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Original Research

Maximal Metabolic Demands During Eccentric Cycling Based on True Negative Work

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Abstract

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Eccentric cycling (ECC) is known to be less metabolically demanding than traditional concentric (CON) cycling, making it a promising alternative for various clinical populations and rehabilitation. However, the metabolic advantages may be only present when comparing against maximum CON power output (PO). Yielding ambiguity if the metabolic response during ECC maximum are similar to CON max. Therefore the purpose, was to examine the difference in maximal metabolic demand and peak PO during an eccentric graded exercise test with controlled cadence. Fifteen apparently healthy adults completed four laboratory visits, including a familiarization session on concentric and eccentric cycle ergometers and randomized graded exercise tests on both ergometers. Oxygen consumption, heart rate, rate of perceived exertion, blood lactate, and peak power output were measured during the last 30 seconds of each graded exercise test. Peak power output showed good reliability between eccentric trials (ICC = 0.84). Additionally, peak power output was not significantly different between concentric and eccentric cycling. During the first ECC, only heart rate ($p < 0.05$) and lactate ($p < 0.0001$) were significantly different than CON. During the second ECC (ECC2), oxygen consumption ($p = 0.008$), heart rate ($p = 0.005$), rate of perceived exertion ($p = 0.009$), and blood lactate ($p = 0.001$) were significantly lower compared to CON. Repeated exposure to eccentric cycling resulted in reduced physiological strain without compromising peak workload, suggesting an acute familiarization effect. These findings support ECC's unique efficiency and potential utility in clinical or rehabilitation settings.

Keywords: Repeated-bout Effect, neuromuscular efficiency, exercise prescription

Introduction

Eccentric cycling (ECC), has gained attention as an alternative form of exercise. Eccentric contractions involve muscle lengthening, which is ideal for inducing muscle hypertrophy, leading to increased muscle mass and reduced fat mass. When ECC workload is matched to traditional concentric (CON) cycling, a lower metabolic demand is observed,[1-6] while still promoting significant improvements in health and fitness.[7]

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While concentric and isometric contractions are well described by molecular theories,[8] the mechanics of eccentric contractions remain less understood. For example, the sliding filament theory fails to explain key ECC phenomena, such as the greater force production during the lengthening of the muscle,[9] time-dependent residual force enhancement,[10] and reduced energy expenditure.[11] Several theories and models, such as the mechanical cross-bridge detachment,[12] the three-filament model,[12] and winding filament,[13] highlight the role of titin in force production during eccentric contractions.[14] However, no single model fully explains the mechanical and metabolic demands of ECC.

The lack of standardized exercise prescription guidelines can also contribute to the complexity of ECC. Endurance ECC studies have used different matching strategies to investigate physiological responses. Some of these studies, often using a workload match between modalities, include CON and ECC at the same power output (PO),[1-5,15-17] same oxygen consumption (VO_2),[1,18] and same heart rate (HR).[19] These approaches produce different physiological responses. At the same PO, ECC produces lower VO_2, blood lactate, muscle activation, and cardiovascular demand.[19] Conversely, matching VO_2 results in a greater workload (PO) and a higher cardiac demand in ECC.[19] Matching by HR leads to similar blood lactate concentrations and rates of perceived exertion (RPE) between the two modalities.[19] The variability between these approaches[1-3,15,16,20-26] may limit the understanding of ECC phenomena, but using ECC-POmax exercises could provide deeper insights into the physiological responses associated with eccentric exercise.

To date, there is limited evidence studying maximum physiological demands during ECC[27] with just a few studied physiological variables. Therefore, the present study aimed to explore the maximal metabolic demands and PO of an ECC graded exercise test (ECC-GXT) with controlled cadence. We hypothesize that ECC will produce a higher workload than CON but with a lower metabolic demand.

Methods

Participants

A convenience sample of 15 participants (8 males, 7 females) was recruited. In previous work using brachial shear stress as the target variable, a large effect size (partial eta squared of 0.834) was observed across exercise intensities during concentric cycling.[28] Based on this, a priori power analysis was conducted in RStudio using the R statistical programming language and the "*pwr*" package. Assuming a large effect size (d = 0.80), an alpha level of 0.05, and statistical power of 0.80, the estimated sample size required for a within-subject design was 15 subjects. Inclusion criteria required the subjects to be apparently healthy, normotensive, non-smokers (including e-cigarettes), with no known cardiovascular or cardiac disease, no injuries affecting exercise performance, no use of prescribed medication, no nonsteroidal anti-inflammatory (NSAIDs), or supplements containing antioxidants. Participants were required to refrain from caffeine and exercise for at least 12 hours and from any meal for at least 2 hours before the visits. All participants provided written informed consent approved by the University's institutional review board (IRB) and was carried out fully in accordance with the ethical standards of the *International Journal of Exercise Science*.[29]

Protocol

All participants completed four laboratory sessions, 48hrs between visits, at the same time of the day (±1h) to avoid diurnal variation (Figure 1). During the first lab visit, weight (WB-110A Class

III, Tanita, Japan) and height (Secca 225, Seca Medical, Germany) were measured. Then, subjects completed a familiarization stage on both the ECC and CON cycle ergometers. The familiarization involved 10 minutes of cycling at 60 rpm and 100 Nm torque on the upright eccentric ergometer (Grucox Medical (Pty) Ltd., South Africa), as previously done.[15,16] and 10 minutes on the concentric ergometer (Corival, Lode, Groningen, Netherlands).

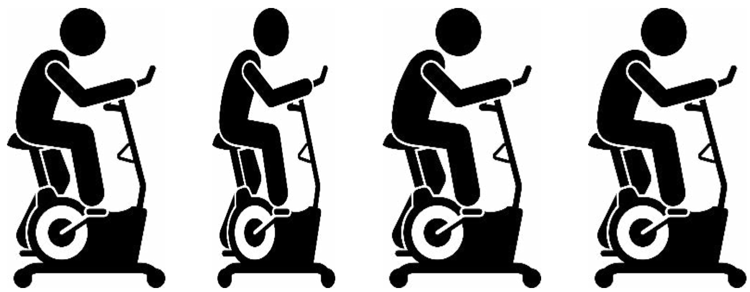


Figure 1. Experimental testing overview.

Visits 2–4 involved two eccentric and one concentric ergometer cardiopulmonary exercise tests (CPETs) with a GXT, performed in random order, to determine maximal oxygen consumption (VO_2max). All GXTs were performed with the ergometer seat adjusted to allow knee flexion of approximately 5˚ to 15˚ during cycling at 60 rpm, starting at 50 W and increasing every two minutes by 40 W for males and 25 W for females until volitional exhaustion, lasting 8 – 12 minutes.[30] During ECC-GXT, participants resisted the backward pedal motion to sustain the prescribed cadence and power output.

Oxygen consumption (VO_2) was measured continuously using a metabolic cart (TrueOne 2400, Parvomedics Inc., Salt Lake City, Utah). HR was monitored using a HR chest strap (H10, Polar Electro, Kempele, Finland). The rate of perceived exertion (RPE) was recorded using Borg's 6-20 scale.[31] Blood lactate levels (BLa) were measured via earlobe puncture using an automatic lactate meter (Lactate Plus, Nova Inc., Waltham, Massachusetts) at the end of each stage, similar to previously done.[15,16,28,32] Peak power output (PO) was determined from the highest completed workload during each GXT.

Statistical Analysis

Data were compiled from each instrument into a master data sheet and analyzed with the R statistical programming language (The R Project for Statistical Computing Ver. 4.3.3). Data normality was assessed via visual analysis of a histogram and via quantitative means using the Shapiro-Wilk test.

Pearson's product-moment correlations were calculated between ECC-GXTs workloads. The magnitude of the associations was interpreted as trivial (0.0), small (0.10-0.29), moderate (0.30-0.49), large (0.50-0.69), very large (0.70-0.89), and nearly perfect (0.90-0.99).[33] Additionally, a two-way random intra-class correlation (ICC, "Agreement") was calculated, with 95% confidence intervals (CIs) for the lower and upper bounds. The magnitude of ICC was interpreted as poor (< 0.50), moderate (0.50-0.74), good (0.75-0.89), and excellent (0.90-1.0).[34]

Friedman tests were used to determine differences in maximum metabolic demands and perceptual responses across cycling modalities, with participants treated as a blocking factor. When a significant main effect was detected in the Friedman test, post-hoc pairwise comparisons between cycling modalities were performed using Wilcoxon signed-rank tests. P-values from all pairwise comparisons were adjusted using the Holm correction to account for multiple testing. Statistical significance was set at an alpha level of <0.05.

Results

Subject Descriptive Characteristics

All descriptive data variables were considered non-normally distributed. Participant demographics are presented in Table 1 as median and interquartile range (IQR).

Maximum Cardiopulmonary Exercise Testing

All cardiopulmonary exercise testing variables from visits two through four were considered non-normally distributed, based on the visual inspection of histograms and the Shapiro-Wilk test. Moderate associations between ECC GXTs ($r = 0.84$, $p < 0.0001$) were observed for workload. Additionally, there was a "good" ICC agreement between ECC GXTs in workload (ICC = 0.841; $p < 0.0001$).

Significant condition effect was observed for VO2max (Friedman $\chi^2(2) = 10.5$, $p = 0.005$). Post hoc analyses revealed significantly lower VO2max during ECC2 compared to CON ($p = 0.008$), with no differences between CON and ECC or between ECC and ECC2 (Figure 2A).

Significant condition effect was observed for HRmax (Friedman $\chi^2(2) = 12.1$, $p = 0.002$). Post hoc analyses revealed significantly lower HRmax during ECC ($p < 0.05$) and ECC2 ($p = 0.005$) compared with CON, with no difference between ECC- GXTs ($p = 0.1$) (Figure 2B).

A significant condition effect was observed for maximum blood lactate concentration (Friedman $\chi^2(2) = < 0.0001$). Post hoc analyses revealed significantly lower maximum blood lactate concentrations during ECC ($p < 0.0001$) and ECC2 ($p = 0.001$) compared with CON, with no difference between ECC- GXTs ($p = 0.1$) (Figure 2C).

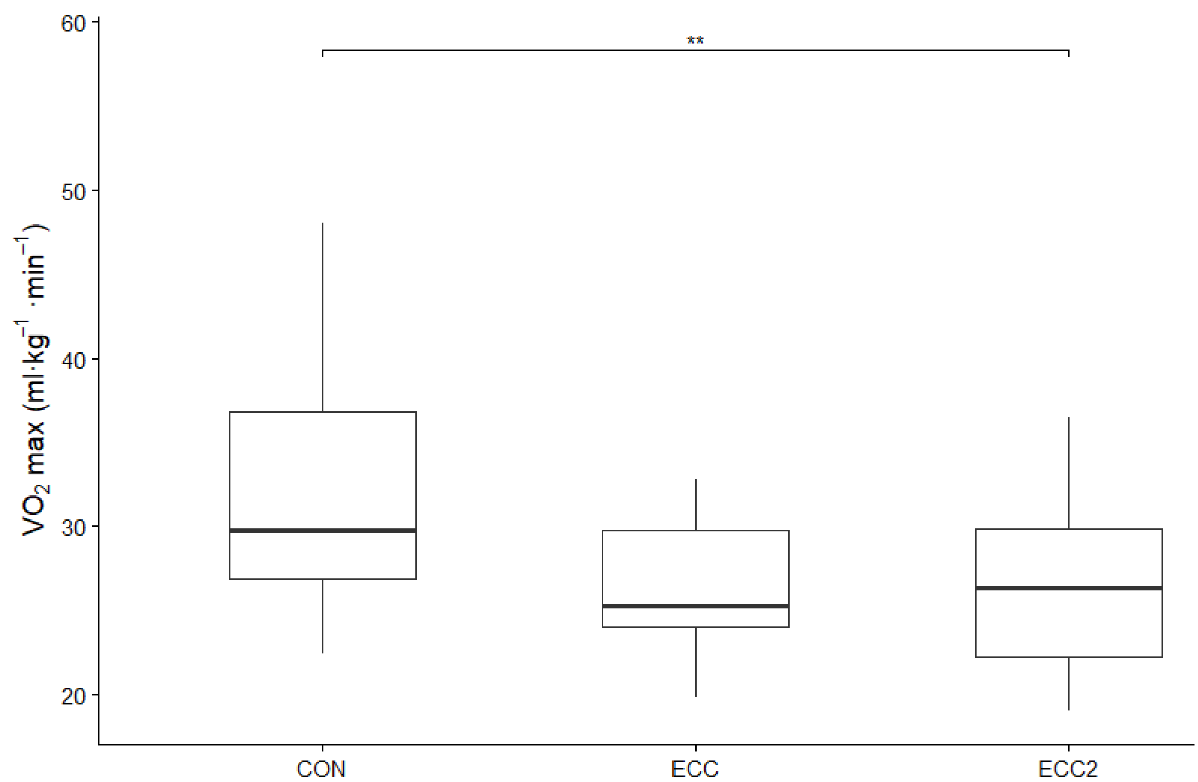
Significant condition effect was observed for RPEmax (Friedman $\chi^2(2) = 8.33$, $p = 0.01$). Post hoc analyses revealed significantly lower RPEmax during ECC2 than during CON ($p = 0.009$), with a trend between ECC and CON ($p = 0.06$). Lastly, no condition effect was observed for maximum workload (Friedman $\chi^2(2) = 1.72$, $p = 0.42$) (Figure 2D).

Table 1. Demographic and maximal descriptive data of the sample.

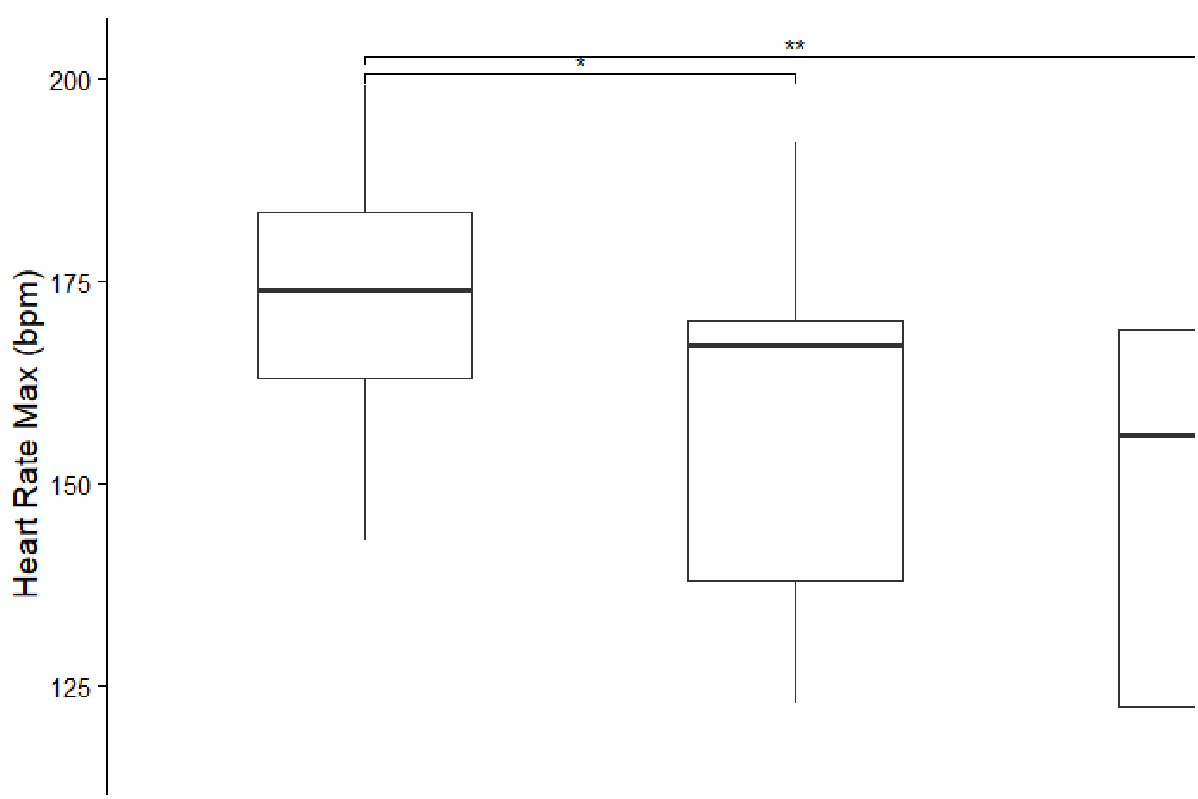
	CON (N=15)	ECC (N=15)	ECC2 (N=15)
Age (yrs)	21.0 [20.0, 22.5]		
Weight (kg)	73.6 [62.0, 94.5]		
Height (m)	1.68 [1.62, 1.75]		
VO2max (ml/kg/min)	29.8 [26.9, 36.8]	25.3 [24.0, 29.8]	26.4 [22.2, 29.9]#
Heart Rate (bpm)	174 [163, 184]	167 [138, 170] +	156 [123, 169]#
Lactate (m/mmol)	6.60 [5.60, 7.75]	4.20 [2.55, 4.45] +	3.40 [2.25, 3.65]#
RPE	19.0 [18.0, 20.0]	17.0 [16.5, 18.5]	16.0 [15.0, 17.0]#
Peak Power (w)	170 [130, 210]	170 [115, 205]	170 [135, 175]

+: p<0.05 CON vs. ECC

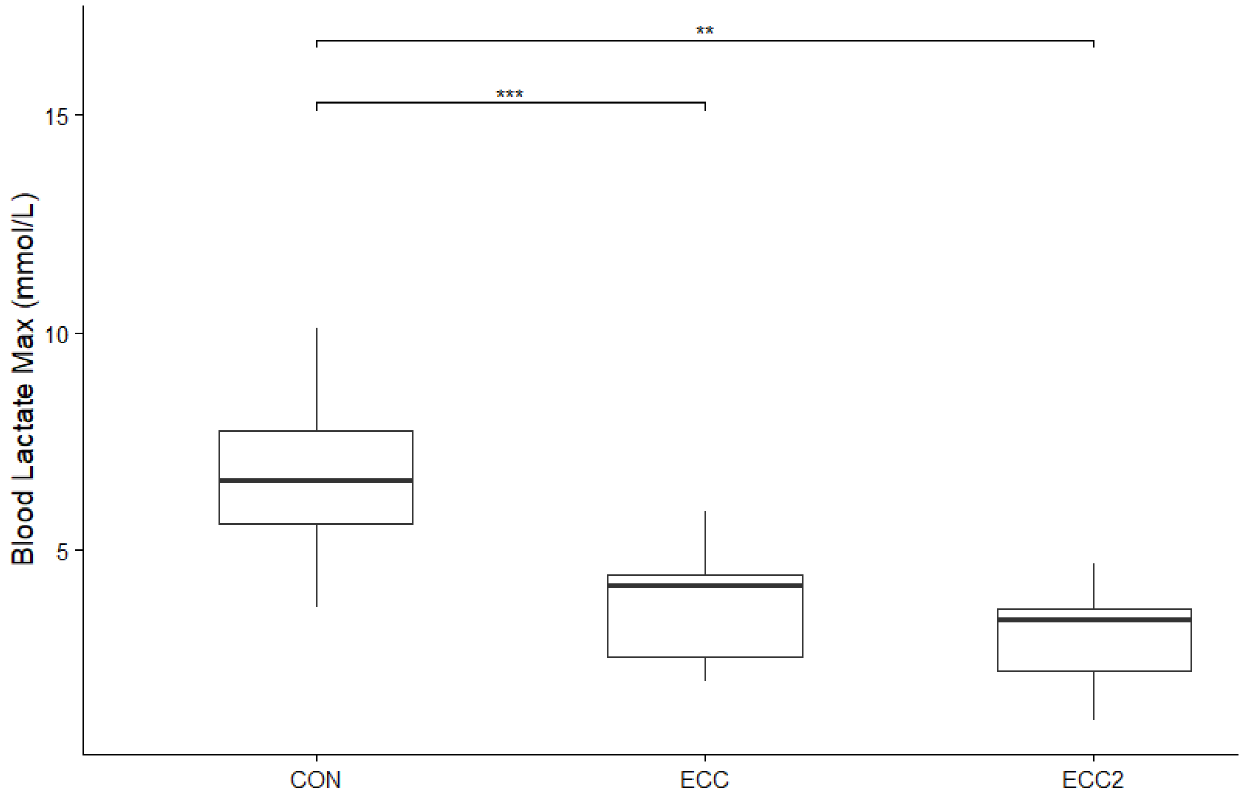
#: p<0.05 CON vs ECC2


VO2 max (ml·kg-1 ·min-1)
60
50
40
30
20
**
CON
ECC
ECC2

A

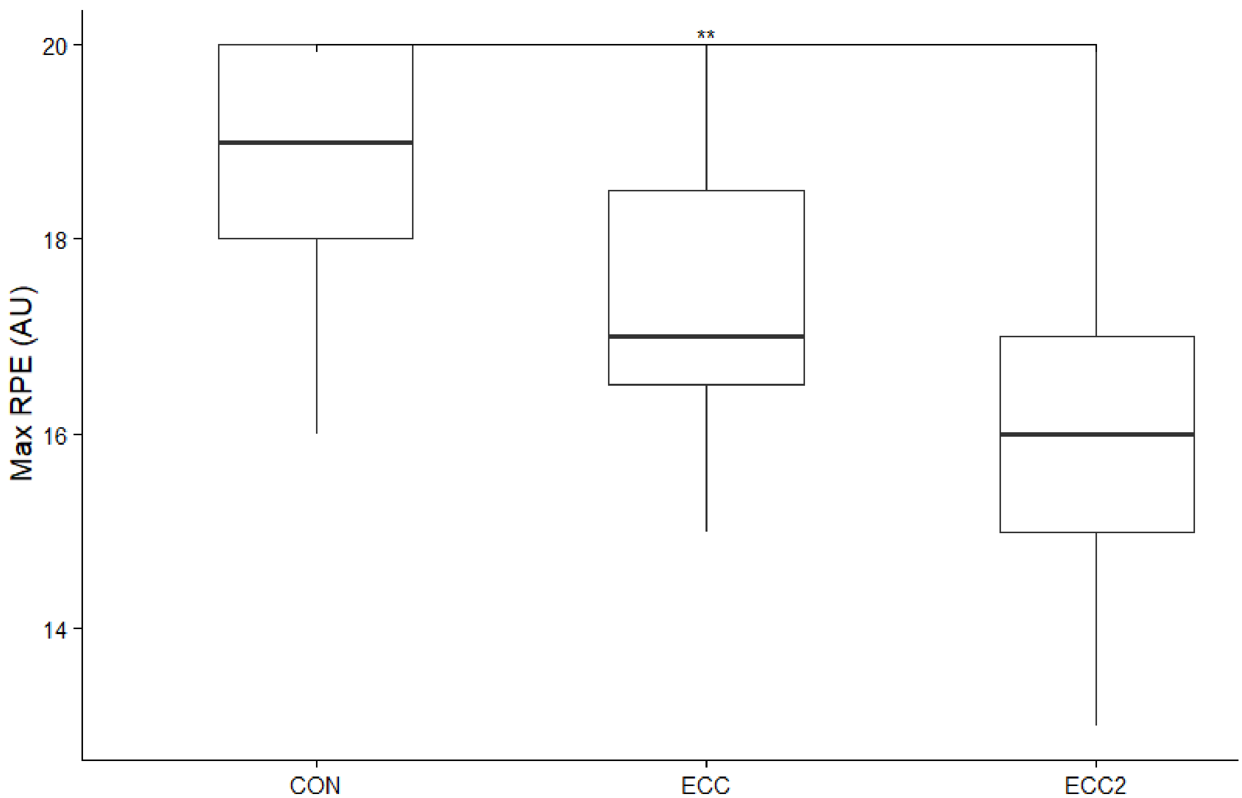

Heart Rate Max (bpm)
200
175
150
125
*
**

B



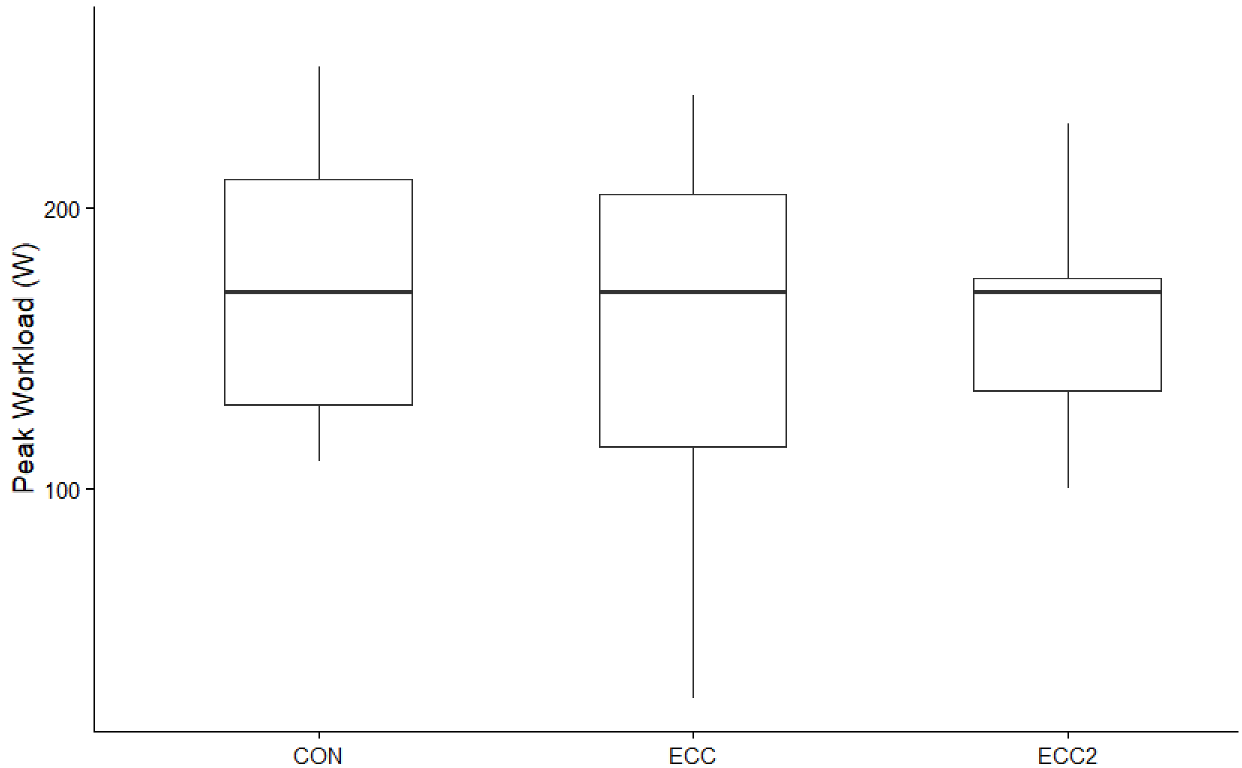
Blood Lactate Max (mmol/L)
15
10
5
***
**
CON
ECC
ECC2

C



Max RPE (AU)
20
18
16
14
**
CON
ECC
ECC2

D



E

Figure 2. a) Maximum Oxygen Consumption b) Maximum Heart Rate c) Maximum Blood Lactate Concentration d) Maximum Rate of Perceived Exertion, e) Maximum Workload. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.0001$.

Discussion

The current study, designed using a randomized approach, aimed to explore the maximum metabolic differences between cycling modalities (ECC vs. CON) during a cadence-controlled GXT. Two main findings were observed: 1) peak workload did not differ between cycling modalities despite the lower metabolic response during all ECC GXTs, and 2) repeated exposure to ECC altered metabolic and perceptual responses during maximal exercise. Specifically, HR and blood lactate concentration were significantly lower during both ECC-GXTs compared with CON, whereas VO□ and RPE were significantly lower only during the second ECC. Altogether, these findings indicate a reduction in cardiovascular and metabolic strain during ECC, as previously seen.[2,5,6,17,35,36] These findings suggest improved efficiency and perceptual adaptation after repeated eccentric exposure, consistent with a short-term protective effect.

The metabolic responses observed during ECC were consistent with previous literature, showing a lower VO□, HR, blood lactate concentration, and RPE compared to CON.[2,5,6] The lower metabolic response observed during ECC could be attributed to the lower motor unit recruitment, as well as the differences in fiber type recruitment.[37] Notably, the significant differences observed only in the second ECC-GXT (i.e., RPE and VO2) reflect a repeated-bout effect. Although a familiarization stage was completed, the first ECC-GXT provided additional exposure, which may have enhanced the neuromuscular efficiency and metabolite-sensitive afferent feedback during the second ECC-GXT.[37]

Blood lactate concentrations and HR were consistently lower during ECC compared to CON, although significant differences were not present between ECC-GXTs. The reduction in blood lactate concentration and lower HR during the second ECC-GXT suggest greater metabolic efficiency, as higher VO□ and lower RPE were observed during the second ECC-GXT compared to the first ECC-GXT, with no difference in total workload (Figure 2E). The lower blood lactate concentration may be attributed to titin's elastic properties, which reduce cross-bridge cycling and ATP demand, thereby decreasing glycolytic demand.[2,38] Previous studies reported ~38% lower muscular amplitude during eccentric contractions than concentric contractions at the same PO, indicating lower motor unit recruitment and metabolic demand.[5] The combination of titin elastic contributions and reduced EMG activity ultimately leads to a decrease in blood lactate concentration and HR. The decrease in HR is a potential effect of reduced muscle recruitment or EMG activity, as afferent activity may have decreased, thereby lowering HR. Overall, the metabolic differences between cycling modalities align with the differences in fiber recruitment.[37] Eccentric exercise primarily recruits fast glycolytic fibers (type II), which are larger fibers capable to generate more torque with less aerobic metabolism than oxidative fibers (type I) used during concentric exercise,[39] reducing the metabolic cost of ECC compared to CON.

To the best of our knowledge, only three studies have utilized an incremental ECC test. Of these, two increased intensity to match CON,[1,18] and only one completed an incremental ECC test to fatigue.[27] In which at matched intensity to CON, Dufour et al and Lechauve et al observed a smaller metabolic demand during ECC compared to CON.[1,18] These results align with the well-established metabolic efficiency of eccentric contractions, attributed to the lower motor unit recruitment and difference in fiber recruitment. Moreover, only one study has performed an incremental ECC GXT to fatigue. Lipski et al reported a higher peak PO during ECC and similar peak HR between cycling modalities, suggesting that ECC may offer mechanical advantages under certain testing conditions.[27]

In contrast, the present study did not observe a higher peak PO during any ECC-GXT (Table 1). Several methodological differences, such as cadence, stage duration, and cycling mode, were noted compared with Lipski et al.[27] The current study utilized a steady cadence of 60rpm while Lipski et al., utilized free cadence. Differences in cadence can further affect PO production. This is expected, as higher velocities during eccentric contractions yield greater force production, according to the force-velocity curve. Secondly, differences in stage duration between the current study and Lipski et al were noted. In which Lipski utilized a one-minute stage opposed to our two-minute stages, differences in the duration may have caused different fatigue responses. Further research is needed for fatigue responses with different stage durations during ECC. Thirdly, cycling modes differed between studies; our study utilized the isokinetic mode (constant cadence with variation in PO), whereas Lipski et al. used the isopower mode (variable cadence with torque-based velocity adjustments to maintain pre-set PO).[40] Isopower mode allows for higher production of force, following the force-velocity curve. An isokinetic mode, thereby, may have limited the peak PO produced.

Furthermore, Lipski et al. reported that peak HR was similar between modalities, opposed to the current study, in which a significant difference was noted between cycling modalities (Table 1). This discrepancy in HR may be attributed to differences in mechanosensory feedback or neuromuscular adaptations between studies, or to greater exposure to ECC, which creates a more pronounced repeated-bout effect at higher intensities, further enhancing the prior familiarization stage and the first ECC-GXT. Therefore, multiple exposures to ECC may have maximized neuromuscular efficiency and decreased the cardiovascular strain during the second ECC-GXT.[39]

Limitations

Although the sample size was sufficient to address the primary aim of the study based on our priori power calculations, the study was not powered to detect potential sex-differences. Additionally, because our population included only apparently healthy young participants, the generalizability of these findings to older or clinical populations remains unknown. Additionally, our cycle ergometer mode may have a limited maximum workload during the ECC- GXTs. Furthermore, our familiarization stage for ECC was brief, which may have affected metabolic and neuromuscular adaptation.

The current study found no significant differences in peak power generated between cycling modalities during a graded exercise test with controlled cadence. In addition, ICC analyses revealed high agreement between the two ECC-GXTs, indicating consistent workload performance. The reduction in physiological demand during the second ECC-GXT suggesting an acute familiarization effect, likely facilitated by enhanced neuromuscular efficiency and reduced cardiovascular strain. Given the lower metabolic and cardiovascular responses observed during maximal ECC, future studies should investigate the neural and muscular mechanisms responsible for these differences. Simultaneous assessment of cortical activity, muscle activation, and cardiorespiratory responses may help clarify the contributions of central and peripheral factors to the physiological response during maximal ECC.

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