1;}$ $p < 0.001$), and RPE (12 ± 1 vs. 11 ± 1; $p < 0.001$), respectively. Total time under tension was 48% greater in CONT compared to INT ($p < 0.001$), whereas average torque (during exercise) was 40% greater during INT compared to CONT ($p < 0.001$). Interval eccentric cycling exacerbates muscle soreness, decrements in muscle function, and lengthens recovery compared to a work matched continuous bout, which is attributable to increased force rather than time under tension.

Introduction

During eccentric cycling a motor drives pedals towards the user at a pre-determined cadence [1–3]. The act of resisting the pedals elicits lengthening muscle actions, predominately of the quadriceps [4,5]. Typically, this type of exercise is performed on a recumbent ergometer [4,6,7]. The cyclical nature of this exercise allows a high volume of eccentric contractions to be performed in a relatively short timeframe compared to alternative modes of eccentric training such as isokinetic dynamometry or motorised leg press exercise. When prescribed at a constant sub-maximal intensity, 7– 8 weeks of eccentric cycle training can increase peak power during a countermovement jump, concentric cycling peak power, and isometric knee extensor strength [1,8,9]. When used maximally, eccentric cycling has the potential to elicit a greater mechanical stimulus to the lower limbs than can be achieved with concentric cycling [4]. To exploit this mechanical characteristic, it might be advantageous to perform eccentric cycling as a series of shorter-duration, higher intensity intervals as opposed to a continuous lower intensity bout for a longer duration. The perceived enjoyment of shorter eccentric cycling intervals is reported to be similar to continuous eccentric cycling, further highlighting interval eccentric cycling as a feasible training method [7].

Conceptually, interval eccentric cycling can provide a large mechanical stimulus without increasing metabolic load to a prohibitively difficult magnitude, at least for individuals without existing cardiovascular limitations. When compared with continuous eccentric cycling $\dot{V}O_2$ (oxygen uptake) is elevated during interval eccentric cycling although still remains at a relatively low level (<60% of $\dot{V}O_{2peak}$ (peak oxygen uptake))[7]. A single bout of low intensity interval, or moderate intensity continuous, eccentric cycling can cause an immediate reduction in countermovement jump height, squat jump height, isometric knee extensor force, and rate of force development, that can persist for several days post-exercise [2,10,11]. However, to our knowledge, no work has yet examined the effect of eccentric cycling at high power outputs on

the magnitude or duration of subsequent decrements in muscle function, damage, and soreness. At low intensities (< 20% peak concentric power output), it has been observed that altering interval intensity during eccentric cycling does not affect post-exercise decrements in muscle function[10]. Whilst this intensity is relavant for clinical application these results are unlikely to represent the response of an athletic population engaging in high intensity eccentric cycling for the purpose of eliciting positive muscular adaptation. A greater understanding of the responses to high intensity eccentric cycling will allow coaches and sports practitioners to more effectively integrate eccentric cycling into athlete training programs.

The reduction in the ability to produce muscular force after concentric cycling has been apportioned to changes in neuromuscular function; specifically a reduction in the contractile capability of the muscle and an inability to voluntarily activate the muscle [12–14]. However, no work has yet examined the recovery of neuromuscular function after interval and continuous eccentric cycling. For concentric cycling, when power output is highly varied (50 – 200% maximal aerobic power; MAP) greater decrements in voluntary activation and peak doublet force have been observed post session compared to a work-matched continuous bout (70% MAP)[14]. However, when power output was only varied by ±15% no differential effects on neuromuscular function were observed compared to a continuous session [15]. Understanding the aetiology of reductions in force generating capacity after eccentric cycling, and the effect of structuring a session as interval or continuous training is critical in understanding the consequences of eccentric cycling and how best to utilise this as a training modality. Therefore, the aim of this study was to determine the effect of session structure on decrements in neuromuscular function following a single bout of eccentric cycling. It was hypothesised that structuring eccentric cycling as intervals would increase strength loss post exercise and delay recovery time compared to a work matched continuous bout.

Methods

Participants

Fourteen recreationally active males were allocated to interval (INT; n = 7, mean ± SD; age = 23 ± 3 years; body mass = 78.4 ± 7.1 kg; stature = 181 ± 5 cm) and continuous (CONT; n = 7, mean ± SD; age = 25 ± 6 years; body mass = 78.9 ± 5.6 kg; stature = 182 ± 6 cm) exercise groups. Based on an expected 23% decline in MVC force following eccentric cycling (Penailillo *et al*., 2013) it was calculated that 6 participants were required per group to achieve 95% statistical power at an alpha of 0.05 (G*Power 3.1.9.2, Faul et al., 2007). All participants were unaccustomed to eccentric cycling and had no history of lower limb injuries or neurological disorders. All participants provided written, informed consent and were deemed healthy by a physical activity readiness questionnaire. Ethical approval was granted prior to the start of all procedures by the Northumbria University Faculty of Health and Life Sciences Ethics committee in accordance with the Declaration of Helsinki.

Experimental design

Participants attended the laboratory on seven separate occasions in a rested state, having been asked to avoid exercise, caffeine, and alcohol in the preceding 24 h. During two preliminary visits, participants completed a laboratory-based cycle ergometer test to determine $\dot{V}O_{2peak}$ and MAP (maximal aerobic power) (visit 1) and undertook two eccentric cycling familiarisation sessions (visits 1 and 2). Participants were then split into two groups, matched for MAP (n = 2 × 7), and performed a session of either interval (INT) or continuous (CONT) eccentric cycling (visit 3). Seven days separated visits 2 and 3. To compare the time course of recovery after INT and CONT exercise, neuromuscular function and serum creatine kinase activity [CK] were measured pre, immediately post, and 24, 48 and 72 h post-exercise. Additionally, perceived muscle soreness was recorded 24, 48 and 72 h post-exercise. After at least 3 days of additional recovery, participants completed the final laboratory session (visit 7) involving the eccentric

cycling session they had not undertaken in visit 3. This was in order to compare the within-session demands between INT and CONT in a repeated measures cross-over design. Recovery was not assessed after this second bout of eccentric cycling as it was considered more appropriate to compare recovery using an independent measures design to remove any confounding influence of the repeated bout effect.

Incremental cycle test

Peak oxygen uptake ($\dot{V}O_2$ peak) was determined by a continuous incremental cycling ramp test to volitional exhaustion on an electro-magnetically braked cycle ergometer (Schoberer Rad Messtechnik [SRM], Germany). After a 10 min warm-up at 100 W the power output was increased by 30 W per minute (5 W every 10 s) until volitional exhaustion or a drop of >10 rpm in cadence. Maximum aerobic power (MAP) was defined as the highest average power output achieved during a 60 s epoch. Breath-by-breath gas exchange data was quantified via an automated open circuit metabolic cart (Vyntus CPX, Vyaire, IL, USA) that was calibrated according to manufacturer's recommendations. Respiratory gases were measured throughout the maximal cycling assessment test, with $\dot{V}O_2$ peak defined as the greatest continuous sample of $\dot{V}O_2$ averaged over 30 s.

Familiarisation trials

All eccentric cycling was conducted on a custom built recumbent eccentric cycling ergometer (BAE systems, London, UK) as described in [4]. Participants were instructed to resist the pedals in the opposite direction of motion. Following the $\dot{V}O_2$ peak test a 15 min rest period was observed prior to a 5 min bout of eccentric cycling at 80% MAP and 60 rpm. The second familiarisation (visit 2) consisted of 10 min continuous eccentric cycling (80% MAP) followed by 2 x 2 min (120% MAP) of interval based eccentric cycling with one-minute recovery. These

familiarisations served to minimise the difference in metabolic demand between the two experimental bouts of eccentric cycling and ensure the subsequent muscle damage response was comparable to that expected if regularly partaking in eccentric cycling [2].

Experimental trials

During the two separate experimental trials participants completed 30 min of continuous eccentric cycling (CONT) or 30 min of interval eccentric cycling (INT) consisting of 10 × 2 min repetitions with 1 min passive recovery. In order to match the work done between sessions CONT was conducted at 80% MAP and INT at 120% MAP. Pilot work suggested that 80% MAP was a realistic continuous training intensity for the cohort and is above that considered achievable during concentric cycling. Thus, the continuous session still exploited the greater absolute power output sustainable during eccentric cycling. During the recovery period between intervals the ergometer was stopped, and no work was done. Throughout all sessions cadence was set to 60 rpm to maximise reliability of power output and muscle activation [3]. A 20 μL capillary blood sample was obtained from the earlobe at 5 min intervals throughout each exercise session to measure blood lactate concentration [BLa] using an automated device (Biosen, EKF, Germany). Ratings of perceived exertion (RPE) were also collected at 5 min intervals using the Borg RPE scale (6-20) [16]. Respiratory gasses were measured throughout as detailed previously for the initial preliminary visit.

Surface electromyography

For each muscle of interest, two, 20 mm diameter electrodes (Ag/AgCl; Kendall 1041PTS, Covidien, Mansfield, MA, USA) with an inter-electrode distance of 20 mm were placed according to the SENIAM guidelines for EMG placement [17] on the left leg. The muscles used for analysis were the *rectus femoris* (RF) and *vastus lateralis* (VL). The skin was shaved and abraded with an alcohol swab and a reference electrode was placed on the patella. The positions

of the electrodes were marked with permanent ink to ensure a consistent placement between trials. Surface electromyography (sEMG) signals were sampled at 4 kHz (CED 1401, Cambridge Electronic Design, UK), then amplified (×1000; 1902, Cambridge Electronic Design, Cambridge, UK), notch filtered (50 Hz), band-pass filtered (20-2,000 Hz), and rectified (Spike 2 version 8.02, Cambridge Electronic Design, UK). Prior to the start of each INT or CONT session participants completed three, 5 s maximal voluntary isometric concentric knee extensions of the right leg at a knee angle of 90° separated by 3 mins on a custom build knee extension chair. A pelvic seatbelt was used to minimise extraneous movement. Using a 0.2 s root-mean-square (RMS) window, the maximum sEMG activity from the three MVC efforts for each muscle was used to obtain a reference value for normalization purposes. Muscle activation was calculated throughout each session as the average RMS value for each 10% section of work done (i.e. 3 min time period).

Femoral nerve stimulation

Single electrical stimuli (200 μs duration) were delivered to the right femoral nerve via surface electrodes (CF3200; Nidd Valley Medical Ltd., Harrogate, United Kingdom) using a constant-current stimulator (DS7AH; Digitimer Ltd., Welwyn Garden City, United Kingdom) at rest and during MVC. The cathode was placed over the nerve high in the femoral triangle; the anode was positioned midway between the greater trochanter and the iliac crest [18]. The exact positioning was determined by the response that elicited the maximum quadriceps twitch amplitude (Q_{tw}) and M-wave (M_{max}) at rest. To determine stimulation intensity, single stimuli were delivered in 20 mA increments from 100 mA until a plateau in Q_{tw} and M-wave were observed. To ensure a supramaximal stimulus, the final intensity was increased by 30%. Membrane excitability was determined by measuring the peak-to-peak amplitude and area of the electrically evoked M_{max} [19]. Measures of muscle contractility were derived for each resting twitch, as follows: twitch amplitude, maximum rate of force development (MRFD), maximum

relaxation rate (MRR), contraction time (CT), and one-half relaxation time ($RT_{0.5}$). Voluntary activation (VA) was measured through stimulation of the femoral nerve and quantified using the twitch interpolation method [20]. Briefly, the amplitude of the superimposed twitch force (SIT), measured during MVC, was compared with the amplitude of the potentiated twitch force ($Q_{tw,pot}$) assessed 2 s after MVC at rest. VA (%) = $(1 - [SIT/Q_{tw,pot}] \times 100)$. The reproducibility of the primary outcome measures of interest (MVC, $Q_{tw,pot}$ and VA) are between 3.1 – 4.8% (CV) and 0.89 – 0.96 (ICC)[21].

Muscle soreness

Participants were asked to complete a bi-lateral squat to a knee angle of 90º and rate perceived upper-thigh soreness on a 200 mm visual analogue scale [22]. The scale consisted of a line from 0 mm (no pain) to 200 mm (unbearably painful).

Creatine kinase

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

Statistical analyses

Statistical testing was performed using SPSS 24 (IBM, New York, USA). Mean responses during exercise were compared between INT and CONT using a paired samples t-test ($\dot{V}O_2$, RER, time under tension, average torque, [BLa], RPE, and RF and VL activation). To examine

the degree of similarity between INT and CONT groups in the independent measures design, work done, and all baseline measures were compared using independent samples t-tests. Neuromuscular and creatine kinase responses were compared between the INT and CONT groups using a 5 × 2 mixed model ANOVA (Time: PRE, POST, 24, 48, 72 h, and group: INT, CONT) with a focus on the interaction effect to determine whether session structure had an effect on the immediate post-session response, and recovery in the days post-exercise. Due to no muscle soreness being observed at baseline a 3 × 2 mixed model ANOVA was used to compare muscle soreness between groups (Time: 24, 48, 72 h, and group: INT, CONT). To assess the effect of eccentric cycling on all measures, pre-planned *a-priori* paired t-tests were performed separately on CONT and INT group data and also on combined CONT and INT data (PRE v POST, 24H, 48H, and 72H). All pairwise comparisons were corrected for multiple comparisons using a Bonferroni adjustment. Significance was set at an alpha level of 0.05. Greenhouse-Geisser corrections were applied to significant F-ratios that did not meet Mauchly's assumption of sphericity. All data are presented as mean ± standard deviation.

Results

Exercise responses

As intended, total work done within each session was similar between the independent recovery groups, which were subsequently utilised for the determination of fatigue and recovery (n = 2 × 7; INT, 466 ± 79 kJ vs. CONT, 485 ± 71 kJ; p = 0.87). This equated to an average power output of 388 ± 66 W (INT) and 270 ± 40 W (CONT) during the work bouts. The within session demands of eccentric cycling are examined using the repeated measures design in which work done was also similar between experimental trials (n = 14; INT, 473 ± 71 kJ; CONT, 478 ± 69 kJ; p = 0.13). Average exercising intensity during the work bouts in the repeated measures design was 266 ± 38 W and 394 ± 59 W for CONT and INT respectively. Total time under

tension was 48% greater in CONT (983 ± 142 s) compared to INT (664 ± 131 s, $p < 0.001$), whereas average torque production during cycling (excluding rest periods) was greater during INT compared to CONT (56 ± 13 N·m v 40 ± 9 N·m , $p < 0.001$; Figure 1). A modest increase in physiological strain was observed during INT compared to CONT by means of increased average $\dot{V}O_2$ (% of $\dot{V}O_{2peak}$, 32 ± 6% vs. 28 ± 6%, $p < 0.001$), BLa (1.0 ± 0.4 vs. 0.8 ± 0.2 $mmol \cdot L^{-1}$, $p < 0.001$), and RPE (12 ± 1 vs. 11 ± 1, $p < 0.001$). Respiratory exchange ratio was similar between INT (0.87 ± 0.05) and CONT (0.86 ± 0.07) ($p = 0.39$) and average RF and VL activation was greater during INT compared to CONT (13 ± 5% v 10 ± 5%, $p = 0.006$ and 14 ± 6% v 11 ± 5%, $p = 0.007$, respectively).

Neuromuscular function

All neuromuscular measures are presented in Table 1. There were no differences between experimental groups for baseline measures of neuromuscular function. Eccentric cycling resulted in significant reductions in $Q_{tw,pot}$ (INT; −56 N, CONT; −33 N, $p < 0.001$), VA (INT; −9%, CONT; −5%, $p = 0.048$), and MVC (INT; −123 N, CONT; −90 N, $p < 0.001$) immediately post exercise (Figure 2). There was a decrease in MVC_{rms} and membrane excitability (M_{max} area and M_{max} amplitude) during the MVC and potentiated twitch post exercise (Table 1). There was an interaction effect of time and session structure on $Q_{tw,pot,}$ which reduced to a greater extent after INT compared to CONT ($F_{(4, 48)} = 4.9$, $p = 0.02$). Furthermore, *post-hoc* analysis revealed $Q_{tw,pot}$ recovery was longer after INT (48 h) compared to CONT (24 h). All other measures of neuromuscular function and muscle contractility had returned to baseline by 24 h.

Muscle soreness

There was a significant interaction effect of session structure and time on muscle soreness after eccentric cycling ($F_{(2, 24)} = 5.3$, $p = 0.01$, Figure 3). Between 24 – 48 h post exercise muscle soreness increased to a greater extent post-INT compared to post-CONT (+33 ± 29 mm and −4 ± 17 mm respectively). However, post-hoc analysis did not reveal a significant difference between INT and CONT at 24 h ($p = 0.99$), 48 h ($p = 0.09$), or 72 h ($p = 0.31$). Thereafter (48 – 72 h), muscle soreness reduced in both INT and CONT (−42 ± 27 mm and −30 ± 17 mm respectively). Overall, muscle soreness peaked at 48 h after INT (84 ± 45 mm) and 24 h after CONT (47 ± 19 mm).

Creatine kinase

Creatine kinase data are shown in Table 1. There was no significant interaction effect of session structure and time on CK activity ($F_{(2.0, 24)} = 0.7$, $p = 0.50$). Nor was there an overall effect of session structure ($F_{(1, 12)} = 0.1$, $p = 0.78$) on CK activity. Paired t-tests with pooled group data revealed no difference between CK activity at baseline and all subsequent time points (post exercise, $p = 0.4$; 24 h, $p = 0.99$; 48 h, $p = 0.69$; and 72 h, $p = 0.2$).

Discussion

The aim of the present study was to examine the effect of structuring eccentric cycling as interval or continuous exercise on subsequent neuromuscular function, muscle damage, and muscle soreness. Despite a greater time under tension during continuous eccentric cycling, the interval session caused greater decrements in muscle contractility and higher perceptions of muscle soreness (Table 1, Figure 3). These data indicate that during eccentric cycling absolute mechanical tension has a greater influence on post exercise neuromuscular function and muscle soreness than total time under tension. Furthermore, we have highlighted that with the

appropriate familiarisation, continuous and interval eccentric cycling can be undertaken with only small increases in muscle soreness (Figure 3), a negligible CK response, and a relatively modest metabolic cost. Despite the inclusion of two familiarisation sessions, muscle function can take up to 48 h to recover after interval eccentric cycling (Figure 2). Collectively, these data suggest that interval eccentric cycling causes a greater reduction in muscle function and increases recovery time compared to a continuous session, although not to a magnitude that should prohibit prescription. The results of the study have important implications for practitioners wishing to exploit the potential of eccentric cycling as a training stimulus.

Interval eccentric cycling induced greater reductions in $Q_{tw,pot}$ compared to the continuous session (Table 1, Figure 2). In concentric cycling, similar effects of session structure have been observed in which varying power output resulted in greater decrements in neuromuscular function, and longer recovery times, compared to an even-paced work-matched session [14]. It has been suggested that the greater decrements in neuromuscular function observed after a variable concentric cycling session could be due to increased metabolite accumulation, greater RPE, or increased muscle tension [14]. However, due to the relatively low metabolic stress that eccentric cycling elicits in comparison to concentric work [5] we consider metabolite accumulation an unlikely candidate for reductions in $Q_{tw,pot}$ between groups. This is substantiated by the low BLa and $\dot{V}O_2$ throughout the exercise in both groups (< 1.5 mmol·L^{-1} and < 40% $\dot{V}O_2$ peak, respectively). Given the low metabolic cost and the relatively short exercise duration it is also unlikely that glycogen depletion was limiting. More likely, the greater reduction in potentiated twitch after INT was due to increased muscle tension and a subsequent increase in sarcomere disruption, sarcolemma disruption, or impairment to the excitation-coupling process [23]. When eccentric cycling intensity is kept low (< 20% concentric peak power output) decrements in muscle function do not differ between varied workout intensities[10]. A caveat to this observation is that CK remained low, and muscle soreness was

modest in INT, which suggests sarcomere disruption was not extensive. Conversely, it would appear that the greater time under tension observed during CONT did not increase post-exercise force reduction or recovery time compared to INT. Collectively, these data suggest that the post exercise reduction in $Q_{tw,pot}$ following eccentric cycling is a function of intensity and not volume.

Recovery of $Q_{tw,pot}$ took longer following INT (48 h) compared to CONT (24 h) (Table 1, Figure 2). This is similar to the recovery of MVC after 30 min of pre-familiarised eccentric cycling at a similar intensity [2]. Although, the precise time-frame of recovery from eccentric cycling is likely dependent on intensity, duration, and number of familiarisations [2]. The prescribed intensity in the current study was considered practical and appealing to coaches and athletes who may be reluctant (or risk averse) to engage in shorter, higher intensity, bouts. However, shorter, more intense, intervals are likely to exacerbate the observed differences. Muscle soreness was elevated following only INT (Figure 3) and achieved its peak 48 h post exercise despite the recovery of muscle function at this time point. This disconnect between muscle function and delayed onset muscle soreness (DOMS) is common and substantiates the poor relationship between the two variables [24,25]. It is possible that the greater levels of muscle tension during INT contributed to the increased perceived leg soreness 72-hours post-exercise. Increased muscle soreness has also been observed after the harder of two low intensity eccentric cycling interval sessions[10]. Of note in the current study, however, are the relatively modest levels of muscle soreness which are similar to previous observations after 30 minutes of eccentric cycling (0 – 30%, 10 mm VAS)[2]. Such findings suggest that, when familiarised, eccentric cycling can be used as a training modality without inducing high levels of muscle soreness. Furthermore, despite the limitations of traditional blood indices of muscle damage, the absence of elevations in CK indicates a modest degree of damage, which further highlights

353 the feasibility of this training modality to provide a relatively high mechanical load, with little
354 negative consequences.

355

356 Total work done during the sessions and all baseline neuromuscular variables (Table 1) were
357 similar between the INT and CONT exercise groups, demonstrating effective matching.
358 Furthermore, levels of voluntary activation pre-exercise were consistent with previous research
359 using the same twitch technique which indicates that participants arrived in a rested state [12,26].
360 In agreement with previous studies, eccentric exercise elicited reductions in MVC, peripheral
361 muscle contractility, and VA [27–29]. The overall decrease in knee extensor MVC immediately
362 post exercise (17%) is consistent with that observed after a similar eccentric cycling protocol
363 (~19%)[2]. Our data indicated that reductions in muscle contractility might partially result from
364 changes in sarcolemma excitability as demonstrated by a reduction in M_{max}. Proske and Allen
365 [30] suggest that sarcolemma disruption can occur following eccentric exercise due to an
366 accumulation of mechanically damaged sarcomeres and loss of calcium mediated homeostasis
367 leading to lipolysis and proteolysis. However, M-wave was depressed only immediately post-
368 exercise whereas muscle function remained suppressed at 24 h. Therefore, whilst decreased
369 sarcolemma excitability might contribute to the reductions in twitch force observed
370 immediately following eccentric exercise it is unlikely to be the primary mediator of prolonged
371 muscle function impairment [31]. It is likely that the changes in muscle contractility observed in
372 the current study stem from sarcomere disruption [23,32] or non-sarcolemma related impairment
373 of the excitation-coupling process [33,34] such as sarcoplasmic reticulum dysfunction [35].

374

375 In conclusion, we provide new data to show that structuring eccentric cycling as a set of
376 intervals exacerbates muscle soreness and reductions in muscle function compared to a work
377 matched continuous bout, which is likely due to increased force and muscle tension.
378 Additionally, prescribing eccentric cycling as intervals extends muscle function recovery time.

However, neither the duration of muscle function recovery nor the modest levels of muscle soreness should be considered prohibitive to engaging in regular eccentric cycling (either interval or continuous). The increase mechanical stress possible during interval eccentric cycling can be achieved without substantial disruption to muscle function, large increases in muscle soreness, or substantial metabolic cost. Therefore, interval eccentric cycling appears a viable training modality that could be used to elicit an enhanced adaptive response.

388 References

389 1. Leong CH, Mcdermott W, Elmer SJ, Martin JC. Chronic eccentric cycling improves
390 quadriceps muscle structure and maximum cycling power. Int J Sports Med
391 2013;34:1–7.

392 2. Peñailillo L, Blazevich A, Numazawa H, Nosaka K. Metabolic and muscle damage
393 profiles of concentric versus repeated eccentric cycling. Med Sci Sports Exerc
394 2013;45:1773–1781.

395 3. Green DJ, Thomas K, Ross E, Pringle J, Howatson G. Familiarisation to maximal
396 recumbent eccentric cycling. Isokinet Exerc Sci 2017;25:17–24.

397 4. Green DJ, Thomas K, Ross EZ, Green SC, Pringle JS, Howatson G. Torque, power
398 and muscle activation of eccentric and concentric isokinetic cycling. J Electromyogr
399 Kinesiol 2018;40:56–63.

400 5. Penailillo L, Blazevich AJ, Nosaka K, Peñailillo L, Blazevich AJ, Nosaka K. Factors
401 contributing to lower metabolic demand of eccentric than concentric cycling. J Appl
402 Physiol 2017;123:884–893.

403 6. Peñailillo L, Guzman N, Cangas J, Reyes A, Zbinden-Foncea H. Metabolic demand
404 and muscle damage induced by eccentric cycling of knee extensor and flexor muscles.
405 Eur J Sport Sci 2017;17:179–187.

406 7. Lipski M, Abbiss CR, Nosaka K. Oxygen consumption, rate of perceived exertion and
407 enjoyment in high-intensity interval eccentric cycling. Eur J Sport Sci 2018;18:1390–
408 1397.

409 8. Elmer S, Hahn S, McAllister P, Leong C, Martin J. Improvements in multi-joint leg
410 function following chronic eccentric exercise. Scand J Med Sci Sports 2012;22:653–
411 61.

9. LaStayo PC, Pierotti DJ, Pifer J, Hoppeler H, Lindstedt SL. Eccentric ergometry : increases in locomotor muscle size and strength at low training intensities. Am J Physiol - Regul Integr Comp Physiol 2000;278:1282–1288.

10. Mavropalias G, Koeda T, Barley OR, Poon WCK, Fisher AJ, Blazevich AJ, Nosaka K. Comparison between high- and low-intensity eccentric cycling of equal mechanical work for muscle damage and the repeated bout effect. Eur J Appl Physiol 2020;8:1015–1025.

11. Elmer SJ, McDaniel J, Martin JC. Alterations in neuromuscular function and perceptual responses following acute eccentric cycling exercise. Eur J Appl Physiol 2010;110:1225–33.

12. Thomas K, Goodall S, Stone M, Howatson G, St Clair Gibson A, Ansley L. Central and peripheral fatigue in male cyclists after 4-, 20-, and 40-km time trials. Med Sci Sport Exerc 2015;47:537–546.

13. Bentley DJ, Smith A, Davie AJ. Muscle activation of the knee extensors following high intensity endurance exercise in cyclists. Eur J Appl Physiol 2000;81:297–302.

14. Theurel J, Lepers R. Neuromuscular fatigue is greater following highly variable versus constant intensity endurance cycling. Eur J Appl Physiol 2008;103:461–468.

15. Lepers R, Theurel J, Hausswirth C, Bernard T. Neuromuscular fatigue following constant versus variable-intensity endurance cycling in triathletes. J Sci Med Sport 2008;11:381–389.

16. Borg GA V. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982;14:377–381.

17. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol

436 2000;10:361–374.

437 18. Goodall S, Romer LM, Ross EZ. Voluntary activation of human knee extensors
438 measured using transcranial magnetic stimulation. Exp Physiol 2009;94:995–1004.

439 19. Fowles JR, Green HJ, Tupling R, O'Brien S, Roy BD. Human neuromuscular fatigue
440 is associated with altered Na+ -K+ -ATPase activity following isometric exercise. J
441 Appl Physiol 2002;92:1585–1593.

442 20. Merton PA. Voluntary strength and fatigue. J Physiol 1954;123:553–564.

443 21. Thomas K, Elmeua M, Howatson G, Goodall S. Intensity-Dependent Contribution of
444 Neuromuscular Fatigue after Constant-Load Cycling. Med Sci Sports Exerc
445 2016;48:1751–1760.

446 22. Goodall S, Howatson G. The effects of multiple cold water immersions on indices of
447 muscle damage. J Sport Sci Med 2008;7:235–241.

448 23. Proske U, Morgan DL. Muscle damage from eccentric exercise: Mechanism,
449 mechanical signs, adaptations and clinical applications. J Physiol 2001;537:333–345.

450 24. Cleak MJ, Eston RG. Muscle soreness, swelling,stiffness and strength loss after
451 intense eccentric exercise. Br J Sports Med 1992;26:267–272.

452 25. Nosaka K, Newton M, Sacco P. Delayed-onset muscle soreness does not reflect the
453 magnitude of eccentric exercise-induced muscle damage. Scand J Med Sci Sport
454 2002;12:337–346.

455 26. Brownstein CG, Dent JP, Parker P, Hicks KM, Howatson G, Goodall S, Thomas K.
456 Etiology and recovery of neuromuscular fatigue following competitive soccer match-
457 play. Front Physiol 2017;8:831.

458 27. Goodall S, Thomas K, Barwood M, Keane K, Gonzalez JT, St Clair Gibson A,
459 Howatson G. Neuromuscular changes and the rapid adaptation following a bout of

damaging eccentric exercise. Acta Physiol 2017;220:486–500.

28. Prasartwuth O, Taylor JL, Gandevia SC. Maximal force, voluntary activation and muscle soreness after eccentric damage to human elbow flexor muscles. J Physiol 2005;567:337–348.

29. Prasartwuth O, Allen TJ, Butler JE, Gandevia SC, Taylor JL. Length-dependent changes in voluntary activation, maximum voluntary torque and twitch responses after eccentric damage in humans. J Physiol 2006;571:243–252.

30. Proske U, Allen TJ. Damage to skeletal muscle from eccentric exercise. Exerc Sport Sci Rev 2005;33:98–104.

31. Sayers SP, Peters BT, Knight CA, Urso ML, Parkington J, Clarkson PM. Short-term immobilization after eccentric exercise. Part I: Contractile properties. Med Sci Sports Exerc 2003;35:753–761.

32. Lauritzen F, Paulsen G, Raastad T, Bergersen LH, Owe SG. Gross ultrastructural changes and necrotic fiber segments in elbow flexor muscles after maximal voluntary eccentric action in humans. J Appl Physiol 2009;107:1923–1934.

33. Corona BT, Balog EM, Doyle JA, Rupp JC, Luke RC, Ingalls CP. Junctophilin damage contributes to early strength deficits and EC coupling failure after eccentric contractions. Am J Physiol Cell Physiol 2010;298:C365-376.

34. Warren GL, Ingalls CP, Lowe DA, Armstrong RB. Excitation-Contraction Uncoupling: Major Role in Contraction-Induced Muscle Injury. Exerc Sport Sci Rev 2001;29:82–87.

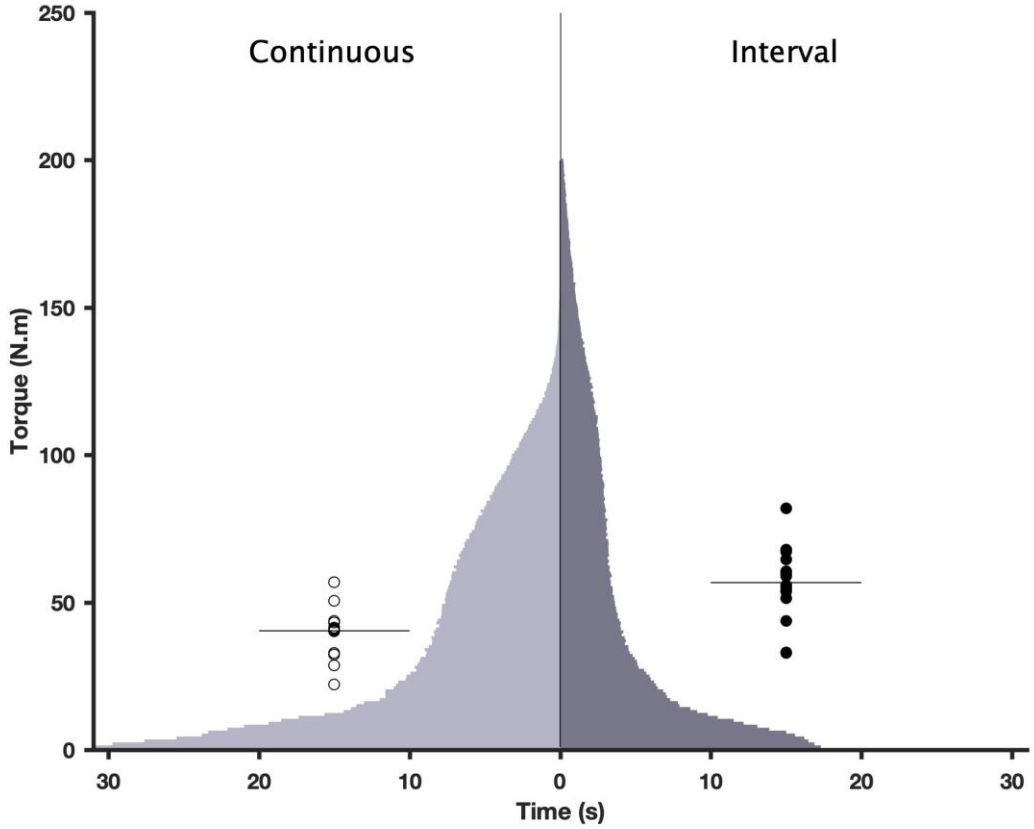
35. Hill CA, Thompson MW, Ruell PA, Thom JM, White MJ. Sarcoplasmic reticulum function and muscle contractile character following fatiguing exercise in humans. J Physiol 2001;531:871–878.

484

485 **Table 1.** Data are neuromuscular and creatine kinase responses to interval (INT, n = 7) and continuous (CONT,
486 n = 7) eccentric cycling. Data is displayed as mean (standard deviation).

		Baseline	Post	24 h	48 h	72 h
MVC (N)	INT	660 (160)	537 (163)* †	608 (194)	653 (204)	683 (209)
	CONT	686 (59)	596 (82)*	673 (94)	697 (89)	693 (88)
$Q_{tw,pot}$ (N)	INT **	178 (49)	122 (42)* †	152 (44)* †	187 (52)	182 (52)
	CONT	181 (25)	148 (31)*	170 (26)	184 (31)	181 (23)
MRFD ($N \cdot ms^{-1}$)	INT	5.22 (1.68)	3.57 (1.69) †	4.52 (1.95)	5.66 (2.30)	5.31 (1.91)
	CONT	5.61 (1.64)	4.71 (1.34)	5.18 (1.45)	6.21 (1.93)	6.11 (1.81)
CT (ms)	INT	82 (3)	68 (4)* †	80 (3)	82 (4)	80 (5)
	CONT	81 (9)	71 (5)	82 (5)	82 (8)	87 (9)
MRR ($N \cdot ms^{-1}$)	INT **	−2.08 (0.79)	−1.98 (0.69)	−1.82 (0.69)	−2.15 (0.80)	−1.94 (0.77)
	CONT	−1.89 (0.30)	−2.38 (0.55)	−1.76 (0.29)	−1.89 (0.38)	−1.83 (0.22)
$RT_{0.5}$ (ms)	INT	68 (15)	44 (8)* †	63 (13)	65 (15)	75 (9)
	CONT	77 (12)	43 (6)*	77 (11)	77 (12)	80 (7)
VA (%)	INT	90 (3)	81 (13) †	89 (5)	91 (5)	91 (5)
	CONT	90 (5)	85 (12)	90 (7)	90 (9)	90 (7)
Surface EMG (vastus lateralis)						
Resting responses						
M_{max} amplitude (mV)	INT	7.26 (4.45)	5.19 (3.72)* †	5.65 (3.10)	6.40 (2.59)	6.03 (3.05)
	CONT	5.44 (3.15)	4.84 (3.28)*	5.43 (3.98)	5.11 (3.02)	4.69 (3.00)
M_{max} area ($\mu V \cdot s^{-1}$)	INT	49.8 (25.1)	33.4 (19.4)* †	40.1 (20.0)	44.6 (14.7)	44.0 (17.2)
	CONT	41.7 (22.0)	32.0 (18.7)*	43.3 (28.9)	39.8 (19.7)	37.8 (21.0)
During MVC						
MVC_{RMS} (mV)	INT	0.37 (0.16)	0.25 (0.09)* †	0.30 (0.11)	0.34 (0.11)	0.33 (0.13)
	CONT	0.43 (0.24)	0.27 (0.11)	0.45 (0.35)	0.32 (0.18)	0.30 (0.20)
M_{max} amplitude (mV)	INT	6.86 (3.54)	4.68 (3.11)* †	5.06 (2.29)	5.99 (1.91)	5.85 (3.13)
	CONT	5.10 (1.43)	4.27 (1.93)	4.95 (2.12)	4.91 (2.07)	4.32 (2.07)
M_{max} area ($\mu V \cdot s^{-1}$)	INT	51.8 (21.4)	33.5 (14.4)* †	39.6 (15.3)	46.5 (15.8)	43.6 (16.3)
	CONT	40.0 (12.6)	31.1 (13.2)*	39.5 (20.0)	37.5 (13.1)	34.2 (14.5)
Creatine kinase ($IU \cdot L^{-1}$)	INT	190 (104)	206 (111)	243 (159)	172 (75)	149 (59)
	CONT	197 (128)	197 (112)	190 (78)	160 (68)	147 (46)

487 ** session structure × time interaction effect. * difference from baseline, within group. † difference from
488 baseline, INT and CONT groups combined. MVC, maximum voluntary contraction; $Q_{tw,pot}$, potentiated
489 twitch force; MRFD, maximum rate of force development; CT, contraction time; MRR, maximum rate
490 of relaxation; $RT_{0.5}$, one half relaxation time; VA, voluntary activation.



491

492 **Figure. 1.** Average torque during time spent cycling for each participant during CONT (30 min, ○) and INT (20

493 min, •). Shaded areas represent a histogram of time spent at different levels of torque during cycling for CONT

494 (light grey) and INT (dark grey). Values are for the left leg only (n = 14).

495

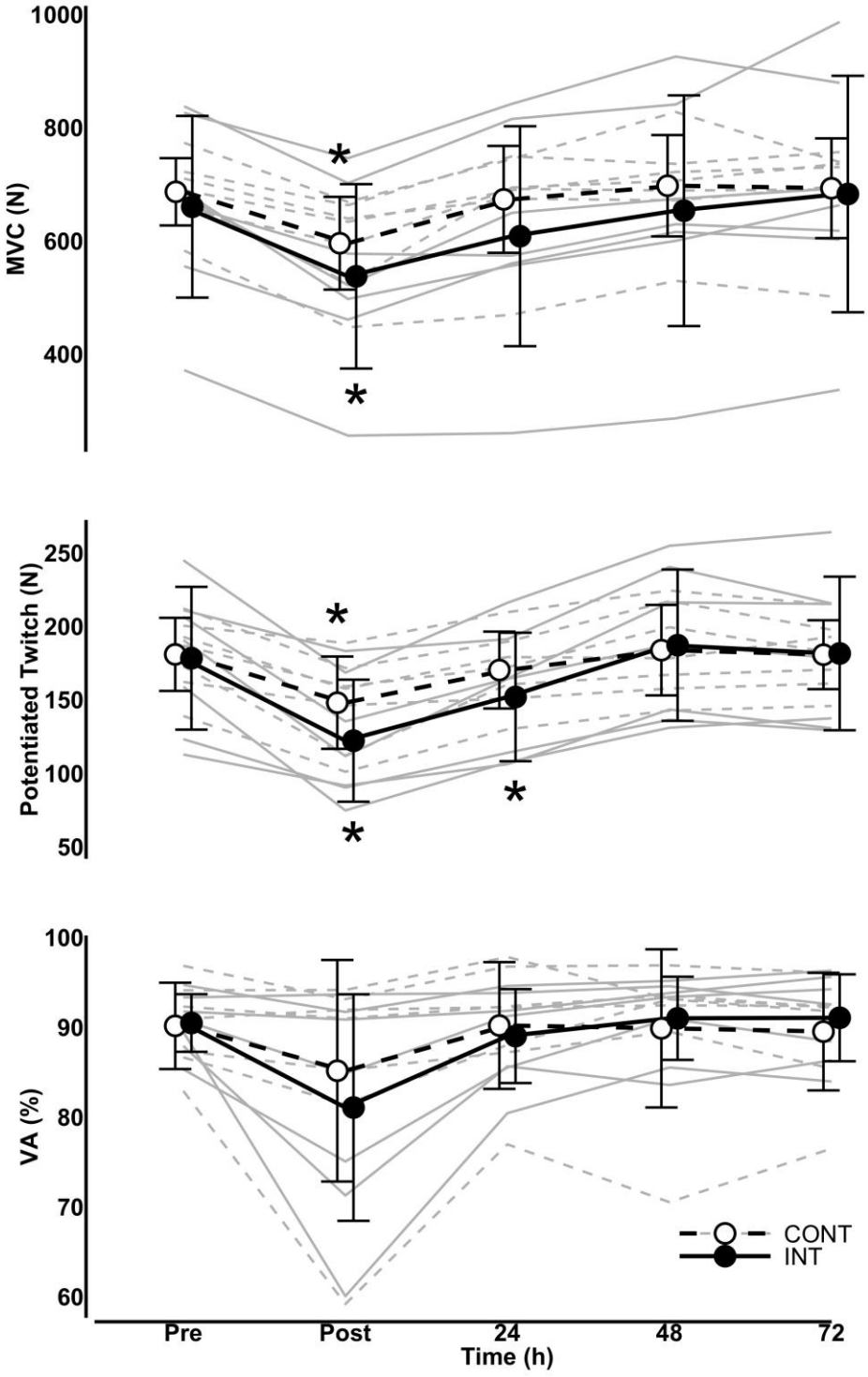


Figure 2. Maxmial voluntary contraction (top), potentiated twitch force (middle), and voluntary activation (bottom) pre, post and 24, 48, and 72 h post eccentric cycling for INT (•, n = 7) and CONT (○, n = 7). * denotes significant difference from within group baseline ($p < 0.05$). Data are mean ± SD.

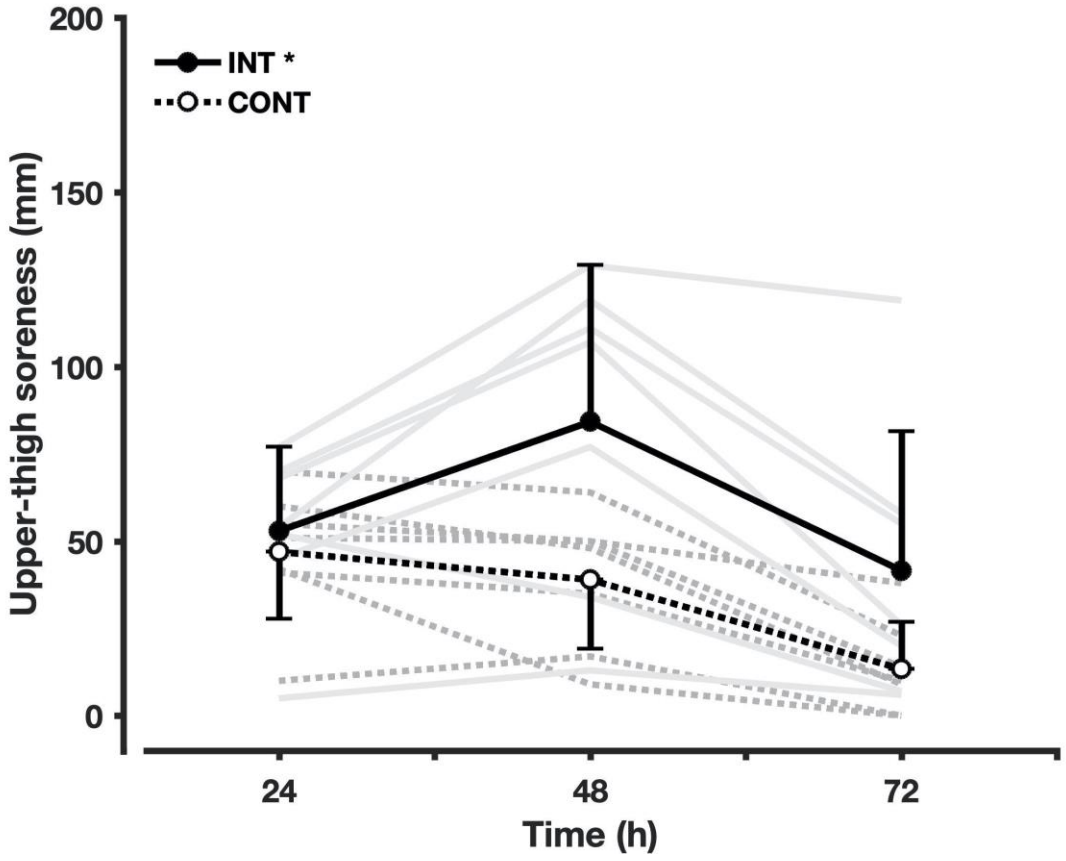


Figure 3. Muscle soreness at 24, 48, and 72 h post interval (INT •, n = 7) and continous (CONT ○, n =7) eccentric cycling, asseseed using a 200 mm visual analogue scale. * denotes significant session structure × time interaction effect ($p < 0.05$). Data are mean ± SD.