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The effect of low vs high cadence interval training on the freely chosen cadence and performance in endurance trained cyclists.

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ABSTRACT

The aim of this study was to determine the effects of high and low cadence interval training on the freely chosen cadence (FCC), and performance in endurance trained cyclists. Sixteen male endurance-trained cyclists completed a series of submaximal rides at 60% W_{max} at cadences of 50, 70, 90, 110 rpm and their FCC to determine their preferred cadence, GE, RPE and crank torque profile. Performance was measured via a 15-min time trial which was preloaded with a cycle at 60% W_{max} . Following the testing, the participants were randomly assigned to a high (HC, 20% above FCC) or low cadence (LC, 20% below FCC) group for 18 interval-based training sessions over 6 weeks. The HC group increased ($p=0.01$) their FCC from 92 to 101 rpm after the intervention whereas the LC group remained unchanged (93 rpm). GE increased from 22.7 to 23.6% in the HC group at 90 ($p=0.05$), from 20.0 to 20.9% at 110 rpm ($p=0.05$) and from 22.8 to 23.2% at their FCC. Both groups significantly increased their total distance and average power output following training with the LC group recording a superior performance measure. There were minimal changes to the crank torque profile in both groups following training. This study demonstrated that the FCC can be altered with HC interval training and that the determinants of the optimal cycling cadence are multifactorial and not completely understood. Furthermore, LC interval training may significantly improve time trial results of short duration due to an increase in strength development or possible neuromuscular adaptations.

Keywords: metabolic efficiency · central pattern generators· muscular demands

Introduction

The optimal pedalling rate in cycling may be defined as the cadence that is the most comfortable, metabolically efficient, or best for performance (Patterson and Moreno 1990; Marsh and Martin 1997; Foss and Hallen 2005). The freely chosen cadence (FCC) is multi-factorial with differences reported for high mountain passes (71.0 ± 1.4 rpm), flat mass start stages (89.3 ± 1.0 rpm) and time-trials (92.4 ± 1.3 rpm) (Lucia et al. 2001; Foss and Hallen 2005; Nesi et al. 2005; Mora-Rodriguez and Aguado-Jimenez 2006; Leirdal and Ettema 2009; Nimmerichter et al. 2011; Emanuele et al. 2012). At a range of exercise intensities, the FCC has been reported as being significantly higher than the metabolically optimal cadence (50-60 rpm) (Ahlquist et al. 1992; Lucia et al. 2001; Mora-Rodriguez and Aguado-Jimenez 2006). This suggests that unlike other endurance based skills such as walking, running and rowing, cadence selection in cycling may be based on variables other than the metabolic demands of the task (Sparrow et al. 1999).

Recent work has demonstrated that the most economical cadence actually increases linearly with power output at high workloads (>300 W), (Lepers et al. 2001; Nielsen et al. 2004; Foss and Hallen 2005; Samozino et al. 2006) suggesting that cadence selection and metabolic efficiency may be more closely related than previously postulated (Vercruyssen and Brisswalter 2010). Alternatively, cadence selection has been proposed to be closely linked to the muscular demands of the task, with cyclists selecting higher cadences to minimise local muscle stress (Patterson and Moreno 1990; Takaishi et al. 1996) and lower crank forces. Research has also shown that well-trained cyclists may select a higher cadence in order to reduce mean (T_{mean}) and peak torque (T_{peak}) and peripheral muscular fatigue (Bertucci et al. 2005) as measured by the crank torque profile.

Previous research on elite cyclists has utilized interval training to investigate performance changes (Westgarth-Taylor et al. 1997; Stepto et al. 1999; Burgomaster et al. 2008), metabolic adaptations (Burgomaster et al. 2005; Aughey et al. 2007) and skeletal muscle adaptations (Gibala et al. 2006; Hauswirth et al. 2010). More recently, it has been suggested that during human rhythmic movement, motor coordination is most likely delegated to neural networks located in the spinal cord, termed central pattern generators (Zehr and Duysens 2004; Zehr 2005). Evidence that cycling cadence may be controlled by these central patterns generators, stems from the fact that the FCC in cycling is largely individual (50 to 100 rpm) and is robust to acute changes such as mechanical and cardiopulmonary loading (Hansen and Ohnstad 2008; Hartley and Cheung 2013; Hansen 2015). Also, both internal (e.g experience) and external (e.g., performance type) factors are known to alter the FCC (Zehr 2005; Hartley and Cheung 2013; Sardroodan et al. 2014; Hansen 2015). Therefore, it has been suggested that the FCC in cycling represents a voluntary rhythmic leg movement frequency, under the primary influence of central pattern generators (Zehr 2005; Hartley and Cheung 2013; Sardroodan et al. 2014; Hansen 2015).

Despite these recent training studies and insights in cadence selection and performance, to the best of our knowledge, no previous study has analysed the impact that interval training for 6 weeks at manipulated cadences has on the FCC and performance, in endurance-trained cyclists. Accordingly, the aims of this study were to determine whether 1) a training protocol undertaken at either above or below the preferred cadence could alter the selection of the FCC in an already established movement pattern such as those seen in endurance-trained cyclists, 2) measurements of GE, comfort mode and the crank torque profile before and after training could provide further insight into the variables most responsible for influencing

cadence selection, and 3) the training protocol could improve performance in a 15 min pre-loaded time trial (Jeukendrup et al. 1996).

Therefore, it was hypothesised that despite a well-developed movement pattern, the training protocol would alter the FCC of the cyclists in the direction of the training stimulus that was undertaken. It was also hypothesised that the variables associated with minimising the muscular demands of the task rather than metabolic efficiency would change significantly and therefore be more closely related to the selection of the FCC. Finally, it was hypothesised that performance in both groups would improve as a result of training for 6 wks at 70% W_{max} .

Materials and Methods

Participants

Sixteen male endurance-trained cyclists volunteered to participate in this study and gave their written informed consent. Their mean (SD) age was 31.4 (6.2) yr, body mass (BM) 74.6 (6.1) kg, and maximal oxygen uptake ($\dot{V}O_{2max}$) was 4.85 (0.5) L·min⁻¹. All participants were training > 300 km·wk⁻¹. At the time of the testing and training program, participants were requested to follow their normal diet and refrain from performing any training during the 48h prior to any laboratory testing. Before volunteering, each participant was fully informed of the purposes, protocol and procedures of this experiment and any associated risks. The study was approved by the Human Research Ethics Committee at the University of Technology Sydney.

Ergometer

All experimental procedures were conducted on an SRM cycling ergometer (Schoberer Rad Messtechnik, Jülich, Germany) equipped with fully adjustable seat position and handlebars.

Participants were able to adjust the position of the ergometer to replicate their “normal” cycling position. The SRM ergometer consists of a precision strain gauge based crank arm and sprocket dynamometer that radio transmits data to the SRM screen (Powercontrol unit) fixed on the handlebars. The SRM powercontrol unit sampled (10Hz) and stored the power output (W), the pedalling data (eg. cadence) and measured the torque (200 Hz). The validity of the SRM cycling ergometer has been previously reported by Smith et al (2001) who reported that power outputs measured using the SRM powermeter were highly reproducible for both laboratory-based and actual 40 km time-trial cycling performance. Prior to testing, the SRM and the torque analysis software were calibrated according to the manufacturers’ recommendation (offset of powermeter slope).

Research design

During the testing period participants completed three laboratory sessions over three weeks. Each set of laboratory tests were separated by at least three days and were conducted at the same time of the day. Participants then performed a prescribed training regime over a six week period. A minimum of two days after completing the final training session, each participant repeated the same set of tests.

At the first testing session, the participants were accustomed to the experimental procedures and $\dot{V}O_{2\max}$ was measured using an incremental exercise test until exhaustion. The participants warmed up for 5 minutes at 100 W and then began the test at a workload of 100 W at a cadence of 80 rpm and increased the workload by 25 W every minute. The participant’s maximum power ($W_{\max}$) achieved on this test was recorded and used to determine the work rate for the sub-maximal steady state test along with the workloads for the six week training period. During the tests, respiratory gas exchange measures were

collected in breath by breath mode and averaged every 30s (Max-1, Physio-Dyne Fitness Instrument Technologies, USA). The open air metabolic cart and flowmeter were calibrated prior and following each test utilizing gases of known concentration according to manufacturer's guidelines. Heart rate was measured using a Polar monitor (Polar, Kempele, Finland). Each exercise test was terminated either; when the participant reached volitional exhaustion or failed to maintain 80 rpm (Whitty et al. 2009).

Participants returned to the laboratory a second time to conduct a sub maximal steady-state test at various cadences. Participants cycled at $60\%W_{\max}$ at five pedalling frequencies (50, 70, 90, 110 rpm, and a FCC), each for six minutes. These were conducted in a random order, separated by an 8 minute recovery period and / or until HR dropped below $80 \text{ beats} \cdot \text{min}^{-1}$. The optimal metabolic cadence was examined by determining the gross efficiency of the mean of the last two minutes of the exercise bout. Gross efficiency (GE) was calculated as the ratio of work accomplished per minute (i.e., W converted to $\text{kcal} \cdot \text{min}^{-1}$) to energy expended per minute (i.e., average $\dot{V}O_2$ for the last 2 min of each 6-min bout, in $\text{kcal} \cdot \text{min}^{-1}$) using the corresponding energy equivalent for each $\dot{V}O_2$ value based on RER (Chavarren and Calbet 1999). Ratings of perceived exertion (RPE) were measured using Borg's CR-10 scale (Borg 1990). The RPE values were recorded at the start of the 5th minute of each cadence condition. The RPE for each participant was recorded for 1) a central or "heart and lungs" rating ($\text{RPE}_{\text{central}}$), and 2) a peripheral or "legs" rating ($\text{RPE}_{\text{peripheral}}$) (Marsh and Martin 1997). During familiarisation and prior to each test, each participant received detailed instructions on the use of the Borg CR-10 scale and was given examples of how they might rate central and peripheral exertion.

The crank torque profile was analysed by dividing the crank cycle into four 90° power output sectors, as depicted in Figure 1. Sectors 1 (between 315° and 45°) and 3 (between 135° and 225°) are associated with the top (DP_{top}) and the bottom (DP_{bot}) dead point of the crank cycle respectively (Bertucci et al. 2005). Typically, these two sectors are associated with the production of minimal crank torque. Sector 2 (45° and 135°) corresponds to the propulsion or pushing down phase, and sector 4 (225° and 315°) to the pulling or recovery phase (Bertucci et al. 2005).

Insert Figure 1 here

In this study, the DP_{top} was the crank angle when the torque was minimal in sector 1 (left crank arm near top position), while torque at the DP_{top} represented the torque value at this crank angle. The DP_{bot} was the crank angle when the torque was minimal in sector 3 (left crank arm near bottom), while the torque at DP_{bot} represents the torque value at this crank angle. The T_{peak} was the maximal torque in sector 2. The T_{peak} , the torque at DP_{top} , the torque at DP_{bot} , and the torque corresponding to the angles of 0° ($T_{0\ deg}$), 45° ($T_{45\ deg}$), 90° ($T_{90\ deg}$), 135° ($T_{135\ deg}$) and 180° ($T_{180\ deg}$) were determined with respect to the lower limb (Fig.2). Figure 2 shows an example of the method of analysis of the crank torque profile for one participant pedalling at 50 rpm recorded at 200 Hz and averaged over 30 s. The crank angle at 0° corresponds to the vertical position of the left crank arm (pedalling high position).

Insert Figure 2

On their third visit to the laboratory, participants conducted a performance test. The test started with a preload of 15 min at $60\%W_{\max}$. Thereafter, a 15-min time trial followed in which participants had to perform as much work as possible. During the first 15 min the electromagnetically braked ergometers were in the hyperbolic mode, so that the work rate ($60\%W_{\max}$) was independent of pedalling rate. During the 15-min time trial the ergometer was in the linear mode so that with increasing pedalling rate the work rate increased. In this way the participant could pace himself and try to either maintain a high pedalling rate or change gears appropriately over 15 min to maximize power output. The participants were motivated to perform as much work as possible in 15 min. The total amounts of work (power output over 15 min) as well as total distance were taken as measures of performance. To avoid test retest influence, the participant received no information about the amount of work performed, heart rate, or pedalling rate. The participants were only aware of time. The cycle ergometer was connected to a computer which recorded the work rate every second and immediately calculated the total amount of work performed (Jeukendrup et al. 1996).

In week 1 of testing participants were made familiar of the gears on the SRM ergometer and how they might be used in the performance test. In the performance tests, participants were allowed to manipulate the gear any time throughout the test. To avoid test retest influence, the participant received no information about the distance covered, heart rate, or pedalling rate. The participants were only aware of time. The cycle ergometer was connected to a computer, which recorded the total amount of distance covered immediately. A Polar S710 heart rate monitor continuously measured heart rate (Polar Electro, Oy, Finland).

Training Intervention

After the preliminary tests, cyclists were randomly assigned to one of two training groups: a high cadence (HC) and low cadence (LC) group. The HC group pedalled at 20% above their individual FCC whilst the LC group pedalled at 20% below their FCC. Each cyclist completed three interval sessions per week for six weeks, resulting in a total of 18 supervised sessions. All laboratory training sessions were supervised by the same investigator and performed on the same cycle ergometer (Model 819, Monark, Varberg, Sweden) under standard environmental conditions (ambient temperature 20-22°C, relative humidity 55-60%). These ergometers allowed the participants to alter both the seat height and their handlebar height to their preferred cycling position. Each training session lasted between 45 - 60 mins.

The participants were asked to maintain their prescribed training cadence throughout the entire session for the six week training period. Each individual session consisted of a 10 minute warm up divided into two bouts of 5 minutes at 100 and 125 W. For Weeks 1 and 2 the interval sessions were comprised of four bouts of 4 minute intervals at 70% W_{max} with two minutes of pedalling at a workload of 100 W between cycling intervals. This was increased to five bouts of 4 minutes in weeks 3 and 4 and six bouts of 4 minute intervals for weeks 5 and 6 with the same recovery used as in weeks 1 and 2. Participants also completed a warm down of 10 mins at 100 W. The training protocols were devised in consultation with coaches, cyclists, and sport scientists to represent training sessions that endurance trained riders would be willing to undertake in order to improve performance.

From the time they entered into investigation each participant recorded their training distance, duration, and perceived training effort in a logbook. These records were used

subsequently to calculate the weekly training distances that the participant undertook during the investigation. The only restriction on the training outside the controlled laboratory sessions was that participants were not to undertake any interval training and to ensure that when they performed training sessions outside the laboratory sessions, they were required to pedal at their prescribed cadence from their interval sessions. Both groups replaced part of their usual training with the 18 interval sessions at a specified cadence.

Statistical Analyses

IBM SPSS Statistics for Windows (version 17.0; IBM Corp., Armonk, N.Y., USA) was used for data analysis, with standard statistical methods used for the calculations of means and standard deviations (SD). All measures were analysed using a two way (work rate * cadence) repeated-measures analysis of variance (ANOVA). With all the multivariate tests, the average F statistic was used to identify significant within-subject effects and within-subject factor by order effects. If the ANOVA reached significance level, a Bonferonni test was performed as post hoc analysis. Statistical significance was determined by an alpha level of $p \leq 0.05$.

Results:

All participants completed the allotted 18 interval sessions in the 6 week training period. The training cadences ranged from 96 to 121 rpm in the HC group and 60 to 81 rpm in the LC group. The optimal pedalling frequency was analysed in accordance to variables associated with the muscular demands of the task along with metabolic, psychological and performance factors. There were no between-group differences before training in any of the variables that were analysed.

Freely Chosen Cadences for Submaximal test and Time Trial

There were significant main effects for FCC to increase post-training at 60% $W_{\max}$ for the high cadence (HC) and low cadence (LC) groups ($F = 21.91$, $p = 0.001$). The participants in the HC group increased their FCC from 92 to 101 rpm ($F = 39.05$, $p = 0.002$). The FCC in the low cadence group (93 rpm) did not change with training ($F = 0.07$, $p = 0.809$). There were no differences in the FCC in the time trial performance test between the HC (100-102 rpm) ($F = 3.13$, $p = 0.151$) and the LC (102 to 103 rpm) ($F = 0.15$, $p = 0.72$) either pre or post training.

Maximum power and $\dot{V}O_{2\max}$

There were significant improvements in $W_{\max}$ between the groups following the training. Both the HC (363 W to 383 W, $F = 7.35$, $p = 0.05$) and the LC group (365 W to 388 W, $F = 6.30$, $p = 0.05$) improved their maximum power output during the $\dot{V}O_{2\max}$ test following the training period. Furthermore, both the HC (4.55 L·min⁻¹ to 4.72 L·min⁻¹, $F = 10.34$, $p = 0.02$) and the LC group (4.55 L·min⁻¹ to 4.64 L·min⁻¹, $F = 23.46$, $p = 0.01$) demonstrated an elevated $\dot{V}O_{2\max}$ after the training.

Heart Rate

Table 1 shows there were no differences in HR between pedalling rates from pre- to post-test for either group. However, both the HC and the LC groups displayed a significant increase in HR as cadence increased in both the pre-test (HC: $F = 3.40$, $p = 0.02$; LC: $F = 10.57$, $p = 0.01$) and the post-test (HC: $F = 5.10$, $p = 0.02$; LC: $F = 8.14$, $p < 0.01$) when cycling at 60% $W_{\max}$.

Insert Table 1 here

Cycling efficiency

Figure 3 displays the Gross efficiency values for the HC and the LC for pre- and post-training. For both groups the optimal metabolic cadence was 50 rpm before and after the training. For both the HC ($F = 7.99$, $p = 0.01$) and the LC group ($F = 9.15$, $p = 0.01$) there was a significant decrease in GE as cadence increased in the post-test. The HC group displayed a significant increase in GE at 90 rpm ($F = 6.99$, $p = 0.05$) and 110 rpm ($F = 5.74$, $p = 0.05$) from pre- to post-test. Furthermore, although not significantly different, there was an increase in GE for the HC group at the FCC from pre (22.8%) to post training (23.2%).

Insert Figure 3 here

RPE peripheral and central

Results analysing the most comfortable cadence were analysed via measurement of central and peripheral RPE (Table 1). $RPE_{\text{peripheral}}$ for the HC group was minimised at 70 rpm for the pre-test and 90 rpm at the post-test. When examining changes in $RPE_{\text{peripheral}}$ at specific cadences, there was a significant decrease in $RPE_{\text{peripheral}}$ at 90 ($F = 9.00$, $p = 0.03$) and 110 rpm from pre- to post-test ($F = 5.31$, $p = 0.05$) in the HC group. For the LC group, $RPE_{\text{peripheral}}$ was minimised at 70 rpm for the pre-test and 50 rpm for the post-test. There were no differences in $RPE_{\text{peripheral}}$ as cadence increased for either group at either the pre- or post-test.

For the HC group RPE_{central} was minimised at 70 rpm for the pre-test and 50 rpm for the post test. There was a significant increase in RPE_{central} as cadence increased at the pre-test ($F = 5.00$, $p = 0.04$) and the post-test ($F = 5.98$, $p = 0.01$, Table 1). Further, there was a significant decrease in RPE_{central} following the training at 50 ($F = 10.00$, $p = 0.03$), and 90 rpm ($F = 6.00$, $p = 0.05$). For the LC group, RPE_{central} was minimised at 50 rpm for the pre-test and 70 rpm

for the post-test (Table 1) and there was a significant reduction in RPE_{central} after the training period at 90 rpm ($F = 12.27$, $p = 0.01$).

Crank torque variables

There were no differences between the HC and the LC group at either the pre-test or the post-test for any of the crank torque variables. The within-group changes that occurred in the HC and the LC group from pre-to post-tests are presented in Table 2. The HC group recorded a significant decrease in T_{peak} ($F = 37.606$, $p = 0.01$) and the crank angle at T_{peak} at the FCC ($F = 9.33$, $p = 0.04$). There was also a significant decrease in the crank angle at the DP_{top} at the FCC ($F = 7.562$, $p = 0.05$). For the LC group there was a significant increase in the torque at DP_{top} ($F = 6.63$, $p = 0.05$) and DP_{bot} ($F = 40.06$, $p = 0.03$) at 50rpm rpm ($F = 8.559$, $p = 0.04$).

Insert Table 2 here

The preloading component

For the LC group, the average power output for the preloaded 15 submaximal test on day 3 in the pre-test was 225W and was performed at an average HR of 147 bpm. This represented an average absolute $\dot{V}O_{2\text{max}}$ of $2.72 \text{ L}\cdot\text{min}^{-1}$ at an average 65.2% of $VO_{2\text{max}}$. For the HC group, the average power output was 218 W and was performed at an average HR of 141 bpm. This represented an average absolute $\dot{V}O_{2\text{max}}$ of $2.74 \text{ L}\cdot\text{min}^{-1}$ at an average of 66% of $VO_{2\text{max}}$.

In the post-test, the average power output for the preloaded 15 submaximal test on day 3 for the LC group was 233W and was performed at an average HR of 143 bpm. This represented an average absolute $\dot{V}O_{2\text{max}}$ of $2.66 \text{ L}\cdot\text{min}^{-1}$ at an average of 61% of $\dot{V}O_{2\text{max}}$. For the HC group; the average power output was 231W and was performed at an average HR of 140

bpm. This represented an average absolute $\dot{V}O_2$ of $2.69 \text{ L}\cdot\text{min}^{-1}$ at an average of 63% of $\dot{V}O_{2\text{max}}$.

Performance for TT (distance and power output)

The LC group improved performance output to a significantly greater extent than the HC group following the training ($F = 5.28$, $p = 0.04$). The HC group recorded a 4% improvement ($F = 63.95$, $p < 0.01$) from pre-test (9.8 km) to post test (10.2 km), whereas the LC group showed a 7% improvement from pre-test (9.8 km) to post test (10.5 km) ($F = 56.54$, $p = 0.01$) in total distance covered over the 15 min maximal effort. The LC group increased their average power output in the TT to a greater extent than the HC group following the training ($F = 16.20$ $p = 0.02$). The average power output for the LC group in the time trial increased by 16% ($F = 28.32$, $p = 0.03$) from pre-test (269 W) to post test (312 W), whereas the HC group showed an 8% improvement from pre-test (269 W) to post test (291 W) ($F = 7.34$ $p = 0.04$). For the LC training group the average HR in the TT in the pre-test was 168 bpm and in the post-test was 171 bpm. For the HC training group the average HR in the TT in the pre-test was 172 bpm and in the post-test was 171 bpm.

Discussion

The principal finding of the current study was that endurance-trained cyclists who completed six weeks of interval training at 20% above (HC) their preferred cadence increased their FCC; whereas those that trained at 20% below (LC) demonstrated no changes in cadence selection. These findings were observed in both the submaximal FCC test at $60\%W_{\text{max}}$ completed on day 2 of testing as well as in the preloading component of the performance test on day 3 at the same workload. It was initially hypothesised that both groups would alter their FCC in accordance to their training cadence, however this was not the case. These results

suggest that an established movement pattern as seen in a cyclist's FCC can be altered with six weeks of specific high-cadence training. In support of the findings of the current study, previous research has revealed that cyclists prefer to pedal at high cadences in lab and field based studies over a range of exercise intensities and terrains (Lepers et al. 2001; Lucia et al. 2001; Foss and Hallen 2004; Lucia et al. 2004; Foss and Hallen 2005). One of the strengths of the current study was the individual nature of the cadences utilised in training, meaning that all participants were cycling at an equal percentage either above or below their FCC. The individualised nature of cadence selection in endurance trained cyclists has previously been highlighted as an important characteristic to identify when undertaking research on cadence selection in cycling (Hansen 2015).

Another key finding of the current study was that both groups demonstrated a significant improvement in performance after six weeks of training, with the LC training group improving to a greater extent. Notably, these findings are supported by previous research which has shown that training and performing at low cadences may be more beneficial to improving performance in endurance-trained cyclists over shorter distances than at higher cadences (Paton et al. 2009; Nimmerichter et al. 2011; Stebbins et al. 2014; Hirano et al. 2015). For example, Paton et al (2009) found that LC interval training increased performance in a maximal 60-s test when compared to HC training using similar training cadence to the current study. Furthermore, Hirano et al (2015) also found that two weeks of training at a LC (35 rpm), but not at a HC (75 rpm), improved work completed at lactate threshold). It is possible that the performance improvements seen in low cadence training in previous research and in the current study may be due to the use of higher forces, which could have a positive benefit by either improving strength or generating specific neuromuscular adaptations.

In contrast to the findings of the current study, Kristoffersen and colleagues (2014) reported no improvement in performance for veteran cyclists following 12 weeks of low cadence interval training when pedalling at an absolute rate of 40 rpm. This may have been due to the use of an absolute, rather than relative power measure and that 40 rpm is significantly lower than the pedalling rate that an endurance cyclist would adopt in any conditions. The current study utilised relative measures of cadence for the interval training sessions and were only 20% lower than their FCC and therefore similar to a cadence they may utilise when negotiating uphill terrain (Kristoffersen et al. 2014). Low cadence training to improve cycling performance is becoming increasingly popular with coaches and sports scientists and may warrant further research to better understand the mechanisms responsible.

The exact mechanisms that influence cadence selection in endurance-trained cyclists is not yet fully understood. It has been proposed that cadence selection is linked to minimising the muscular demands of the task as shown by reductions in T_{peak} and T_{mean} and changes in the crank torque profile (Patterson and Moreno 1990; MacIntosh et al. 2000; Bertucci et al. 2005). The hypothesis that the FCC would be closely associated with the need to minimise the muscular demands of the task was only partly supported. The only significant changes to the crank torque profile were seen in the HC group, with expected reductions in T_{peak} , and the crank angle at T_{peak} , considering the FCC increased from pre to post training.

It has been documented that endurance trained cyclists select a preferred cadence that is significantly higher than the most optimal metabolic cadence (Chavarren and Calbet 1999). Therefore this study hypothesised that cadence selection would not be tightly coupled with

metabolic efficiency. Interestingly, cyclists in the HC group, who increased their FCC from 92-101 rpm following training, also increased their GE solely at 90 and 110 rpm, which coincided with their mean training cadence. These findings suggest that metabolic efficiency and cadence selection may be more closely related than previously proposed. In addition, the GE at the FCC following training also increased in the HC group despite the fact that the FCC increased from 92 to 101 rpm. Normally an increase in cadence would lead to a reduction in GE, especially at higher values (Chavarren and Calbet 1999; Faria et al. 2005). Contrary to the initial hypothesis, cyclists in the HC group altered their FCC, which resulted in these cyclists selecting a preferred pedalling rate that was metabolically superior when compared to their preferred pedalling rate in the pre-test. To our knowledge this is the first study to show that the FCC can be altered with training. In support of these findings more recent research demonstrated that cadence selected was strongly coupled with metabolic efficiency but not pedalling technique and force effectiveness (Leirdal and Ettema 2011). However, despite these findings, the FCC recorded for both groups before and after training was higher than the optimal metabolic cadence with the lowest GE values recorded at 50 rpm for both groups before and after training.

The current study showed support for the notion that the FCC in cycling is a voluntary rhythmic leg movement possibly controlled by neural networks located in the spinal cord termed central pattern generators (CPG) (Zehr and Duysens 2004; Zehr 2005; Hansen 2015). Findings showed that the FCC was highly individual, ranging 80-103 on submaximal testing and 78-106 rpm on the performance test and had a strong between day reliability as seen in both groups. For example, the HC group recorded a FCC on day 2 of testing at 60% $W_{\max}$ of 93 rpm and also recorded an average of 95 rpm at the same workload on day 3. This strong between day reliability was replicated in the post-test for the HC group and in both the pre

and post-test for the LC group.

Further support for control of FCC being related to CPG were seen in the cadences for the TT on day 3 of testing. Both groups recorded significantly higher preferred cadences in the TT in the pre test when compared to their FCC recorded on the submaximal test on day 2 and pre loading aspect of the performance test on day 3. This may have been due to external factors such as experiencing an increase in power output when completing the performance test. This increase in power may have caused an increase in mechanoreceptor stimulation causing an increase in perceived exertion (Hansen 2015). To counteract this both groups may have therefore increased their FCC to decrease peak torque and decrease RPE. Alternatively, according to CPG theorists, the change in FCC may have been due to higher power outputs causing an increase in rate of force development requiring increased muscle activation, including increased common drive from supraspinal centres to the CPG and contribute to larger net excitability of the CPG. Furthermore, the FCC for the TT remained the same for both groups from pre to post test suggesting a robust movement pattern.

Finally of interest was that the LC group had a FCC that remained unchanged in the TT and a performance measure superior to that recorded by the HC group. In support of these findings, it has been shown that after heavy strength training, FCC remained the same for well-trained cyclists and performance increased (Hansen and Ohnstad 2008; Hansen and Smith 2009; Hansen 2015). The interpretation of this was that strength training improved the pedaling efficacy concomitantly with improved performance in terms of on average 7% higher power output in the all-out trial after the strength-training period. It is possible that the low cadence training with the use of higher forces in the current study could be seen as a type of strength regime for the cycling muscles when compared to the lower peak forces experienced by the

HC group. According to CPG theorists, the increases in performance may have been due to similar reasons for the heavy strength training studies which were interpreted as evidence for enhanced neural efficiency (Hansen et al. 2002; Zehr 2005; Hansen and Smith 2009; Hartley and Cheung 2013; Hansen 2015). One of the limitations of this study was that the crank torque profile and GE data was not collected in the 15 min TT and may have provided further support for CPG control as this would have enabled the researchers to compare the crank torque profile at different power outputs.

The current study also showed the cadence selection is related to comfort mode with $RPE_{\text{peripheral}}$ in the HC group recording its lowest value at 90 rpm following the training period as opposed to 70 rpm at the commencement of training. Also, the HC group displayed a significant decrease in $RPE_{\text{peripheral}}$ at both 90 and 110 rpm from pre to post training whilst the minimal value for $RPE_{\text{peripheral}}$ for the LC group decreased from 70 rpm to 50 rpm after training. These results suggest a strong relationship between cadence selection in cycling as suggested by previous research and $RPE_{\text{peripheral}}$ (Garcin et al. 1998; Jameson and Ring 2000).

The current study demonstrated that the FCC can be altered with high cadence interval training. Training with a relatively high cadence altered FCC and this preferred cadence was more metabolically efficient, produced less T_{peak} , felt more comfortable and led to improved performance output. Training with a relatively low cadence led to a greater improvement in performance possibly due to neurological adaptations, suggesting that low cadence interval training may significantly improve time trial results of short duration.

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Conflicts of interest

The authors declare that there are no conflicts of interest

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References

- Ahlquist, L.E., Bassett, D.R., Jr., Sufit, R., Nagle, F.J. and Thomas, D.P. 1992. The effect of pedaling frequency on glycogen depletion rates in type I and type II quadriceps muscle fibers during submaximal cycling exercise. *Eur J Appl Physiol Occup Physiol* **65**: 360-4.
- Aughey, R.J., Murphy, K.T., Clark, S.A., Garnham, A.P., Snow, R.J., Cameron-Smith, D., Hawley, J.A. and McKenna, M.J. 2007. Muscle Na⁺-K⁺-ATPase activity and isoform adaptations to intense interval exercise and training in well-trained athletes. *J Appl Physiol* (1985) **103**: 39-47.
- Bertucci, W., Grappe, F., Girard, A., Betik, A. and Rouillon, J.D. 2005. Effects on the crank torque profile when changing pedalling cadence in level ground and uphill road cycling. *J Biomech* **38**: 1003-10.
- Borg, G. 1990. Psychophysical scaling with applications in physical work and the perception of exertion. *Scand J Work Environ Health* **16 Suppl 1**: 55-8.
- Burgomaster, K.A., Howarth, K.R., Phillips, S.M., Rakobowchuk, M., Macdonald, M.J., McGee, S.L. and Gibala, M.J. 2008. Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. *J Physiol* **586**: 151-60.
- Burgomaster, K.A., Hughes, S.C., Heigenhauser, G.J., Bradwell, S.N. and Gibala, M.J. 2005. Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. *J Appl Physiol* (1985) **98**: 1985-90.
- Chavarren, J. and Calbet, J.A. 1999. Cycling efficiency and pedalling frequency in road cyclists. *Eur J Appl Physiol Occup Physiol* **80**: 555-63.
- Emanuele, U., Horn, T. and Denoth, J. 2012. The relationship between freely chosen cadence and optimal cadence in cycling. *Int J Sports Physiol Perform* **7**: 375-81.
- Faria, E.W., Parker, D.L. and Faria, I.E. 2005. The science of cycling: factors affecting performance - part 2. *Sports Med* **35**: 313-37.
- Foss, O. and Hallen, J. 2004. The most economical cadence increases with increasing workload. *Eur J Appl Physiol* **92**: 443-51.
- Foss, O. and Hallen, J. 2005. Cadence and performance in elite cyclists. *Eur J Appl Physiol* **93**: 453-62.
- Garcin, M., Vautier, J.F., Vandewalle, H., Wolff, M. and Monod, H. 1998. Ratings of perceived exertion (RPE) during cycling exercises at constant power output. *Ergonomics* **41**: 1500-9.
- Gibala, M.J., Little, J.P., van Essen, M., Wilkin, G.P., Burgomaster, K.A., Safdar, A., Raha, S. and Tarnopolsky, M.A. 2006. Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *J Physiol* **575**: 901-11.
- Hansen, E.A. 2015. On voluntary rhythmic leg movement behaviour and control during pedalling. *Acta Physiol (Oxf)* **214 Suppl 702**: 1-18.
- Hansen, E.A., Jorgensen, L.V., Jensen, K., Fregly, B.J. and Sjogaard, G. 2002. Crank inertial load affects freely chosen pedal rate during cycling. *J Biomech* **35**: 277-85.
- Hansen, E.A. and Ohnstad, A.E. 2008. Evidence for freely chosen pedalling rate during submaximal cycling to be a robust innate voluntary motor rhythm. *Exp Brain Res* **186**: 365-73.
- Hansen, E.A. and Smith, G. 2009. Factors affecting cadence choice during submaximal cycling and cadence influence on performance. *Int J Sports Physiol Perform* **4**: 3-17.
- Hartley, G.L. and Cheung, S.S. 2013. Freely chosen cadence during a covert manipulation of ambient temperature. *Motor Control* **17**: 34-47.

- Hausswirth, C., Argentin, S., Bieuzen, F., Le Meur, Y., Couturier, A. and Brisswalter, J. 2010. Endurance and strength training effects on physiological and muscular parameters during prolonged cycling. *J Electromyogr Kinesiol* **20**: 330-9.
- Hirano, M., Shindo, M., Mishima, S., Morimura, K., Higuchi, Y., Yamada, Y., Higaki, Y. and Kiyonaga, A. 2015. Effects of 2 weeks of low-intensity cycle training with different pedaling rates on the work rate at lactate threshold. *Eur J Appl Physiol* **115**: 1005-13.
- Jameson, C. and Ring, C. 2000. Contributions of local and central sensations to the perception of exertion during cycling: effects of work rate and cadence. *J Sports Sci* **18**: 291-8.
- Jeukendrup, A., Saris, W.H., Brouns, F. and Kester, A.D. 1996. A new validated endurance performance test. *Med Sci Sports Exerc* **28**: 266-70.
- Kristoffersen, M., Gundersen, H., Leirdal, S. and Iversen, V.V. 2014. Low cadence interval training at moderate intensity does not improve cycling performance in highly trained veteran cyclists. *Front Physiol* **5**: 34.
- Leirdal, S. and Ettema, G. 2009. Freely chosen pedal rate during free cycling on a roller and ergometer cycling. *Eur J Appl Physiol* **106**: 799-805.
- Leirdal, S. and Ettema, G. 2011. The relationship between cadence, pedalling technique and gross efficiency in cycling. *Eur J Appl Physiol* **111**: 2885-93.
- Lepers, R., Millet, G.Y. and Maffiuletti, N.A. 2001. Effect of cycling cadence on contractile and neural properties of knee extensors. *Med Sci Sports Exerc* **33**: 1882-8.
- Lucia, A., Hoyos, J. and Chicharro, J.L. 2001. Preferred pedalling cadence in professional cycling. *Med Sci Sports Exerc* **33**: 1361-6.
- Lucia, A., San Juan, A.F., Montilla, M., CaNete, S., Santalla, A., Earnest, C. and Perez, M. 2004. In professional road cyclists, low pedaling cadences are less efficient. *Med Sci Sports Exerc* **36**: 1048-54.
- MacIntosh, B.R., Neptune, R.R. and Horton, J.F. 2000. Cadence, power, and muscle activation in cycle ergometry. *Med Sci Sports Exerc* **32**: 1281-7.
- Marsh, A.P. and Martin, P.E. 1997. Effect of cycling experience, aerobic power, and power output on preferred and most economical cycling cadences. *Med Sci Sports Exerc* **29**: 1225-32.
- Mora-Rodriguez, R. and Aguado-Jimenez, R. 2006. Performance at high pedaling cadences in well-trained cyclists. *Med Sci Sports Exerc* **38**: 953-7.
- Nesi, X., Bosquet, L. and Pelayo, P. 2005. Preferred pedal rate: an index of cycling performance. *Int J Sports Med* **26**: 372-5.
- Nielsen, J.S., Hansen, E.A. and Sjogaard, G. 2004. Pedalling rate affects endurance performance during high-intensity cycling. *Eur J Appl Physiol* **92**: 114-20.
- Nimmerichter, A., Eston, R., Bachl, N. and Williams, C. 2011. Effects of low and high cadence interval training on power output in flat and uphill cycling time-trials. *Eur J Appl Physiol* **112**: 69-78.
- Paton, C.D., Hopkins, W.G. and Cook, C. 2009. Effects of low- vs. high-cadence interval training on cycling performance. *J Strength Cond Res* **23**: 1758-63.
- Patterson, R.P. and Moreno, M.I. 1990. Bicycle pedalling forces as a function of pedalling rate and power output. *Med Sci Sports Exerc* **22**: 512-6.
- Samozino, P., Horvais, N. and Hintzy, F. 2006. Interactions between cadence and power output effects on mechanical efficiency during sub maximal cycling exercises. *Eur J Appl Physiol* **97**: 133-9.
- Sardroodian, M., Madeleine, P., Voigt, M. and Hansen, E.A. 2014. Frequency and pattern of voluntary pedalling is influenced after one week of heavy strength training. *Hum Mov Sci* **36**: 58-69.

- Smith, M.F., Davison, R.C., Balmer, J. and Bird, S.R. 2001. Reliability of mean power recorded during indoor and outdoor self-paced 40 km cycling time-trials. *Int J Sports Med* **22**: 270-4.
- Sparrow, W.A., Hughes, K.M., Russell, A.P. and Le Rossignol, P.F. 1999. Effects of practice and preferred rate on perceived exertion, metabolic variables and movement control. *Human Movement Science* **June**: 137-153.
- Stebbins, C.L., Moore, J.L. and Casazza, G.A. 2014. Effects of cadence on aerobic capacity following a prolonged, varied intensity cycling trial. *J Sports Sci Med* **13**: 114-9.
- Stephens, N.K., Hawley, J.A., Dennis, S.C. and Hopkins, W.G. 1999. Effects of different interval-training programs on cycling time-trial performance. *Med Sci Sports Exerc* **31**: 736-41.
- Takaishi, T., Yasuda, Y., Ono, T. and Moritani, T. 1996. Optimal pedaling rate estimated from neuromuscular fatigue for cyclists. *Med Sci Sports Exerc* **28**: 1492-7.
- Vercruyssen, F. and Brisswalter, J. 2010. Which factors determine the freely chosen cadence during submaximal cycling? *J Sci Med Sport* **13**: 225-31.
- Westgarth-Taylor, C., Hawley, J.A., Rickard, S., Myburgh, K.H., Noakes, T.D. and Dennis, S.C. 1997. Metabolic and performance adaptations to interval training in endurance-trained cyclists. *Eur J Appl Physiol Occup Physiol* **75**: 298-304.
- Whitty, A.G., Murphy, A.J., Coutts, A.J. and Watsford, M.L. 2009. Factors associated with the selection of the freely chosen cadence in non-cyclists. *Eur J Appl Physiol* **106**: 705-12.
- Zehr, E.P. 2005. Neural control of rhythmic human movement: the common core hypothesis. *Exerc Sport Sci Rev* **33**: 54-60.
- Zehr, E.P. and Duysens, J. 2004. Regulation of arm and leg movement during human locomotion. *Neuroscientist* **10**: 347-61.

Table 1: Heart rate and Ratings of perceived exertion at 60%W_{max} at cadences of 50, 70, 90, 110 rpm and freely chosen cadence (n = 16; mean ± SD).

Cadence (rpm)	Group	Test	50	70	90	110	FCC
Heart Rate (bpm)	LC	Pre	139 ± 9	142 ± 5	144 ± 5	157 ± 6	145 ± 4
		Post	140 ± 5	142 ± 7	144 ± 6	156 ± 6	144 ± 2
	HC	Pre	134 ± 8	138 ± 8	145 ± 9	154 ± 11	143 ± 2
		Post	134 ± 11	137 ± 10	141 ± 12	150 ± 10	140 ± 12
RPE central (0-10)	LC	Pre	3.5 ± 2.3	3.7 ± 1.6	4.2 ± 1.9	5.2 ± 2.0	4.7 ± 2.1
		Post	2.7 ± 1.0	2.5 ± 1.5	2.7 ± 1.2*	4.2 ± 2.3	3.5 ± 1.8
	HC	Pre	3.0 ± 0.6	2.7 ± 0.8	3.7 ± 0.5	4.7 ± 1.4	3.5 ± 0.5
		Post	2.3 ± 0.8*	2.5 ± 1.0	3.0 ± 0.6*	4.5 ± 1.0	3.0 ± 0.6
RPE peripheral (0-10)	LC	Pre	4.7 ± 2.4	4.3 ± 1.9	5.3 ± 1.5	6.2 ± 1.7	5.7 ± 2.2
		Post	3.8 ± 1.0	4.3 ± 1.2	3.8 ± 1.7	4.8 ± 2.3	3.7 ± 1.5
	HC	Pre	4.2 ± 1.0	3.7 ± 1.2	4.0 ± 1.3	4.0 ± 1.0	4.0 ± 1.3
		Post	3.5 ± 1.4	3.5 ± 1.0	3.5 ± 0.8*	3.6 ± 1.1*	3.5 ± 1.0

* Significantly different from pre to post training (p <0.05)

Table 2: Crank torque variables for Low Cadence (LC) and High Cadence (HC) group pre test and post test at different cadences. T_{peak} : peak propulsive torque (N m); $T-Dp_{top}$: torque at top dead point (N m); $T-Dp_{bot}$: torque at bottom dead point (N m);

Cycling Condition	Group	Test	50 rpm	70 rpm	90 rpm	110rpm	FCC
T_{peak}	LC	Pre	78.5 ± 4.2	59.1 ± 3.7	48.6 ± 2.7	41.4 ± 2.1	49.7 ± 4.0
		Post	78.5 ± 9.9	58.5 ± 4.6	47.5 ± 5.1	40.4 ± 2.6	48.4 ± 4.1
	HC	Pre	76.5 ± 14.2	56.8 ± 9.1	46.7 ± 8.3	38.9 ± 4.5	54.1 ± 9.0*
		Post	74.5 ± 10.6	56.0 ± 8.6	45.9 ± 7.2	38.9 ± 5.2	44.5 ± 4.4
Crank Angle at T_{peak}	LC	Pre	106 ± 4.6	105 ± 10.2	110 ± 7.4	116 ± 10.8	111 ± 6.9
		Post	102 ± 4.6	108 ± 7.4	112 ± 7.7	120 ± 13.7	112 ± 3.4
	HC	Pre	108 ± 3.9	119 ± 8.3	118 ± 8.8	116 ± 18.3	120 ± 5.9*
		Post	105 ± 5.8	116 ± 7.4	117 ± 8.4	107 ± 3.6	113 ± 5.8
Torque at Dp_{top}	LC	Pre	17.6 ± 2.7*	18.1 ± 2.6	17.0 ± 2.3	14.9 ± 1.6	16.0 ± 2.3
		Post	19.0 ± 1.8	18.0 ± 1.7	16.6 ± 0.8	14.4 ± 1.3	16.9 ± 1.0
	HC	Pre	17.6 ± 3.4	17.9 ± 3.4	19.0 ± 4.5	17.1 ± 5.5	19.10 ± 4.9*
		Post	18.3 ± 3.8	19.4 ± 3.0	19.6 ± 4.4	17.1 ± 5.1	17.3 ± 4.2
Crank Angle at Dp_{top}	LC	Pre	21 ± 4.4	21 ± 4.8	34 ± 4.8	45 ± 2.8	34 ± 6.5
		Post	19 ± 3.0	24 ± 4.8	34 ± 6.1	44 ± 3.2	30 ± 6.5
	HC	Pre	20 ± 4.7	20 ± 4.8	34 ± 11.8	48 ± 11.9	35 ± 4.5
		Post	18 ± 3.3	22 ± 5.8	36 ± 5.7	46 ± 5.3	39 ± 4.8
Torque at Dp_{bot}	LC	Pre	15.0 ± 1.8*	15.9 ± 2.2	15.6 ± 1.7	14.9 ± 2.4	15.1 ± 1.9
		Post	17.1 ± 1.5	16.8 ± 2.5	17.0 ± 2.5	15.1 ± 2.1	17.0 ± 2.3
	HC	Pre	17.0 ± 4.6	18.4 ± 4.0	18.8 ± 5.5	17.1 ± 5.2	18.4 ± 5.2
		Post	17.6 ± 3.4	18.7 ± 4.2	19.2 ± 5.4	17.0 ± 4.2	17.4 ± 4.7
Crank Angle at Dp_{bot}	LC	Pre	201 ± 4.4	202 ± 5.5	215 ± 6.1	224 ± 4.5	215 ± 6.4
		Post	201 ± 4.1	204 ± 4.5	215 ± 4.5	223 ± 3.1	212 ± 4.6
	HC	Pre	200 ± 3.1	203 ± 6.2	214 ± 13.6	229 ± 3.7	214 ± 13.5
		Post	198 ± 3.6	202 ± 6.0	213 ± 6.3	229 ± 5.9	213 ± 10.9

*= Significantly different from pre to post training ($p < 0.05$)

Figure. 1. Definitions of top dead center (DP_{top}), bottom dead center (DP_{bot}). θ_c is the crank pedal angles.

Figure 2. Method for determination of maximal and minimal torque, T_{peak} peak propulsive torque (Nm), DP_{top} top dead point ($^\circ$), D_{bot} bottom dead point ($^\circ$).

Figure 3. Gross efficiency data for HC and LC groups at $60\%W_{max}$ pre and post training.

* = Significantly different from pre to post training ($p < 0.05$)

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