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Joint specific power production in cycling: the effect of cadence and athlete level

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Summary in Norwegian

Introduksjon: Intervalltrening med lav tråkkfrekvens (<60 rpm) er en vanlig treningsmetode blant syklister. Effekten av tråkkfrekvens og arbeidsbelastning på leddspesifikk kraftutvikling i sykling har tidligere blitt studert, men forskning har primært fokusert på tråkkfrekvens over 60 rpm uten å undersøke effekten av lav tråkkfrekvens på de ulike leddenes bidrag til kraftproduksjon. Målet med denne studien var å undersøke den leddspesifikke kraftutviklingen hos rekreasjons- og elitesyklister under lav- og moderat sykling ved et utvalg forskjellige tråkkfrekvenser, samt å fastslå om lav tråkkfrekvens på moderat intensitet kan gi samme hofteleddskraft og assosiert muskelaktivitet som sykling på høy intensitet med selvvalgt tråkkfrekvens. **Metode:** Ti rekreasjons- og ni elitesyklister gjennomførte sykkelintervaller på syv forskjellige tråkkfrekvenser og fire intensiteter. Leddspesifikk effekt ble kalkulert fra kinematiske målinger og pedalkraft ved hjelp av inverse dynamics. Muskelaktivitet i gluteus maximus (GM) og vastus lateralis (VL) ble målt med overflate-EMG. **Resultater:** En effekt av tråkkfrekvens og utøvernivå ble funnet på den relative hofte- og kneleddskraften. Økt tråkkfrekvens førte til økt kneleddskraft og minkende hofteleddskraft, med unntak ved lav tråkkfrekvens (<60 rpm), hvor det ikke var noen effekt av tråkkfrekvens. Elitegruppen hadde høyere relative hofteleddskraft og lavere relative kneleddskraft sammenlignet med rekreasjonsgruppen. Hofteleddskraften ved høy intensitet med selvvalgt frekvens var ikke forskjellige fra hofteleddskraften ved moderat intensitet med en lav frekvens (<60 rpm). **Diskusjon:** Denne studien demonstrerer at det er en effekt av tråkkfrekvens på hofte- og kneleddsbidraget i sykling, men at effekten kun er til stede fra 60 rpm og oppover. Den demonstrerer også at det er en forskjell i leddbidraget hos elite- og rekreasjonssyklister, samt viser at det er mulig å oppnå samme hofteleddskraft ved moderat intensitet som ved høy intensitet ved å forandre tråkkfrekvensen. **Konklusjon:** Resultatene fra denne studien indikerer at det er en forskjell i tråkkteknikken hos rekreasjons- og elitesyklister, og at effekten av tråkkfrekvens på det relative hofte- og kneleddsbidraget kun er til stede fra 60 rpm og oppover.

Abstract

Introduction: Low cadence (<60 rpm) interval training is a commonly used training method among cyclists. The effect of cadence and work rate on the joint specific power production in cycling has previously been studied, but research has primarily focused on cadences above 60 rpm, without examining the effect of low cadence on joint contribution to power. The purpose of this study was to investigate joint specific power production in recreational and elite cyclists during low- and moderate cycling at a range of different cadences, and to determine if a low cadence at moderate intensity could provide similar hip joint power and associated muscle activity as cycling at high intensity with a freely chosen cadence. **Method:** Ten recreational cyclists and nine elite cyclists performed cycling bouts at seven different pedalling rates and four intensities. Joint specific power was calculated from kinematic measurements and pedal forces using inverse dynamics. Muscle activity in gluteus maximus (GM) and vastus lateralis (VL) was measured using surface EMG. **Results:** A main effect of cadence and athlete level on the relative hip- and knee joint power was found. Increasing cadence led to increasing knee joint power and decreasing hip joint power, with the exception at low cadence (<60 rpm), where there was no effect of cadence. The elite group had higher relative hip joint power and lower relative knee joint power compared to the recreational group. The hip joint power at high intensity with a FCC did not differ to the hip joint power at moderate intensity with a low cadence (<60 rpm).

Discussion: The present study demonstrates that there is an effect of cadence on the hip- and knee joint contribution in cycling, however, the effect only occurs from 60 rpm and upward. It also demonstrates that there is a difference in joint contribution between elite- and recreational cyclists, and provide evidence for the possibility of achieving similar hip joint power at moderate intensity as at high intensity by altering the cadence. **Conclusion:** The results from the present study indicates that there is a difference in pedalling technique between recreational and elite cyclists, and that the effect of cadence on relative hip- and knee joint contribution is present only from and above 60 rpm.

Key Words: Joint specific power, Electromyography, Cycling, Cadence, Biomechanics, Pedalling

Acknowledgement

I would like to thank my supervisor Gertjan Ettema and my co-supervisor Knut Skovereng for their help and guidance. I would also like to thank everyone who participated in the study. Additionally, I would like to thank the employees at The Center for Elite Sport Research (SenTIF) and The Olympic Sports Center (region mid-Norway) for all the support and help.

TABLE OF CONTENTS

List of abbreviations

EMG = surface electromyography

FCC = freely chosen cadence

GM = gluteus maximus

HR = heart rate

Int_{55} = work rate (W) at 55% of LT.

Int_{85} = work rate (W) at 85% of LT.

Int_{LT} = work rate (W) at 100% of LT.

Int_{20min} = work rate (W) corresponding to 20 min all out

LT = work rate at lactate threshold, defined as Onset of Blood Lactate Accumulation (4 mMol)

nEMG = EMG normalized to a reference value equivalent to a work rate at LT with 60 rpm.

RPE = rate of perceived exertion

RPM = revolutions per minute

VL = vastus lateralis

W = watt

1. Introduction

The effect of cadence on cycling performance has been studied extensively with a majority of studies focusing on cycling energetics [1]. A number of studies have also focused on the effect of cadence on cycling technique and coordination [2-4]. These studies show that changing cadence leads to numerous technical responses, such as changes in muscle activation and force effectiveness [1, 5, 6].

A technical parameter that could provide insight into the coordination strategy during cycling is the analysis of the relative joint-moments distribution. Power delivered to the pedals are produced by muscles that pass the ankle-, knee- and hip-joint [7-11]. Inverse dynamics can be used to calculate the joint specific contribution to the total external work rate. This method of analysing the relative joint contribution in a lower limb activity during a cycling task was initially presented by Ericson et al. [12] who studied the percentage contribution of hip, knee and ankle joint power. Following the study by Ericson et al. other studies have investigated the effect of different factors on the joint contribution in cycling tasks. Two of the major factors that have been studied are cadence and work rate. Skovereng et al. [13] and Mornieux et al. [9] both showed that an increase in cadence led to a decrease in relative hip joint contribution and a increase in relative knee joint contribution, while there were no significant effect of cadence on the relative ankle joint contribution. McDaniel et al. [11] on the other hand showed that relative hip and knee joint powers were not influenced by cadence. The conflicting results with regard to relative hip power may be caused by a difference in the range of pedalling rates and work rate included in the different studies. While Skovereng et al. [13] and Mornieux et al. [9] studied pedalling rates up to 110 and 100 revolutions per minute (rpm) at moderate intensity, McDaniel et al. [11] included pedalling rates up to 180 rpm at a 3-sec maximal intensity. While the studies on the effect of cadence are conflicting, the studies reporting a change in relative joint power as a response to changes in workload seems to show consensus. Mornieux et al. [9] and Skovereng et al. [8] showed that an increase in work rate led to an increase in relative hip joint contribution and a decrease in relative knee joint contribution. This is supported by Elmer et al. [10] who found decreasing relative knee joint contribution with increasing work rate. There is a lack of studies evaluating the effect of athlete level on the joint specific power contribution in cycling.

Because cyclists train and compete over a broad range of different cadences and work rates it is important that the interplay between a change in either cadence or work rate on the one hand, and joint power on the other, is understood. A widely used training method for both elite and recreational cyclists where cadence is altered to facilitate a different stimulus is interval training at low cadence. This method is characterized by intervals at a moderate intensity with a pedalling rate as low as 40 rpm. Many studies have compared the effect of low-cadence and freely chosen cadence/high cadence interval training. The general conclusion is that low cadence interval training doesn't provide favourable improvements in cycling performance compared to interval training at freely chosen/high cadence [14, 15]. Thus, currently there is no strong evidence for a benefit of training at a low cadence [16]. Even though there is a lack of evidence, the method is widely used by some of the best road cyclists in the world. This may be because competitive cycling is a non-steady-state activity that is often performed with brief periods of low and high cadence and workload, and cyclists therefore may find it beneficial to incorporate specific low cadence training into their training program. Studying the effect of lowering the cadence below 60 rpm at different intensities on joint specific power could provide important information in the understanding of possible effects of low cadence interval training. The majority of training performed by cyclists is done at relatively low intensity [17], while it is expected that the outcome of cycling competitions is decided at high power outputs. Thus, the majority of training is performed at a work rate shown to demand less hip joint power than knee joint power [8], while races are won at near maximal intensity with a predominant contribution of the hip joint [7]. Examining the opportunity to produce high hip joint power at a low intensity could possibly present valuable information to cycling coaches and athletes.

To the author's knowledge, no previous studies have evaluated the joint specific power characteristic of top-level cyclist, nor are there any studies including pedalling rates lower than 60 rpm. The aim of the current study was therefore to investigate (1) joint-specific power production in recreational and elite cyclists during low- and moderate cycling at a range of different cadences and to (2) determine if a low cadence at moderate intensity could provide similar hip joint power as cycling at high intensity with a FCC.

2.0 Methods

2.1 Participants

Nineteen male cyclists (mean ± SD: age 31.4 ± 11.4 years; height 183.4 ± 5.7 cm; body mass 82.4 ± 16.1 kg) were recruited through several different cycling clubs in Norway. The cyclists were divided into two groups based on performance level. One group with elite riders (n=9; age 22.0 ± 1.6 years; height 182.6 ± 5.7 cm; body mass 73.4 ± 8.8 kg) defined as cyclists competing at continental and world tour level, and one group with recreational riders (n=10; age 39.8 ± 9.6 years; height 184.1 ± 5.8 cm; body mass 90.5 ± 17.4 kg) with previous cycling experience. The study was registered, and approved by Norwegian Social Science Data Services. Prior to obtaining written informed consent, the protocol and procedures were explained both in writing and verbally to each subject individually, and were also informed explicitly that they could withdraw at any time without giving any reason. The study was conducted in accordance with the Declaration of Helsinki.

2.2 Experimental protocol

The current protocol was part of a larger study. The subjects came to the laboratory for two occasions separated by a maximum of three days. The subjects performed a total of five different tests during the two days. Additional tests, not of relevance for this study included cycling at LT or lower intensities with a maximal duration of 4,5 minutes.

2.2.1 Lactate threshold test

The lactate threshold test was performed as 4-7 submaximal 5-min steps to identify the workload at 4 mMol/l, which was used to set the relative intensity used in the main test. All subjects started with 5 min cycling at 125 W with 50 W increments every 5 minutes until blood lactate exceeded 2 mMol/l. followed by increments of 25 W until blood lactate exceeded 4 mMol/l. Blood lactate was measured after 4:30 of each work load, and heart rate (HR) and rate of perceived exertion (RPE) using Borg's RPE scale [18] at the end of each workload. Freely chosen cadence (FCC) was used during the test. The external work rate corresponding to 4 mMol/l was used as lactate threshold (LT).

2.2.2 Normalization test

A normalization test was performed to set a normalization value for the EMG data. After warm-up and coming to a steady state the subjects performed a 30 sec interval at 60 rpm at a workload equivalent to LT. EMG was recorded continuously during the 30 sec intervals.

2.2.3 20-min all-out test

A 20-min all-out test was conducted to set a work rate for the high-intensity interval at the main test. The subjects were instructed to try to achieve an as high as possible mean power output for/during 20 minutes. The subjects were not allowed to use private power meters for pacing, thus the pacing was dependent on the subjects own feeling. Encouragement was given throughout the test. HR and power was recorded continuously during the entire test. Kinetic variables and EMG was measured in 30 sec intervals after 3, 8, 13 and 18 min. HR and RPE was measured after 3,8,13 and 18 min, and blood lactate was measured immediately after the test. HR, RPE and blood lactate was collected to be able to confirm that the 20-min test was actually all-out. Freely chosen cadence- and work rate was used.

2.2.4 Main test

The main test was performed to gather data for the analysis of joint power and muscle activity at different cadences and intensities. The main test started with 21 intervals of 60 sec containing 7 different cadences and 3 different intensities. The intervals between cadences at one intensity were separated by 30 sec cycling at 50% of LT with a FCC. The different intensities were completed in the following order: 55% (Int_{55}), 85% (Int_{85}) and100% (Int_{LT}) of a work rate (W) corresponding to the predetermined lactate threshold. The 7 different cadences included in this study were freely chosen, 100, 90, 80, 60, 50 and 40 rpm. All intensities started with FCC while the remaining 6 cadences were randomized using a cross-over design with one group going from low- (40 rpm) to high (100 rpm) cadence and one group from high- (100 rpm) to low (40 rpm) cadence. 30 min of active recovery at 50% of LT separated the different intensities. These 21 intervals were followed by a 30 sec interval at a work rate corresponding to the subjects mean power at the 20 min all-out test ($\text{Int}_{20\text{min}}$) with a FCC. HR and cadence was registered continuously during all intervals. Lactate and RPE was measured at the end of the last interval at every work rate. EMG, pedal forces and kinetic variables were measured for 30 sec of each cadence, totalling 22 measurements. A schematic presentation of the incremental protocol at day 2 is presented in figure 1. The subjects were instructed to remain seated with a stable and constant position with hands placed on the hoods while performing the intervals in order to provide accuracy in the calculation of changes in hip, knee and ankle angles. The participants were not informed about when the EMG and kinetic data were recorded.

2.2.5 Full protocol

The first day of testing started with measuring of height and body mass followed by a 20-min warm-up ride with freely chosen cadence and work rate. The warm-up was followed by the lactate threshold test. Following 5 additional minutes of active recovery the subjects performed a 20-min all-out test. The first day of testing ended with 5 min of active recovery.

The second day consisted of a normalization test, an additional test and the main test. After 20 min of warm-up at 50% of LT with FCC, the subjects conducted a normalization test. After 2 min of active recovery the subjects performed an additional test, and after 2 additional minutes of active recovery they performed the main test. The second day of testing ended with 5 min of active recovery.

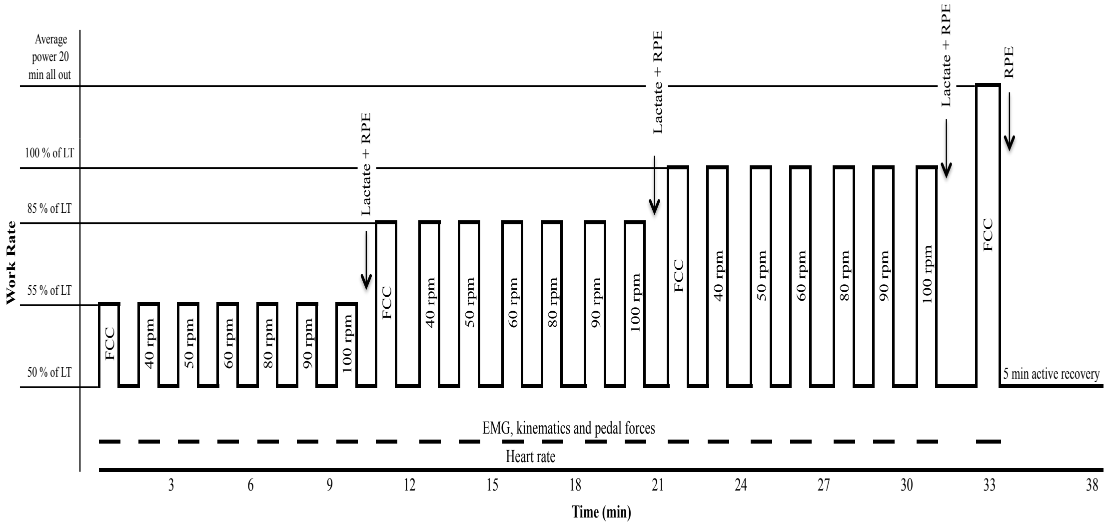

Fig. 1. Schematic presentation of the main test on test day 2. Heart rate, cadence and external work rate (from the indoor trainer) were measured continuously throughout the test, while EMG, kinematics and pedal forces were measured during 30 sec intervals.

2.3 Equipment and measurements

All measurements were performed in a laboratory with steady conditions (temperature ~22 ^{o}C and relative humidity ~45%). The tests were performed on an electronically braked, indoor cycle trainer (CompuTrainer^{TM}, RacerMate® Inc, Seattle, USA) with the participants personal road bicycles. The computrainer cycle trainer was chosen for its ability to select a constant power on a FCC. The rear wheel was pumped to a pressure of 7 bars for all participants. The cycle trainer was calibrated after 15 min according to the manufacturers instructions. Blood lactate was measured using the Biosen C-Line Sport lactate measurement system (EKF Industrial Electronics, Magdeburg, Germany). Heart rate was measured with a heart rate monitor (Polar M400, Polar Electro OY, Kempele, Finland).

Cycling kinematics was measured using an Oqus camera system (Qualisys, Sweden) with eight cameras located in a circle around the cycle trainer. The data was recorded at a sample rate of 100 Hz. Reflective markers was placed on the neck (cervical spine), pelvis (iliac crest), hip (greater trochanter), knee (lateral epicondyle), ankle (lateral malleolus) and on the front and back of custom made extensions placed symmetrically on the pedal axis. Surface electromyography (EMG) was recorded from the right leg with a Noraxon 16-channels TELEmyo Direct Transmission

System (Noraxon U.S.A Inc., Scottsdale, Arizona) using Noraxon HEX dual electrodes (bar dimension 10 mm, inter-electrode distance of 17,5 mm). The EMG data was collected at a sample rate of 1500 Hz. The skin over the included muscles was shaved and cleaned with skin cleansing wipes. The sensors were attached to the skin using adhesive tape and covered with additional tape to avoid sweat and movement artifacts on the signal. The muscles included in the study were gluteus maximus (GM) and vastus lateralis (VL). The sensors were placed over the muscle belly.

Pedal forces on day two were measured with custom pedals equipped with two force cells (Revere Model 9363, capacity 250 kg per cell, the Netherland). The pedals measured vertical and horizontal forces and recorded at a sample rate of 100 Hz. The pedals were calibrated by adding shear and normal forces using different weights (5,10,15,20,25 and 30 kg) fastened on the pedals in vertical and horizontal directions. A description of the force pedal system can be found in Ettema et al. 2009 [19].

2.4 Data analysis

Joint powers for the hip, knee and ankle joints were calculated using inverse dynamics for a linked system of rigid segments [19-21]. In short, the powers at the joints are calculated from the forces measured with the custom pedals, the movements of the body segments, and the inertial estimates (mass and moment of inertia) of these segments, by applying Newton's inertial laws. Guidelines for calculating masses and moments of inertia were taken from Van Soest et al. [22].

The raw EMG data was processed using root-mean-square analysis and the mean amplitude during the 30-second intervals was used in the normalization process. The data were normalized (nEMG) and are presented as a percentage of the amplitude at a work rate corresponding to LT with a cadence of 60 rpm. All raw EMG signals were visually inspected and evaluated before inclusion and abnormal signals was excluded from the study. An example of raw and root-mean-square processed signal is presented in figure 2.

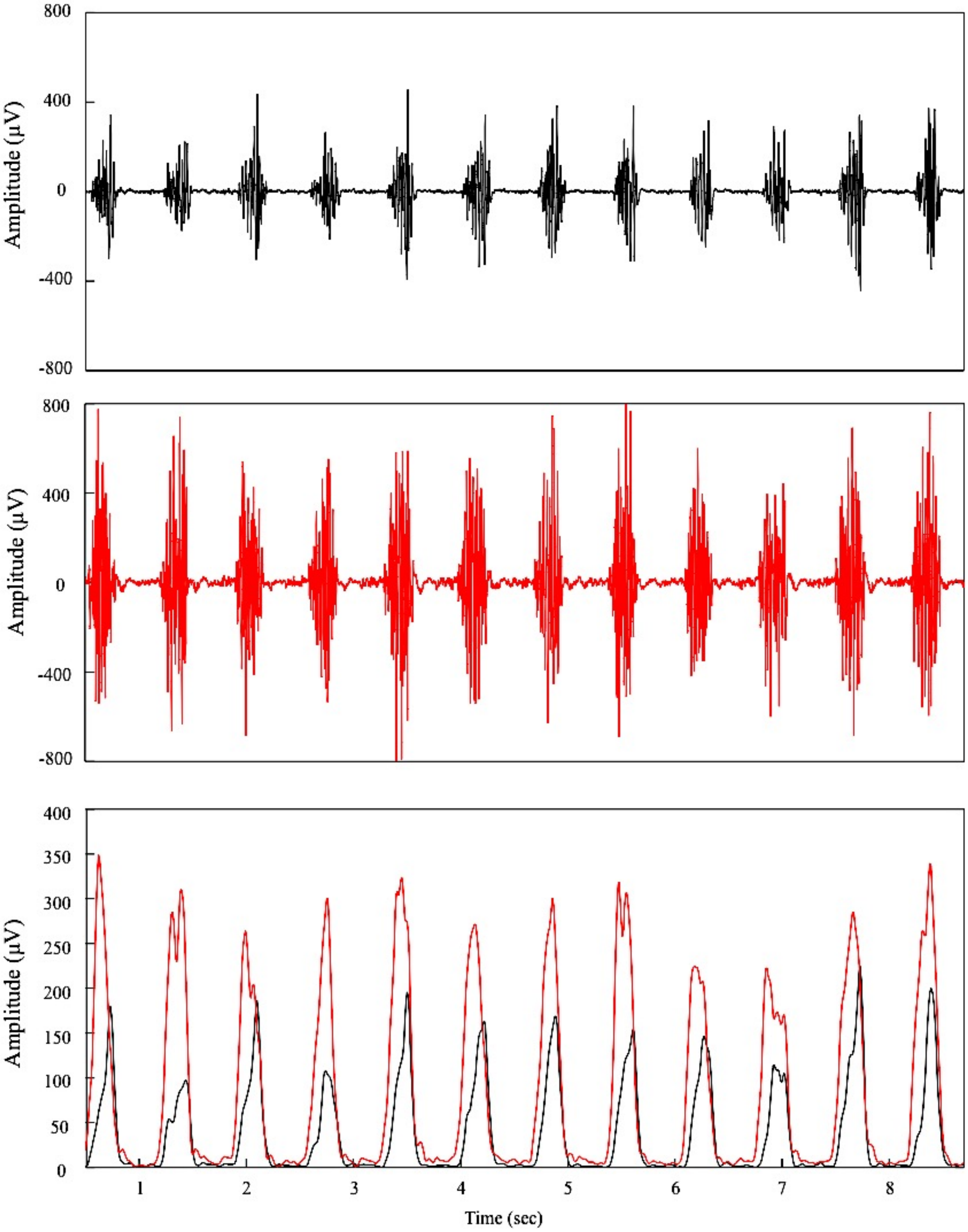

Fig. 2. Examples of raw and root-mean-square processed EMG signal containing twelve pedalling revolutions for GM (black) and VL (red).

2.5 Statistical analysis

All descriptive data are presented as mean ± standard error. A linear mixed model was used to evaluate the effect of cadence, intensity and athlete level on joint specific power and nEMG. Pairwise comparison was used to localise and evaluate the content of the effect. Paired sample t-test was used when comparing hip joint power at moderate intensity with a low cadence (<60 rpm) to the hip power at Int_{20min} with FCC and when assessing the differences between joints. Statistical significance was accepted at $p < 0.05$. All statistical analysis was conducted using SPSS 24.0 (SPSS, Chicago, USA) for mac and Matlab R2015b (joint power) and Matlab R2016b (EMG) (MathWorks Inc. Natic, USA).

3.0 Results

The subject characteristics are presented in table 1. The elite group had significantly lower age and weight, and a higher LT and 20-min all-out power compared to the recreational group. Tables 2 and 3 show the measured and target work rate and cadences at the different intervals in the main test. A significant ($p<0.05$) difference was found between the work rates across the different pedalling rates at low intensity (Int_{55}). The difference in power at the different pedalling rates on the other intensities was very small with a maximal deviation from target work rate of 3% (Int_{85}) and 5% (Int_{LT}) (Table 2). The subjects' actual cadence was not significantly different from the target cadence at any of the measurements (Table 3). There was no significant effect of cadence order on joint power; however, there was a significant effect of cadence order on nEMG activity in both muscles ($p<0.05$). Further analysis revealed a trend where the group starting with a high cadence (100 rpm) and ending with a low cadence (40 rpm) had elevated muscle activity throughout the whole intensity bout compared to the group starting with a low cadence (40 rpm). On the other hand, the group starting at low cadence (40 rpm) had a lower muscle activity throughout the entire intensity compared to the group starting at high cadence (100 rpm). The values from the normalization test differed from the values at the main test even though the cadence and work rate was similar (60 rpm, LT). This may be related to the order of the different tests in the protocol.

Table 1: Subject characteristics

	Elite	Recreational
n	9	10
Age (years)	22.0 (0.5, 19.0-24.0)	39.8 (3.0, 25-51)
Weight (kg)	73.4 (2.8, 62.4-90.1)	90.5 (5.5, 73.4-132.5)
Height (cm)	182.6 (1.9, 173-190)	184.1 (1.8, 174.5-193)
HR_{max} self-reported (bpm)	201.4 (1.6, 190-205)	192.6 (1.8, 180-200)
WR_{LT} (W)	314.8 (8.0, 278.0-345.2)	237.4 (13.8, 125.0-286.2)
WR_{LT} (W/kg)	4.3 (0.2, 3.7-4.9)	2.7 (0.2, 0.9-3.5)
20-min all-out (W)	364.1 (8.7, 331-404)	263.1 (12.6, 184-329)
20-min all-out (W/kg)	5.0 (0.2, 4.4-5.6)	3.0 (0.2, 1.4-4.0)

Mean (SE, range) for subject characteristics. WR_{LT} = work rate in watt at lactate threshold.

Table 2. Measured work rate (W) presented as mean ± SE for all intervals

	WR Int_{55}	WR Int_{85}	WR Int_{LT}	WR $Int_{LT20min}$
Target WR	150.7 ± 6.7	232.9 ± 10.3	274.0 ± 12.1	310.9 ± 14.1
Cad_{40}	137.5 ± 6.2	239.4 ± 11.5	289.1 ± 13.8	
Cad_{50}	141.9 ± 6.9	239.9 ± 11.8	286.3 ± 12.3	
Cad_{60}	143.1 ± 6.8	235.3 ± 10.4	281.4 ± 12.4	
Cad_{80}	149.7 ± 5.5	234.6 ± 9.9	277.5 ± 11.8	
Cad_{90}	154.7 ± 5.2	236.2 ± 9.5	279.2 ± 11.1	
Cad_{100}	160.6 ± 4.8	241.2 ± 9.6	282.3 ± 10.7	
Cad_{FCC}	154.3 ± 6.0	240.2 ± 10.8	282.4 ± 11.7	322.0 ± 14.7
Mean	148.8 ± 5.9	238.1 ± 10.4	282.6 ± 12.0	322.0 ± 14.7

Table 3. Measured cadence (rpm) presented as mean ± SE for all intervals

	Int_{55}	Int_{85}	Int_{LT}	$Int_{LT20min}$	Mean
Cad_{40}	41.0 ± 0.2	40.7 ± 0.2	40.5 ± 0.3		40.8 ± 0.2
Cad_{50}	51.0 ± 0.2	50.5 ± 0.2	50.7 ± 0.2		50.7 ± 0.2
Cad_{60}	60.9 ± 0.2	60.6 ± 0.3	60.5 ± 0.2		60.7 ± 0.2
Cad_{80}	80.2 ± 0.2	79.8 ± 0.1	79.9 ± 0.2		80.0 ± 0.2
Cad_{90}	89.8 ± 0.1	89.7 ± 0.2	89.8 ± 0.2		89.8 ± 0.2
Cad_{100}	99.7 ± 0.2	99.5 ± 0.2	99.7 ± 0.3		99.6 ± 0.2
Cad_{FCC}	90.0 ± 1.8	82.8 ± 1.8	86.0 ± 2.5	90.3 ± 2.7	87.3 ± 2.2

3.1 Effect of pedalling rate

The effect of cadence on absolute- and relative joint power is presented in figure 3 and 4, respectively. The hip joint was the main power producer at low cadence (<60 rpm) at all intensities with significantly higher ($p<0.05$) joint power than the knee- and ankle joint. At high cadence (>80 rpm) the knee joint was the main power-producing joint with a significantly higher ($p<0.05$) joint power than the hip and ankle joint. The ankle joint produced significantly ($p<0.05$) less power than the other two joints at all cadences. The joint power ranged from 33.1 to 129.9 W (20.9 to 50.4% of net power) for the hip joint, 49.4 to 147.1 W (37.1 to 70.1% of net power) for the knee joint and 12.8 to 41.4 W (9.0 to 15.4% of net power) for the ankle joint between 40 and 100 rpm, respectively.

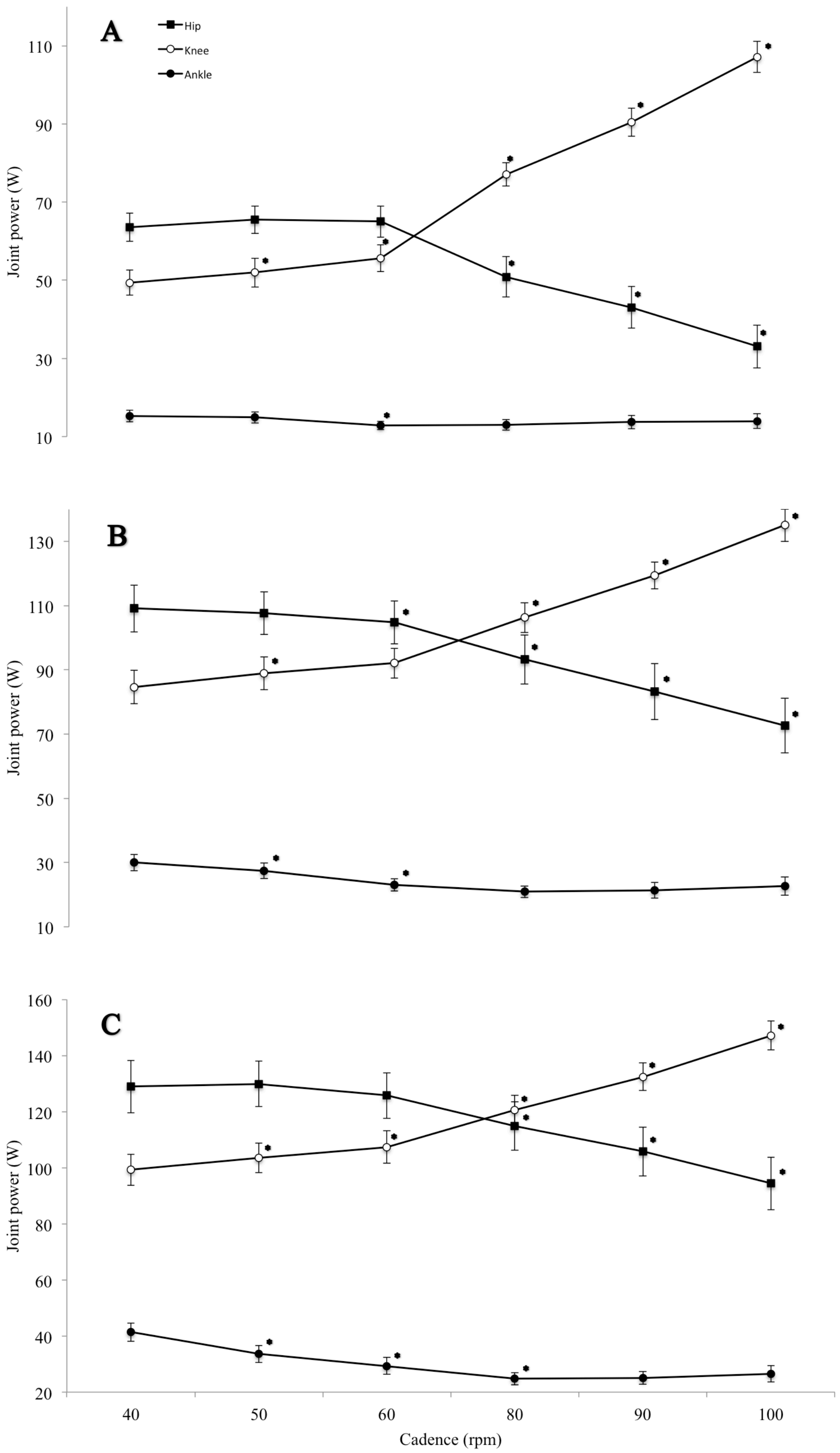

Fig. 3. Group mean and standard error for total joint power in hip (square), knee (open circle) and ankle joint (filled circle) at Int$_{55}$ (A), Int$_{85}$ (B) and Int$_{LT}$ (C). *Asterisk* indicate a significant change in joint power from previous cadence (p<0.05).

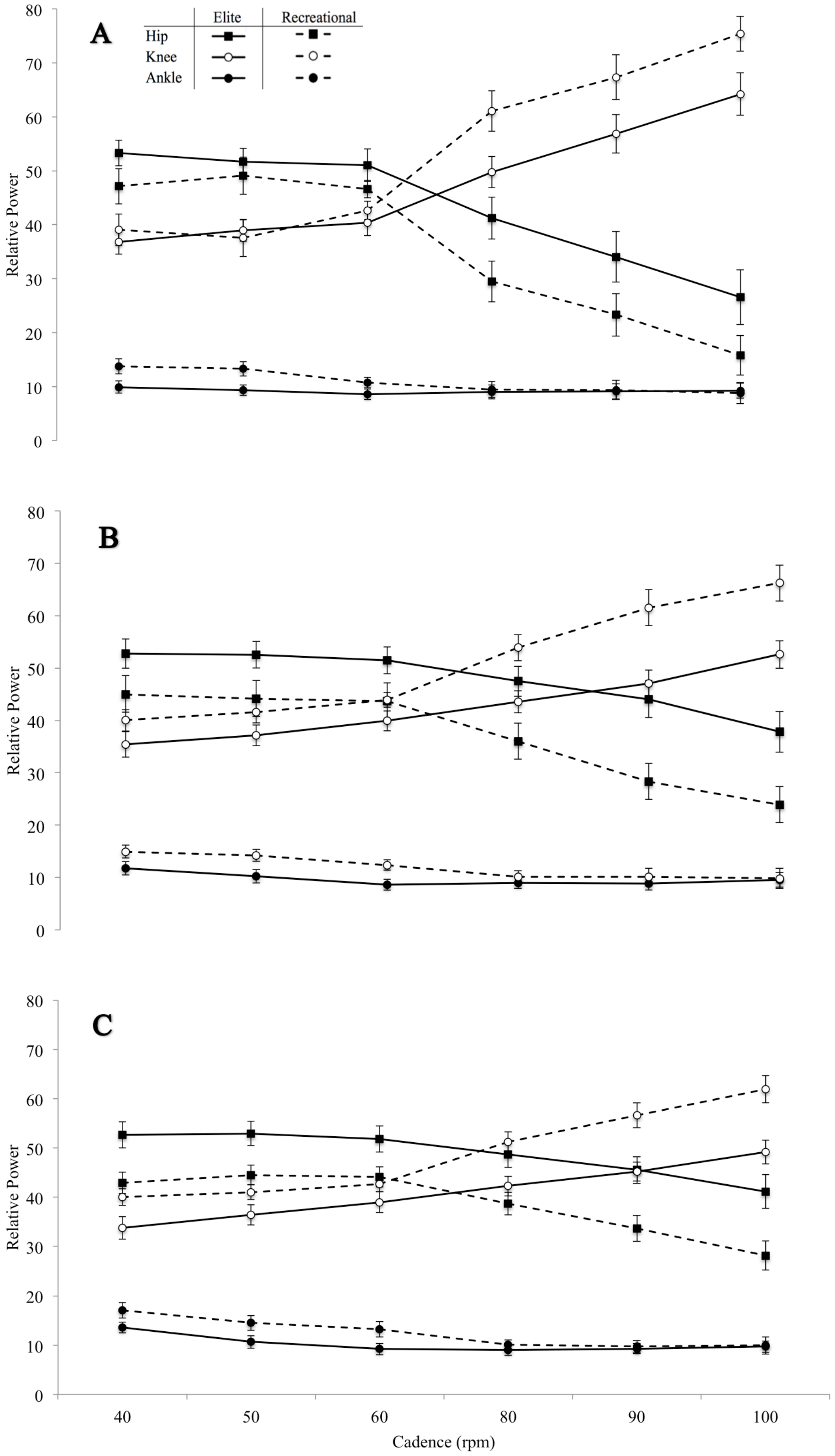

Fig. 4. Group mean and standard error for relative joint power in hip, knee and ankle joint at Int$_{55}$ (A), Int$_{85}$ (B) and Int$_{LT}$ (C) for elite and recreational cyclists.

Because external power was not identical at the different cadences it need to be accounted for. This was done by statistically comparing relative joint power (normalised for absolute external power) rather than using absolute power as a covariant in the analyses. A main effect of cadence on the relative hip- (F(5,306) = 105.96, p = <0.001), knee- (F(5,301) = 150.08, p = <0.001) and ankle joint power (F(5,316) = 33.09, p = <0.001) was found. A stepwise increase in cadence led to a decrease in relative hip joint power and an increase in relative knee joint power (all p<0.05), with the exception of neighbouring cadences up to 60 rpm where there was no significant effect of cadence. Pairwise comparisons revealed a statistically insignificant trend with an increase in cadence leading to a decrease in ankle joint power at low cadence (<60) rpm). There was a significant interaction effect of cadence and intensity on both the relative hip- (F(10,306) = 6.59, p = <0.001) and knee joint contribution (F(10,301) = 5.97, p = <0.001), thus, the effect of cadence was different between the three intensities. An interaction effect of cadence and athlete level was found for the relative knee joint contribution (F(5,301) = 8.14, p = <0.001), where the effect of cadence was larger for the recreational group as seen in figure 4. No interaction effect was found on the relative ankle joint contribution.

The effect of cadence on nEMG is presented in figure 5. There was no significant effect of cadence on GM activity. A significant main effect of cadence on VL activity was found (F(5,274) = 8.46, p = <0.001). An increase in cadence led to an increase in VL activity where the muscle activity was significantly (p<0.05) higher at high cadence (>80 rpm) compared to low cadence (<60 rpm). An interaction effect of athlete level on cadence (F(5,274) = 3.61, p = 0.004) was found, and further analysis revealed a trend where the recreational group had a greater increase in VL activity with a stepwise increase in cadence above 60 rpm.

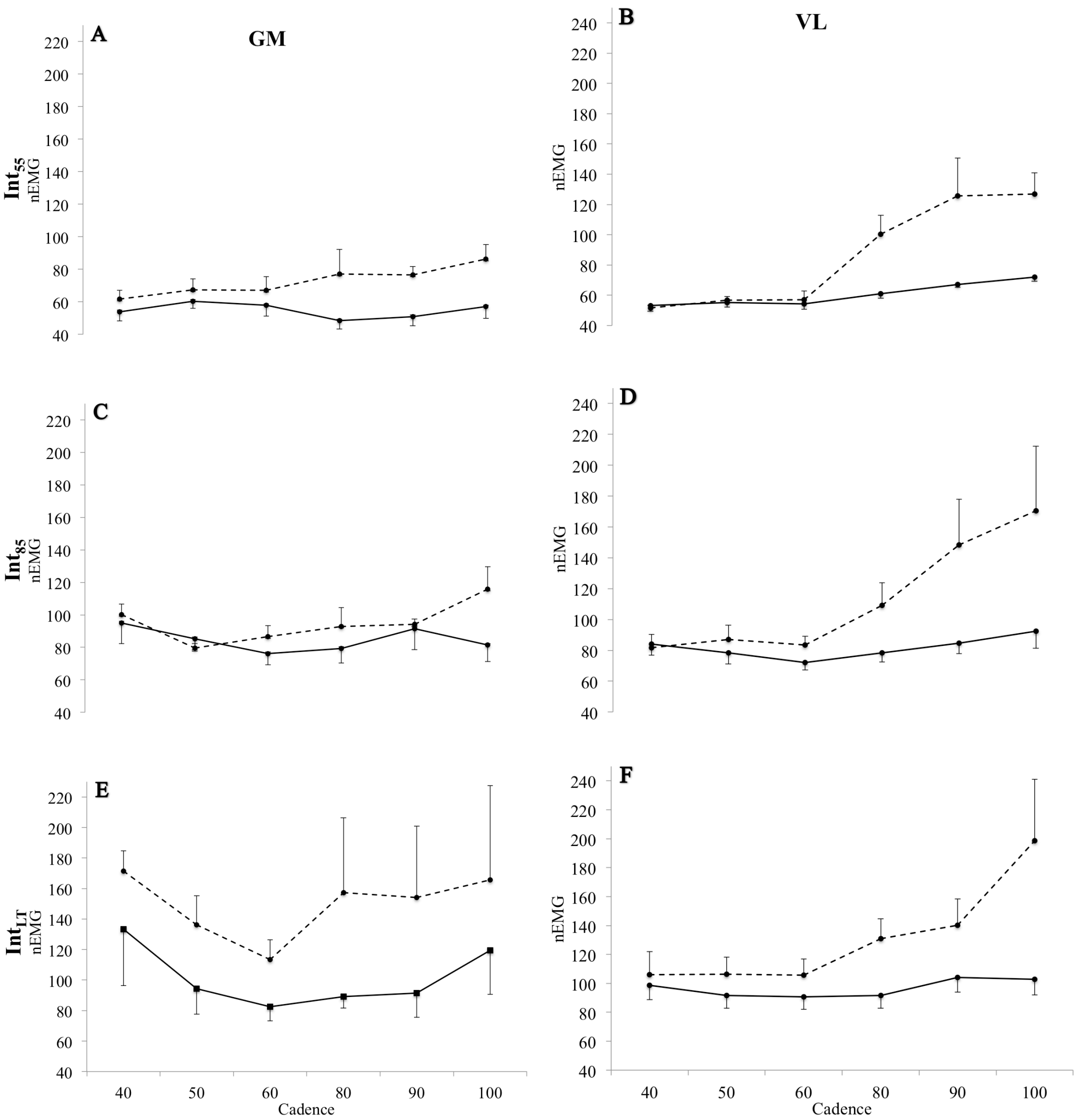

Fig. 5. Group mean and standard error for nEMG in GM (A, C and E) and VL (B, D and F) at Int_{55}, Int_{85} and Int_{LT} for elite (solid line) and recreational (dashed line) cyclists.

3.2 Effect of intensity

A main effect of intensity on the relative hip- (F(2,306) = 15.58, p = <0.001), knee- (F(2,301) = 27.26, p = <0.001) and ankle joint contribution (F(2,316) = 9.03, p = <0.001) was found. The relative hip joint power at low intensity (Int_{55}) was lower than at moderate intensity (Int_{85} and Int_{LT}) ($p<0.05$), while there was no significant difference between Int_{85} and Int_{LT}. An increase in intensity led to a decrease in relative knee joint contribution ($p<0.05$). Increases in intensity led to an increase in ankle contribution were Int_{55} was higher than Int_{85} and Int_{LT} ($p<0.05$), while there was no difference between Int_{85} and Int_{LT}.

An main effect of intensity on both GM activity (F(2,177) = 31.97, p = <0.001) and VL activity (F(2,274) = 21.09, p = <0.001) was found, with an increase in intensity leading to an increase in GM- and VL activity ($p<0.05$). Main results from the main test on day 2 are presented in appendix 1.

3.3 Effect of athlete level

The effect of athlete level on relative joint power is presented in figure 4. There was a main effect of athlete level on both the relative hip- (F(1,17) = 8.61, p = 0.009) and knee- (F(1,17) = 9.35, p = 0.007) joint contribution. The elite group had higher relative hip joint contribution, and lower relative knee joint contribution at all cadences and intensities compared to the recreational group ($p<0.05$), with one exception in relative knee joint power at Int_{55} with 50 rpm. There was no effect of athlete level on the relative ankle joint contribution.

A main effect of athlete level was found on the muscle activity in both GM (F(1,177) = 19.17, p = <0.001) and VL (F(1,274) = 16.75, p = <0.001). The recreational group had higher GM- and VL activity at all cadences compared to the elite group ($p<0.05$). An interaction effect of athlete level on intensity was found (F(2,177) = 5.18, p = 0.006) indicating a different effect of intensity on GM activity between the two groups. The recreational group experienced a significant ($p<0.05$) increase in GM activity when increasing intensity from Int_{85} to Int_{LT}, while no effect was found in the elite group.

3.4 Hip joint power and the effect of work rate and pedalling rate

The relationship between the hip joint power at Int_{20min} with FCC and the hip joint power at low- and moderate intensity with low cadence (<60 rpm) is presented in figure 6. The total joint power at Int_{20min} was 256.86 (± 11.76) W for the recreational group and 355.98 (± 11.01) W for the elite group, where the hip joint contributed with a total of 96.76 (± 6.85) W equivalent to 37.7% in the recreational group and 172.01 (± 11.74) W equivalent to 48.3% in the elite group. For the recreational group, the hip joint power at three of the nine low cadence (<60 rpm) intervals at the main test was significantly different from the hip joint power at Int_{20min}. The hip joint power at cad_{40}, cad_{50} and cad_{60} at Int_{85} and Int_{LT} was not significantly different to Int_{20min}, despite the external power being an average of 10.2 and 32.1% lower than the external power measured at the Int_{20min} interval, respectively. In the elite group, seven of the nine low cadence (<60 rpm) intervals at the main test were significantly different from the hip joint power at Int_{20min}. However, cad_{40} and cad_{50} at Int_{LT} were not significantly different to Int_{20min} despite the external power being an average of 13.8% lower than the external power at the Int_{20min} interval.

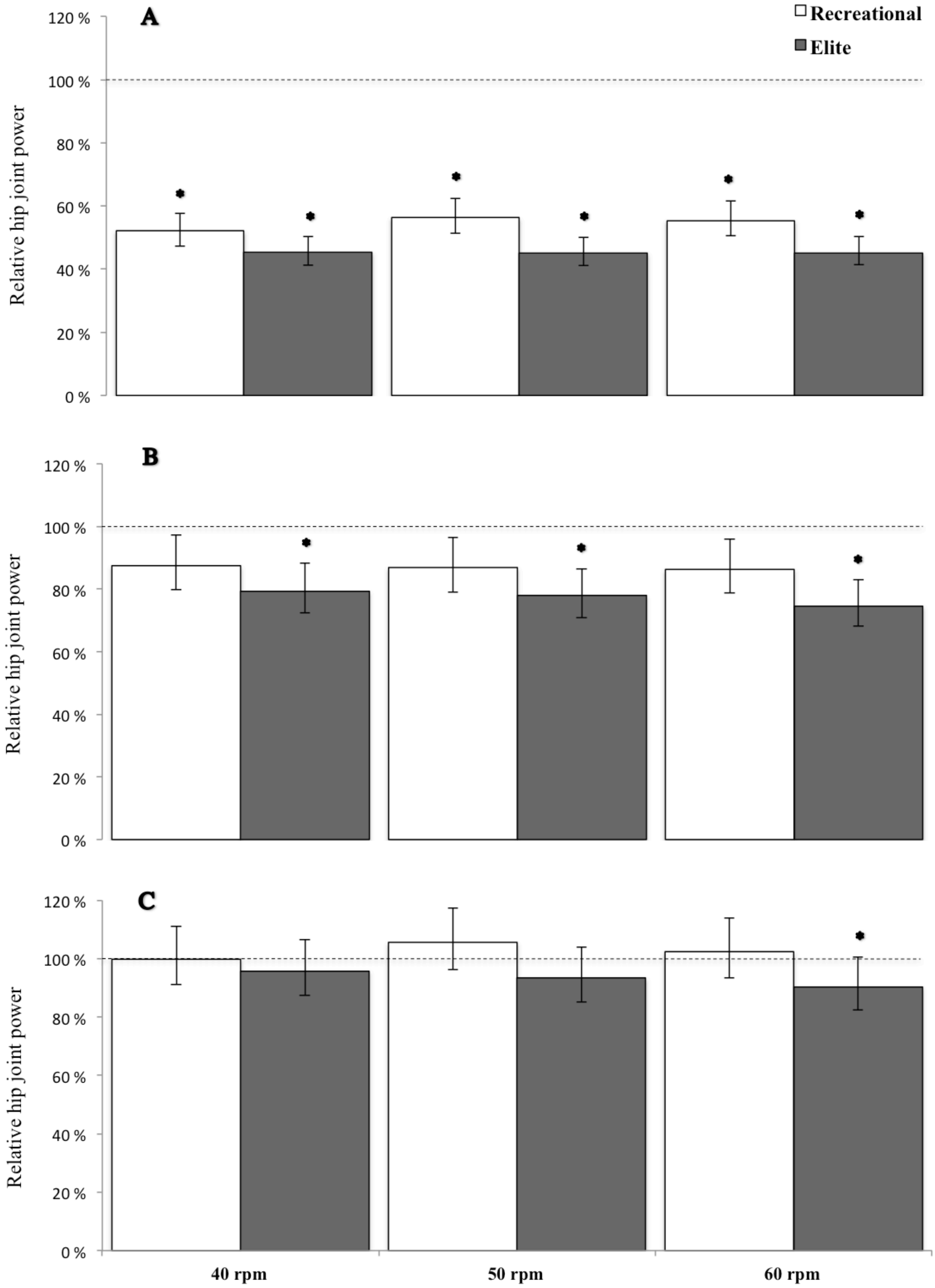

Fig. 6. Group mean and confidence interval for relative hip joint power with three different pedalling rates at Int_{55} (A), Int_{85} (B) and $\mathrm{Int}_{\mathrm{LT}}$ (C) compared to net hip joint power at $\mathrm{Int}_{20\mathrm{min}}$ with FCC (100%, dashed line) for recreational (white) and elite (grey) cyclists. *Asterisk* indicates a significant difference in hip power compared to hip power at $\mathrm{Int}_{20\mathrm{min}}$.

4.0 Discussion

The purpose of this study was to investigate joint-specific power production in recreational and elite cyclists during low- and moderate cycling at a range of different cadences, and to determine if a low cadence at moderate intensity could provide similar hip joint power as cycling at high intensity with a FCC. The main findings of this study were that an increase in cadence leads to a decrease in relative hip joint power and an increase in relative knee joint power. However, the effect of cadence on the relative hip- and knee joint power only occurred from and above 60 rpm. Elite cyclists have higher relative hip joint contribution and lower relative knee joint contribution at all cadences and intensities compared to recreational cyclists, with one exception for relative knee joint power at Int_{55} with 50 rpm. There was no statistically difference between the hip joint power at Int_{85} and Int_{LT} with low cadence ($\leq$ 60 rpm) for the recreational group, and Int_{LT} (cad_{40} and cad_{50}) for the elite group, compared to Int_{20min} with a FCC. Thus, it is possible to achieve similar hip joint power with a moderate intensity and a low cadence (<60 rpm) as with a high intensity at a FCC. However, the difference in external power between the moderate- and the high intensity was relatively small and this finding was not reflected in the GM activity.

The participants used their own road bikes on a stationary trainer during testing. This was done to avoid a potential effect of changing bike geometry. Based on studies showing increased muscle activity in quadriceps and hamstrings when saddle height is lowered from "optimal" height [23], one could possibly expect an effect of saddle height on the joint contribution as well. The work rate between the six included cadences differed within the respective intensities (table 2). This was caused by difficulties with the resistance on the stationary trainer as an effect of including extremely low cadences. The main discrepancy was found at low intensity (Int_{55}) and should therefore not account for the effects of cadence found at moderate intensity in this study. A randomized cross-over design was used to avoid a potential effect of the order of the included cadences in the main test. The results indicated that there was an effect of cadence group (with different order) on the muscle activity in both muscles. Further analysis revealed a trend where the group starting with a high cadence (100 rpm) and ending with a low cadence (40 rpm) had elevated muscle activity throughout the whole intensity compared to the group starting with a low cadence (40 rpm).

Although the effect was significant and the group starting with a high cadence had an average of 21% higher nEMG, the influence on the results is still relatively small. The cross-over randomization in the present study is warranted to achieve valid results. The effect of cadence order found in this study caused a larger variation in nEMG without affecting the mean outcome. Thus, causing less statistical power but valid results. Still, the results emphasises the importance of carefully evaluating the protocol when interpreting EMG data in cycling tasks.

4.1 Effect of pedalling rate

The results regarding the effect of cadence on relative hip- and knee joint power complies with earlier research [9, 13], with the exception of the effect at low cadence (<60 rpm). It was expected that the effect of lowering the cadence on relative hip- and knee joint power found in the present- and previous studies [9, 13] would continue below 60 rpm. My hypothesis that there should be an effect of further decreasing the cadence below 60 rpm on the relative joint contribution in cycling is based on previous research on joint contribution and on the rider's own feeling. Skovereng et al. [13] and Mornieux et al. [9] both found increasing hip joint power and decreasing knee joint power with decreasing cadence. Neither of the aforementioned studies indicated that the effect of cadence would level off at 60 rpm, thus, the results were unanticipated. Also, conversations with high-level athletes performing low cadence interval training regularly indicated a feeling of increased hip joint power when cadences is lowered from 60 to 40 rpm, which is in contradiction to the results found in this study.

Additionally, the relative ankle joint power decreased when cadence increased (<80 rpm). The effect of cadence on the relative ankle joint contribution is interesting since earlier research has shown no significant effect of cadence on the ankle joint power [9, 13]. Largest effect of cadence on relative ankle joint contribution was found at low cadence (< 60 rpm). None of the studies that reported no effect of cadence have included pedalling rates below 60 rpm and this may potentially explain the differences in results.

In accordance with the changes in joint power, the muscle activity in the VL (knee extensor) increased with increasing cadence above 60 rpm. These results regarding the effect of cadence on VL activity comply with other research that has shown an increased activity in knee extensor muscles when cadence is increased [5]. This is also reflected in the knee joint power, where an increase in cadence led to increased knee joint power for both groups, but with a larger increase in the recreational group. The hip joint power findings are not reflected in GM activity as no effect of cadence on GM activity was found in this study. This is surprising since previous studies have shown increasing GM activity with increasing cadence [5, 24]. GM is a major hip extensor and an increase in GM activity would be expected with increasing hip joint power. The lack of an effect of cadence on GM activity may be related to the low number of included subjects due to measurement errors. Only eleven subjects had GM data that were included in the study and this possibly made it difficult to achieve a significant effect. The results show a non-significant trend of increased GM activity with increased cadence above 60 rpm, however, there is a trend of decreasing GM activity with increasing cadence at low cadence (below 60 rpm) at moderate intensity. The trend showing decreasing GM activity with increasing cadence at low cadence (<60 rpm) at moderate intensity is interesting because no effect of cadence were found on the hip joint power at low cadence (<60 rpm). An effect of lowering the cadence below 60 rpm would possibly provide a different training stimulus from low cadence interval training. More research is needed to fully understand the effect of low cadence (<60 rpm) on GM activity.

4.2 Effect of intensity

This is to the author's knowledge the first study examining joint specific power where the subjects use a relative intensity which is unique to the subject's own performance level. The results regarding the effect of intensity on relative hip- and knee joint power complies with previous research [8, 9]. While other studies haven't found an effect of work rate on the relative ankle joint contribution, this study shows that increasing intensity leads to an increase in relative ankle joint contribution. The largest effect of intensity was found at low cadence (<60 rpm), thus may the contradicting findings be caused by the difference in the range of the included cadences. Interestingly, there was no significant effect of increasing intensity from

Int_{85} to Int_{LT} on the relative hip- and ankle joint contribution. Similar results were also found by Elmer et al. [10] who found no effect of increasing external work rate from submaximal to maximal on the relative hip extension power in cyclists. This may indicate that there is an upper limit for the effect of intensity on relative joint contribution. To date there are no studies that include a wide enough range of different work rates to conclude on the matter. Taken together, the current findings indicate that an increase from low- to moderate intensity leads to a shift in technique with a greater contribution from the hip joint and decreasing contribution from the knee joint. However, the effect of increasing intensity from moderate to high and maximal needs more research.

Increasing intensity led to an increase in muscle activity in the included muscles (GM, VL). This increase in muscle activity was expected as the joint power in the hip- and knee joint increased. Previous studies have shown increased muscle activity in GM [25] and VL [25, 26] when work rate is increased. Taken together, the results regarding the effect of intensity on muscle activity was as expected.

4.3 Effect of athlete level

This is to the author’s knowledge the first study to report an effect of athlete level on relative joint power in cycling. The elite group had higher relative hip joint contribution and less relative knee joint contribution compared to the recreational group. The results regarding the effect of athlete level on relative hip- and knee joint contribution was unanticipated. Numerous studies have provided evidence that repeated performance of a movement task could facilitate neuromuscular adaptations which could result in a more skilled movement [27, 28]. Chapman et al.’s [29] findings suggest that highly trained cyclists exhibit more skilled muscle recruitment as a result of neuromuscular adaptations compared to novice cyclists. The difference in joint specific power and muscle activity between the recreational- and elite group in my study could possibly be explained by the difference in task experience and movement skill among the athletes. At the same time, it is surprising that an effect of athlete level on the muscle activity was found when using EMG data that is normalized. The differences in muscle activity between the groups could also possibly be caused by fatigue in the recreational group. Studies have found increased EMG amplitude as a result of fatigue causing one or more of the following responses: recruitment of additional motor units, increased firing frequency and/or synchronization of motor recruitment [5]. The protocol on test day 2 was comprehensive, and while the normalization test was done at the start of the protocol, the main test was performed at the end of test day 2. The strain from the additional tests may therefore have accounted for the increase in muscle activation found in the recreational group in this study. This may be caused by a different degree of fatigue between the groups at the start of the main test. However, the cross-over design ensures that these differences remain unimportant to the main research question.

Care should be taken when interpreting the differences between the groups in this study, as there is a lack of information about the riders past experience with training at a locked cadence different from FCC. If high experience with the cycling task itself or experience with training at a range of different cadences is the underlying explanation could therefore not be established. These results underline the importance of knowledge regarding athlete experience when conducting studies on technique in pedalling tasks.

4.4 Hip joint power and the effect of work rate and pedalling rate

This is to the author's knowledge the first study to present the possibility of achieving similar hip joint power at a moderate intensity (Int_{85} and Int_{LT}) with a low cadence (<60 rpm) as at high intensity (Int_{20min}) with a FCC. This despite that the intervals where the hip joint power did not significantly differ to that found at Int_{20min} had a 10.2 and 32.1% lower power output for the recreational group, and 13.8% lower power output for the elite group. However, as I expected a continuous effect of lowering the cadence below 60 rpm on the hip joint contribution at the different intensities I would have expected it to be possible to achieve the high intensity hip joint power at an even lower intensity than found in this study. The difference between the moderate intensity (Int_{LT}) and the high intensity (Int_{20min}) is significant, but small. If a similar hip joint power could be achieved at low intensity (Int_{55}) as at high intensity (Int_{20min}) one could argue that low cadence interval training could be a way of training the muscles that pass the hip joint without some of the physiological demands from high intensity training. Even though the results from the nEMG indicated a trend of increased GM activity at 40 rpm compared to 60 rpm at moderate intensity, the GM- activity at all intensities with low cadence (<60 rpm) were lower than the activity found at high intensity with a FCC (appendix 1). This indicates that care should be taken when taking the results from the currents study into the field of best practice. To conclude on the matter; it is possible to achieve similar hip joint power at moderate intensity as at high intensity by altering cadence. However, if only the hip joint power is taken into account, the lack of an effect of reducing cadence below 60 rpm mean that low cadence training should possibly be limited to approximately 60 rpm. This may provide evidence that could prove important to researchers, coaches and athletes.

5.0 Conclusion

Increasing cadence leads to a decrease in relative hip joint power and an increase in relative knee joint power, however, the effect of cadence only occurred from and above 60 rpm. Elite cyclists have higher relative hip joint contribution and lower relative knee joint contribution at all cadences and intensities compared to recreational cyclists. These finding indicate that there is a difference in the pedalling technique between recreational and elite cyclists. The study also indicate that there is a possibility of achieving similar hip joint power at a moderate intensity with a low cadence (<60 rpm) as at high intensity with a FCC, however, the difference in work rate is minor and the finding is not reflected in the GM activity. The lack of an effect of lowering the cadence below 60 rpm could have implications for how low cadence training is performed. The findings from the present study provide further knowledge about the differences in joint specific contribution among recreation and elite cyclists.

6.0 References

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Appendix

Appendix 1. Group mean and standard error for total joint power, relative joint power and normalized EMG

Target cadence (rpm)			40	50	60	80	90	100	FCC
Int$_{55}$	Hip *n=19*	Total	63.54 ± 3.63	65.47 ± 3.48	65.00 ± 3.99	50.89 ± 5.16	43.07 ± 5.35	33.07 ± 5.49	44.03 ± 5.38
		Relative	50.05 ± 2.13	50.36 ± 2.13	48.71 ± 1.68	35.04 ± 2.97	28.41 ± 3.22	20.90 ± 3.24	29.49 ± 3.05
	Knee *n=19*	Total	49.38 ± 3.18	51.97 ± 3.70	55.62 ± 3.39	77.10 ± 2.98	90.47 ± 3.61	107.16 ± 4.02	89.96 ± 4.40
		Relative	37.99 ± 1.84	38.21 ± 2.00	41.59 ± 1.43	55.73 ± 2.68	62.36 ± 2.95	70.10 ± 2.77	61.66 ± 2.47
	Ankle *n=19*	Total	15.26 ± 1.48	14.88 ± 1.41	12.81 ± 1.07	13.00 ± 1.42	13.67 ± 1.68	13.97 ± 1.90	12.99 ± 1.69
		Relative	11.96 ± 1.01	11.43 ± 0.95	9.70 ± 0.73	9.23 ± 0.99	9.23 ± 1.11	9.00 ± 1.19	8.86 ± 1.09
	Gluteus M. *n = 11*		57.37 ± 3.93	63.60 ± 3.88	61.98 ± 5.23	61.38 ± 8.30	62.56 ± 5.47	70.23 ± 7.03	68.38 ± 5.01
	Vastus L. *n = 15*		52.49 ± 2.11	55.97 ± 1.97	55.54 ± 3.18	79.32 ± 7.86	94.47 ± 13.64	97.65 ± 9.73	93.84 ± 8.34
Int$_{85}$	Hip *n=19*	Total	109.14 ± 7.31	107.70 ± 6.70	104.77 ± 6.65	93.26 ± 7.65	83.20 ± 8.73	72.64 ± 8.47	98.23 ± 8.27
		Relative	48.69 ± 1.91	48.16 ± 1.98	47.36 ± 1.69	41.44 ± 2.32	35.79 ± 3.07	30.50 ± 3.02	42.90 ± 2.50
	Knee *n=19*	Total	84.65 ± 5.16	88.97 ± 5.12	92.13 ± 4.66	106.33 ± 4.67	119.38 ± 4.21	135.05 ± 5.04	109.19 ± 6.12
		Relative	37.86 ± 1.63	39.47 ± 1.47	42.02 ± 1.22	49.00 ± 2.01	54.70 ± 2.72	59.80 ± 2.68	48.14 ± 2.12
	Ankle *n=19*	Total	29.98 ± 2.50	27.44 ± 2.39	23.01 ± 1.90	20.93 ± 1.81	21.36 ± 2.42	22.69 ± 2.90	20.09 ± 1.98
		Relative	13.45 ± 0.95	12.36 ± 0.97	10.62 ± 0.83	9.56 ± 0.80	9.51 ± 1.04	9.71 ± 1.20	8.96 ± 0.85
	Gluteus M. *n = 11*		97.32 ± 7.19	82.67 ± 4.22	80.87 ± 4.94	85.50 ± 7.13	92.74 ± 6.94	97.04 ± 9.56	95.30 ± 6.33
	Vastus L. *n = 15*		82.99 ± 5.47	82.47 ± 5.72	77.40 ± 3.85	92.65 ± 8.36	114.30 ± 16.07	128.71 ± 22.21	94.50 ± 6.87
Int$_{LT}$	Hip *n=19*	Total	128.91 ± 9.33	129.92 ± 8.19	125.75 ± 8.14	114.92 ± 8.67	105.80 ± 8.73	94.43 ± 9.40	114.52 ± 8.93
		Relative	47.54 ± 2.03	48.49 ± 1.82	47.48 ± 1.85	43.45 ± 2.07	39.29 ± 2.31	34.32 ± 2.66	42.79 ± 2.39
	Knee *n=19*	Total	99.24 ± 5.51	103.43 ± 5.25	107.36 ± 5.79	120.53 ± 5.21	132.44 ± 4.88	147.12 ± 5.17	126.74 ± 6.68
		Relative	37.07 ± 1.56	38.83 ± 1.33	40.92 ± 1.32	47.00 ± 1.73	51.21 ± 2.06	55.87 ± 2.33	47.91 ± 1.98
	Ankle *n=19*	Total	41.38 ± 3.25	33.61 ± 3.03	29.34 ± 2.97	24.77 ± 2.16	25.11 ± 2.31	26.54 ± 2.90	24.71 ± 2.69
		Relative	15.39 ± 1.03	12.67 ± 1.07	11.30 ± 1.08	9.55 ± 0.76	9.49 ± 0.80	9.81 ± 1.04	9.30 ± 0.95
	Gluteus M. *n = 11*		150.74 ± 21.06	113.42 ± 13.61	96.50 ± 8.77	120.14 ± 23.91	119.95 ± 23.72	140. 44 ± 31.20	106.26 ± 12.01
	Vastus L. *n = 15*		101.99 ± 8.85	98.59 ± 7.26	97.60 ± 7.09	109.98 ± 9.33	120.94 ± 10.72	147.50 ± 23.60	118.36 ± 15.40
Int$_{20min}$	Hip *n=19*	Total							132.41 ± 10.95
		Relative							43.00 ± 2.29
	Knee *n=19*	Total							142.33 ± 7.15
		Relative							47.36 ± 2.03
	Ankle *n=19*	Total							29.08 ± 2.71
		Relative							9.64 ± 0.85
	Gluteus M. *n = 11*								169.65 ± 46.25
	Vastus L. *n = 15*								144.93 ± 25.18