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An updated approach to incremental cycling tests: Accounting for internal mechanical power

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Abstract

Internal mechanical power (IP) represents an important mechanical destination of metabolic energy supply, yet it is currently overlooked in cycling incremental protocols. Moreover, the methods by which IP and its associated metabolic cost are calculated are controversial. This study aimed to incorporate into an incremental protocol 1) the quantification of IP using a physiological model and 2) an assessment of negative crank power during the upstroke to describe the transfer of power between external mechanical power (EP) and IP. Cadence was used to elicit changes in IP in this investigation, and eight elite male cyclists completed three cycling incremental tests to exhaustion, beginning at 100 W and increasing by 50 W · 5min^{-1}, at cadences of 50-55, 80-85 and 110-115 rev · min^{-1}. Submaximal $\dot{V}O_2$ values were converted to metabolic power (MP), and the intercept of the EP-MP linear regression, minus resting metabolic rate, yielded the mechanical equivalent of IP. There was a significant increase in IP as cadence increased: 11 ± 5 W, 33 ± 11 W and 70 ± 22 W for cadences of 50-55, 80-85 and 110-115 rev · min^{-1}, respectively. Furthermore, mean negative crank power increased as cadence increased indicating a greater transfer of power from the EP of the downstroke leg, through the bottom bracket and into the upstroke leg to increase its IP. The updated approach to incremental cycle testing described in this study provides a multidisciplinary framework for changes to IP to be quantified, where changes to IP might be caused by a change in cadence or some other intervention.

Keywords: cadence, external mechanical power, metabolic power, crank power, delta efficiency

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Introduction

The human body, as a system that adheres principally to the first law of thermodynamics, has the capacity (or *energy*) to do work, and, at the same time, it produces heat (Whipp & Wasserman, 1969). Of the mechanical power that is performed during cycling, external mechanical power (EP; W), the rate of work usually measured by instrumented pedals or cranks, is the mechanical power with which most people are familiar. This power is frequently referred to as the *workload*. Internal mechanical power (IP; W) is the rate of work done to move the limb segments "through the desired [movement] pattern" (Winter, 1978), against gravitational and inertial forces (Cavagna et al., 1963; Winter et al., 1976). Incremental cycling tests, which are used to identify blood lactate transition thresholds to assist in the formulation and monitoring of cycling training programmes and competition pacing plans (Garvican et al., 2012), also provide an ideal opportunity to obtain information about IP and its associated metabolic cost.

The performance of mechanical work, and specifically, the magnitude of IP, has typically been considered from either a biomechanical *or* a physiological perspective. The biomechanical assessment of IP involves measuring changes in translational and rotational kinetic and potential energies of limb segments from digitised motion footage, and using inverse dynamics to calculate powers at the joints from muscle contractions and forces acting through bone-to-bone contact (Zatsiorsky, 1994). The physiological approach to IP, on the other hand, advocates a partitioning of whole body oxygen consumption (during steady-state exercise) into 1) that which is expended to maintain the body (resting metabolism); 2) that which is used to perform the EP; 3) that which is dissipated to heat, considering some measure of muscular efficiency; and 4) the remainder, most of which is used to perform IP. The biomechanical method is valuable because it provides information about changes in energy of individual segments, as well as the magnitude and direction of flow of energy at particular joints. The physiological method is important because it provides a tangible and all-encompassing measure of the energy expenditure associated with a change in IP, including the additional metabolic costs of heat production, the activation of stabilising, synergistic and antagonistic muscles, and changes in

muscle viscosity. It has, therefore, been referred to as the "golden [sic] standard" (Sjøgaard et al., 2002).

In cycling, a change in IP is usually effected by a change in pedalling cadence, and its mechanical cost has reportedly ranged from 15 to 91 W for cadences of 61-115 rev · min^{-1} (Hansen et al. 2004). Inconsistencies in the magnitude of IP calculated during cycling are largely due to the assumptions of the models used for its calculation. For example, the biomechanical models are limited by assumptions of rigid body links joined by frictionless hinge joints that cannot generate or absorb energy (Aleshinsky, 1986a van Ingen Schenau et al., 1990). Furthermore, while biomechanists often acknowledge such limitations, the models themselves a) tend to neglect the dissipation of a significant portion of the metabolic energy to heat; b) disregard the metabolic cost associated with the activation of agonistic and antagonistic muscles; c) tend not to accommodate recuperation of elastic energy; and d) frequently assume the cost of negative work to be equal to positive work (Zatsiorsky, 1994). While the whole-body oxygen consumption incorporates all of these effects on metabolic cost, the physiological models are limited by their assumption that the total mechanical power is simply the summation of EP and IP. This simple addition has been challenged in the biomechanical literature (van Ingen Schenau, 1998; Zatsiorsky, 1998), where it has been argued that the energy applied to the cranks is not distinct from the energy that is used to move the limbs. Both van Ingen Schenau et al. (1990) and Broker and Gregor (1994) measured segmental energy and joint and muscle power changes throughout the crank cycle to trace the flow of energy from one leg to the other via the crankshaft. They suggested that the additional energy at the pedal during the downstroke, over that required for the EP, is transferred via the cranks and bottom bracket and presented as a negative pedal force on the contralateral side, i.e., a flow of energy from the pedal to the foot, which then flows distally to proximally to change the segmental energies of the contralateral limb (Broker & Gregor, 1994; Kautz & Neptune, 2002; van Ingen Schenau et al., 1990). In other words, some of power that is measured at the pedal or crank and considered to be EP is also used for IP. This "sharing" of power is represented by negative power for the contralateral limb during the pedalling upstroke.

While it is clear that more research is necessary to accurately partition the metabolic energy required for the mechanical destinations during cycling and to resolve the differences between the physiological and biomechanical approaches, valuable information can still be acquired about the characteristics of IP from laboratory tests on cycle ergometers fitted with instrumented pedals or cranks. A physiological model can be employed to attribute the excess oxygen consumption, over that required for the external workload, to the metabolic cost of moving the limbs (Foss & Hallén, 2004). Morover, with the measurement of frequent pedal or crank power data, information about the power transferred from EP to IP, could, at the very least, be indicated when the means to conduct complex kinematic and inverse dynamics analyses are absent. Thus, with the intention of implementing a more comprehensive report following incremental exercise testing of elite cyclists, the aim of this investigation was to describe the effects of cadence on metabolic cost and the partitioning of mechanical work. It was hypothesised that the metabolic cost of cycling would increase with increased IP (i.e., caused by an increase in cadence) at the same EP. It was also expected that energy flow to the contralateral leg, expressed as an increase in negative crank power during the upstroke, would increase with increased IP.

Materials and methods

Participants

Eight healthy, Elite A division (affiliated with Cycling Australia) male road cyclists (mean ± SD: age 31.7 ± 6.6 years, mass 74.7 ± 5.2 kg, stature 1.80 ± 0.04 m, $\dot{V}O_{2peak}$ (the highest peak oxygen consumption recorded in the three incremental tests of this study) 65.3 ± 5.1 ml · kg^{-1} · min^{-1}) participated in the study. Participants trained at least 14 hours per week, completing 487 ± 95 km. They averaged 9.7 ± 5.0 years of racing experience. The study was approved by an ethics committee at The University of Queensland. Participants provided informed consent prior to participating and completed a medical screening questionnaire before being accepted into the study.

Experimental protocol

Participants were asked to refrain from intense physical activity in the 24 hours prior to each testing session and advised to schedule a rest or active recovery day on the day before each laboratory visit. They were provided with dietary guidance to consume 7 g CHO · kg BW^{-1} within the 24 hours before testing and a pre-test meal consisting of 2 g CHO · kg BW^{-1} two hours prior to arrival at the laboratory. All testing sessions were held at the same time of day to account for changes in circadian rhythm. One incremental test was conducted per session, and a minimum of five days separated each session. All trials were completed at the Queensland Academy of Sport, and were conducted under controlled environmental conditions (19.7 ± 1.1 ˚C; 53.2 ± 9.7% RH; 756.9 ± 3.1 mmHg). Participants were cooled throughout the tests with a pedestal fan.

Incremental cycling tests

Cyclists completed three incremental cycling tests to exhaustion, within three discrete cadence ranges: 50-55, 80-85 and 110-115 rev · min^{-1}. These ranges were selected to represent the general range of cadences adopted during training and racing. Each test began with five minutes of cycling at an external mechanical power output (EP) of 100 W, thereafter the EP was increased by 50 W · 5 min^{-1} until volitional fatigue. The three incremental tests were completed in random order.

All tests were performed on the same AXIS cycle ergometer (Swift Performance Equipment, Carole Park, Australia), and participants used their own shoes and

pedals. Measurements of seat height, seat fore-aft position, forward reach, seat-handlebar height difference and crank length were recorded from the participants' own bicycles in order to replicate their usual cycling position during testing and to ensure consistency across trials. The left and right AXIS Cranks (Swift Performance Equipment, Carole Park, Australia) have two full-bridge 350 Ω strain gauge configurations. One configuration measured strain on the crank to provide radial force, and the other measured shear on the crank to provide tangential force. Data was sampled at a rate of 100 Hz. The cranks were calibrated using a dynamic calibration rig, and zeroed daily by storing offsets at 0°, 90°, 180° and 270°. The radial force (F_{rad}; N) and tangential torque (τ_{tan}; Nm) applied to both the left and right cranks and the crank positions at which they were applied (where 0° coincided with the vertical crank position at which the pedal position was highest, i.e., top dead centre, or TDC; 180° offset from this was bottom dead centre, or BDC) were recorded continuously throughout each trial (Swift Performance Equipment, Carole Park, Australia). Custom-written software calculated EP (W) as the product of the τ_{tan} multiplied by the crank angular velocity. This EP data was plotted against angular position (0-360°) from the beginning of the second minute of each stage until ten seconds prior to the end of each stage to provide a mean crank power profile for each cyclist. The time range was chosen to avoid artefacts in the data due to fine-tuning the workload in the first minute and the cyclist preparing for the increase in workload of the following stage during the final ten seconds. Individual mean crank power profiles were then averaged across the participant group so that group mean crank power was plotted against angle for each workload-cadence combination. The negative crank power values from the individual power profiles were averaged to obtain the mean negative crank power per revolution. Group means for negative crank power per revolution were then calculated for each workload-cadence combination. The mean negative power was preferred to the peak negative power as it provides more information about the total negative work per revolution. While it is generally considered that the closer the measurement of EP to the human-bicycle interface (i.e., the foot-pedal) the better, the measurement of crank power in place of pedal power was appropriate for the current investigation because crank power incorporates both the power that goes into rotating the chainring, moving the chain and rotating the rear wheel and any power that flows across the bottom bracket, through the contralateral crank and into the foot of the contralateral leg.

Standard open-circuit spirometry techniques were used throughout trials to determine respiratory gas exchange measures (Moxus Modular V,$\dot{O}_2$ System, AEI Technologies, Pittsburgh, PA, USA). Prior to each testing session, the metabolic cart was calibrated using alpha gases of known concentration (Coregas Pty Ltd, Yennora, Australia) to within ± 0.02%, and the turbine ventilometer was calibrated at various flow rates using a calibration system (Vacumed, Ventura, CA, USA) with a 3-L syringe (Hans Rudolph, Inc., Shawnee, KS, USA) to within ± 3%. Expired gas was collected and averaged over 30-s sampling periods. Samples collected within the final two minutes of each 5-min bout were averaged for inclusion in the analysis. Peak oxygen consumption ($V,\dot{O}_{2peak}$) was calculated as the mean of the highest two consecutive $V,\dot{O}_2$ values.

Calculations

Oxygen consumption ($L \cdot min^{-1}$) was converted to metabolic power (MP; W (where 1 W is equivalent to 1 $J \cdot s^{-1}$)) using the associated respiratory exchange ratio (RER) and Zuntz's (1901) Thermal Equivalents of Oxygen for the Nonprotein Respiratory Quotient (Whipp and Wasserman 1969). Delta efficiency (DE) was the gradient of the linear regression between EP (on the y-axis) and MP (W) This method was applied for each participant and means were then calculated for the three cadence ranges. Resting metabolic rate (RMR) was determined using ACSM guidelines (American College of Sports Medicine 2000) of 3.5 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$, and then converting to $J \cdot s^{-1}$ using the O_2-equivalent for an RER of 0.82 (McArdle et al. 1996). The metabolic cost of IP for each cadence was calculated by subtracting the RMR ($J \cdot s^{-1}$) from the x-intercept of the respective linear regression between EP (on the y-axis) and MP (Francescato et al. 1995). The result was multiplied by DE to determine the mechanical equivalent of IP (W). This method produced one value for IP for each cadence.

Data Analysis

Data for all variables from stages one to five were included for analysis of the incremental test at 50-55 $rev \cdot min^{-1}$ since all participants were still exercising submaximally (RER ≤ 1.0) during the fifth stage (300 W). Four and three participants were still cycling submaximally at 300 W during the tests at 80-85 and 110-115 $rev \cdot min^{-1}$, respectively. Values for IP were calculated for these participants for comparative purposes, although caution was exercised in interpreting the generalizability of these results. Crank power data was included for analysis for all participants at all five stages of each incremental test. Normality of the data was tested using the Kolmogorov-Smirnov test. One-way repeated measures ANOVAs were used to compare means for normally distributed data. Fisher's least significant difference was used post-hoc to locate significant differences. For data that was not normally distributed, means were compared using a Friedman's test, and a Wilcoxon-signed rank test was used to locate the differences. Data were analysed using SPSS software (PASW Statistics v18.0.3, Chicago, USA) with an alpha level set at 0.05 *a priori*, and are presented as means ± SD.

Results

The differences in MP between 50-55 and 110-115 $rev \cdot min^{-1}$ and between 80-85 and 110-115 $rev \cdot min^{-1}$

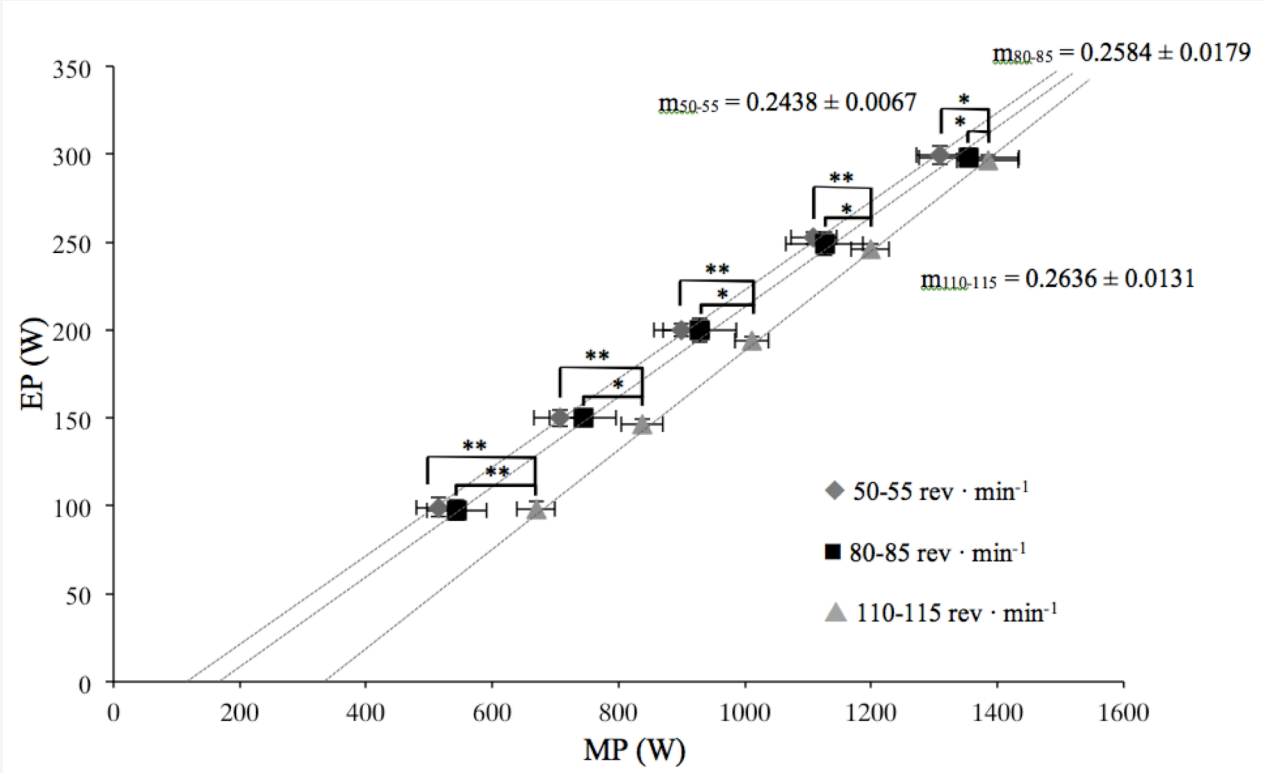

Figure 1. Metabolic power changes with external mechanical power and cadence. Metabolic power during each stage was significantly different from each other stage in the same test ($p < 0.001$). Mean gradients (m) for the linear relationships between EP and V,˙O2 represent Delta Efficiencies (DE) for the respective cadence. *$p < 0.05$ **$p < 0.001$. EP, External Mechanical Power; MP, Metabolic Power

at the same EP became smaller as EP increased (Figure 1). MeaDE values (the gradient, m) obtained from the linear regression between MP and EP for the three incremental tests are shown in Figure 1. As cadence increased, DE increased, with a significant differences between DE at 50-55 and 80-85 rev · min^{-1} ($p = 0.042$) and at 50-55 and 110-115 rev · min^{-1} ($p = 0.01$). Values for IP were 11 ± 5 W, 33 ± 11 W and 70 ± 22 W for cadence ranges of 50-55, 80-85 and 110-115 rev · min^{-1}, respectively, increasing significantly with increased cadence (50-55 vs 80-85 rev · min^{-1}: $p = 0.012$; 50-55 vs 110-115 rev · min^{-1}: $p = 0.018$; 80-85 vs 110-115 rev · min^{-1}: $p = 0.018$). Mean data for IP for each of the cadence ranges are presented in Figure 2.

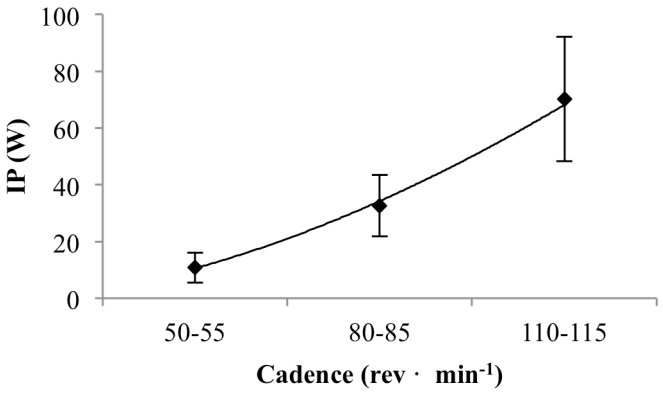

Figure 2. Mean ± SD for IP within each of the cadence ranges

Figure 3 illustrates the mean EP, i.e., the crank power, recorded throughout the 360º crank cycle at 100, 150, 200, 250 and 300 W EP and at the three cadence ranges. Data were recorded for both the left and right cranks; the right crank data was shifted in phase by 180º to demonstrate the same relative position in

Table 1. Mean negative crank power during the upstroke for each EP and cadence.

	Mean Negative Crank Power During the Upstroke (W)		
	50-55 rev·min^{-1}	**80-85 rev·min^{-1}**	**110-115 rev·min^{-1}**
Stage 1 (100 W)	-39.5 ± 7.8^{b,c}	-76.2 ± 14.5^{a,c}	-129.3 ± 23.3^{a,b}
Stage 2 (150 W)	-32.5 ± 7.1^{b,c}	-70.4 ± 13.1^{a,c}	-135.6 ± 34.8^{a,b}
Stage 3 (200 W)	-24.2 ± 5.1^{b,c}	-62.2 ± 8.9^{a,c}	-130.8 ± 32.0^{a,b}
Stage 4 (250 W)	-13.0 ± 7.5^{b,c}	-50.4 ± 6.8^{a,c}	-123.6 ± 30.3^{a,b}
Stage 5 (300 W)	-10.5 ± 8.4^{b,c}	-37.3 ± 8.3^{a,c}	-108.3 ± 26.9^{a,b}

[a]Mean negative crank power was significantly different to that measured at 50-55 for the equivalent stage ($p < 0.05$); [b]Mean negative crank power was significantly different to that measured at 80-85 rev · min^{-1} for the equivalent stage ($p < 0.05$); [c]Mean negative crank power was significantly different to that measured at 110-115 rev · min^{-1} for the equivalent stage ($p < 0.05$)

the crank cycle as the left crank. Crank power increased as workload increased, and positive and negative crank powers were typically larger and smaller, respectively, as cadence increased. Negative crank power measured at 50-55 rev · min^{-1} gradually diminished as EP increased such that there was almost no negative power recorded during the upstroke at 300 W. Mean ± SD values for the mean negative crank power during the upstroke for each cadence and each EP are reported in Table 1.

Discussion

This study showed that additional analysis of data collected during a routine incremental cycling test can provide further information about the flow of metabolic energy to its mechanical destinations. Specifically, one can input the $\dot{V}O_2$, RER and EP values into a physiological model to calculate MP and DE and to estimate IP and its metabolic cost for a particular cadence. It was shown here that, in a group of elite male cyclists, mechanical equivalents of physiologically estimated IP increased as cadence increased, from 11 ± 5 W at 50-55 rev · min^{-1} to 33 ± 11 W and 70 ± 22 W at 80-85 and 110-115 rev · min^{-1}, respectively (Figure 2). This increase is in accordance with findings of previous studies (Francescato et al. 1995; Wells et al. 1986; Willems et al. 1995), and the current values of physiologically estimated IP are similar in magnitude to those reported by Hansen et al. (2004), especially at low and moderate cadences. In addition, mean negative crank power during the upstroke was shown to increase as cadence increased (Figure 3 and Table 1). This finding supports an increase in the amount of power applied to the crank of the downstroke leg contributing to increasing the total mechanical energy (potential and kinetic energies, i.e., the IP) of the upstroke leg.

Physiological estimation of internal mechanical power

A number of physiological models have calculated an increase in IP with cadence. For example, Martin et al. (2002) reported the metabolic cost of moving the legs to be 98 ± 38 W and 144 ± 58 W in adults, at cadences of 60 and 90 rev · min^{-1}, respectively. The mechanical equivalents of these results, converted using a measure of muscular efficiency (e.g., 25%) (Gaesser and Brooks 1975), would be approximately 24.5 W and 36 W, respectively. In 2004, Hansen et al. reported mechanical equivalents to be 15.1, 40.9 and 91.0 W for cycling at cadences of 61, 88 and 115 rev · min^{-1}, respectively, which were similar to those of the current study, particularly at the low and moderate cadences. Hansen et al. (2004) concluded that their results compared favourably to the results of kinematic models by Willems et al. (1995) and Winter (1979) (Hansen et al. 2004). The method used to estimate IP in the current study was based on the method of Francescato et al. (1995), however the equation first described by Sjøgaard et al. (2002) and used by Hansen et al. (2004) is similar, in principle, to the Francescato et al. (1995) method. Mean values for IP of 1, 6, 20 and 64 W (for the unloaded limbs condition) for cadences of 40, 60, 80 and 100 rev · min^{-1} could be deduced from reported y-intercepts (MP on the y-axis) and DE by Francescato et al. (1995). Differences between the values for IP in this study and IP reported in previous physiological studies may be traced to differences in the values required for its calculation. For example, some researchers measured resting metabolic rate (Francescato et al. 1995), while others used a particular value e.g., 0.00417 L · s^{-1} (*sic*) (Hansen et al. 2004) and 0.00333 L · s^{-1} (*sic*) (Sjøgaard et al., 2002), or calculated it from equations that considered factors such as body mass, height, surface area and age (as in this study; Martin et al. 2002). There were also differences in the conversions of oxygen consumption, in ml · min^{-1} or L · min^{-1} to W. Caloric equivalents of 20.6 kJ · L O_2^{-1} (Martin et al. 2002) or 20.9 J · ml O_2^{-1} (Francescato et al. 1995) have sometimes been used for all submaximal exercise intensities, while other studies used an O_2-equivalent for the respective RER at each intensity (as in this study; Hansen et al. 2004). Still others have assumed the same caloric cost for rest and exercise by using the same O_2-equivalent for resting $\dot{V}O_2$ as that of the particular exercising $\dot{V}O_2$ under consideration, i.e., total caloric equivalent = ($\dot{V}O_{2exercise}$ - $\dot{V}O_{2rest}$) x O_2-equivalent (Hansen et al. 2004). Finally, differences in the values for DE may have contributed to differences in IP estimates.

In addition to differences in the values used in the calculation of IP in this compared to other physiological studies, differences in the participant groups are likely to have also affected the calculation. Specifically, the participants in this study were well-trained cyclists who spent at least 14 hours each week cycling. It is likely that they were more efficient across a wider range of cadences, which may explain why the observed metabolic cost of moving the limbs was smaller in the present study, particularly at the higher cadences, compared to others who used less-experienced and less-economical participants (Francescato et al. 1995; Hansen et al. 2004; Martin et al. 2002).

Biomechanical indicators of internal mechanical power

It is appealing to attribute the increased oxygen consumption at a constant EP to the metabolic cost of moving the limbs faster. As cadence is increased, the translational and rotational velocities of the limb segments must increase to achieve the same distance (i.e., a pedal revolution) in a shorter amount of time, and therefore the kinetic energies (KE) of the segments increase. The rate of change of the segmental velocities, and hence the rate of change of KE, increases with increased cadence in a fashion similar to the rate of change of oxygen consumption. It is worth noting here that other explanations exist, however, for the additional $\dot{V}O_2$ at higher cadences, or at least for part of it. Minetti (2011) summarised that possible differences in patterns of muscle fibre-type recruitment, the activation of agonistic and antagonistic muscles and the resistance offered by extramuscular structures including joint cartilage, ligaments and tendons may

contribute to the additional $\dot{V}O_2$. He collectively termed these 'viscous internal work' (Minetti 2011). Moreover, the major premise of the physiological models is that the sum of EP and IP is equal to the total mechanical power, as represented by the $\dot{V}O_2$ (Francescato et al. 1995; Hansen et al. 2004; Wells et al. 1986). In other words, subtracting the known EP (divided by DE) from the measured $\dot{V}O_2$ will leave IP (and RMR). This model was originally derived by Winter (1979) and applied to gait, which worked reasonably well because EP for level-ground walking and running is equal to zero. More recent biomechanical investigations in cycling have suggested that EP and IP should not be considered independent and that there may be some sharing of energy or transfer between them via the bottom bracket (Kautz and Neptune 2002; van Ingen Schenau 1998; Zatsiorsky 1998).

This study demonstrated that when a routine cycling incremental test is conducted on an ergometer with instrumented pedals or cranks, information about the flow of EP and IP can be obtained by analysing the instantaneous crank power throughout the pedal stroke. It has been shown that when the power transferred to the pedal is greater than the power developed by the muscle sources (determined from inverse dynamics analyses), the segmental energies decrease (Broker and Gregor 1994; van Ingen Schenau et al. 1990). This means that the additional energy at the pedal during the downstroke flowed from the decreasing segmental energies of the lower limb attached to that pedal. The rate of this energy is then expressed as negative pedal power during the upstroke of the crank cycle, or 180º-360º. The energy then flows distally to proximally through the contralateral leg, increasing the total mechanical energy of its segments (Broker and Gregor 1994).

Importantly, the crank power profiles recorded in this study (Figure 3) indicate that the amount of energy transferred between the legs per pedal stroke varies with cadence. During the downstroke, crank power was larger from ~45º to 180º as cadence increased. This illustrated a greater transfer of energy from the downstroke leg to the pedal and then the crank as cadence increased (Broker and Gregor 1994; van Ingen Schenau et al. 1990; Winter and Robertson 1978). Additionally, the negative powers during the upstroke (BDC to TDC) were greatest in this study at 110-115 rev · min^{-1}, and were also larger at 80-85 rev · min^{-1} than at 50-55 rev · min^{-1} ($p < 0.05$) (Table 1). Further, for some participants, the crank power remained positive or very close to zero throughout the second half of the pedal stroke while cycling at the lowest cadence (50-55 rev · min^{-1}) and the higher EP (-10.5 ± 8.4 W; Table 1). Indeed, in the lowest panel of Figure 3, the plot of the mean crank power barely passes below the zero-line at 50-55 rev · min^{-1} and 300 W. Using the previous reasoning, the contralateral limb actively pulled itself up in this case, rather than relying on the drive-side leg to push it during the upstroke. In other words, it appears that at low compared to high cadences, more of the energy, and in some cases, all of the energy, from the downstroke leg is "used usefully to achieve the task" (van Ingen Schenau et al. 1990), i.e., to produce EP and not contribute to IP. Kinetic and kinematic analyses are necessary to substantiate these differences in the flow of energy across the cadence range.

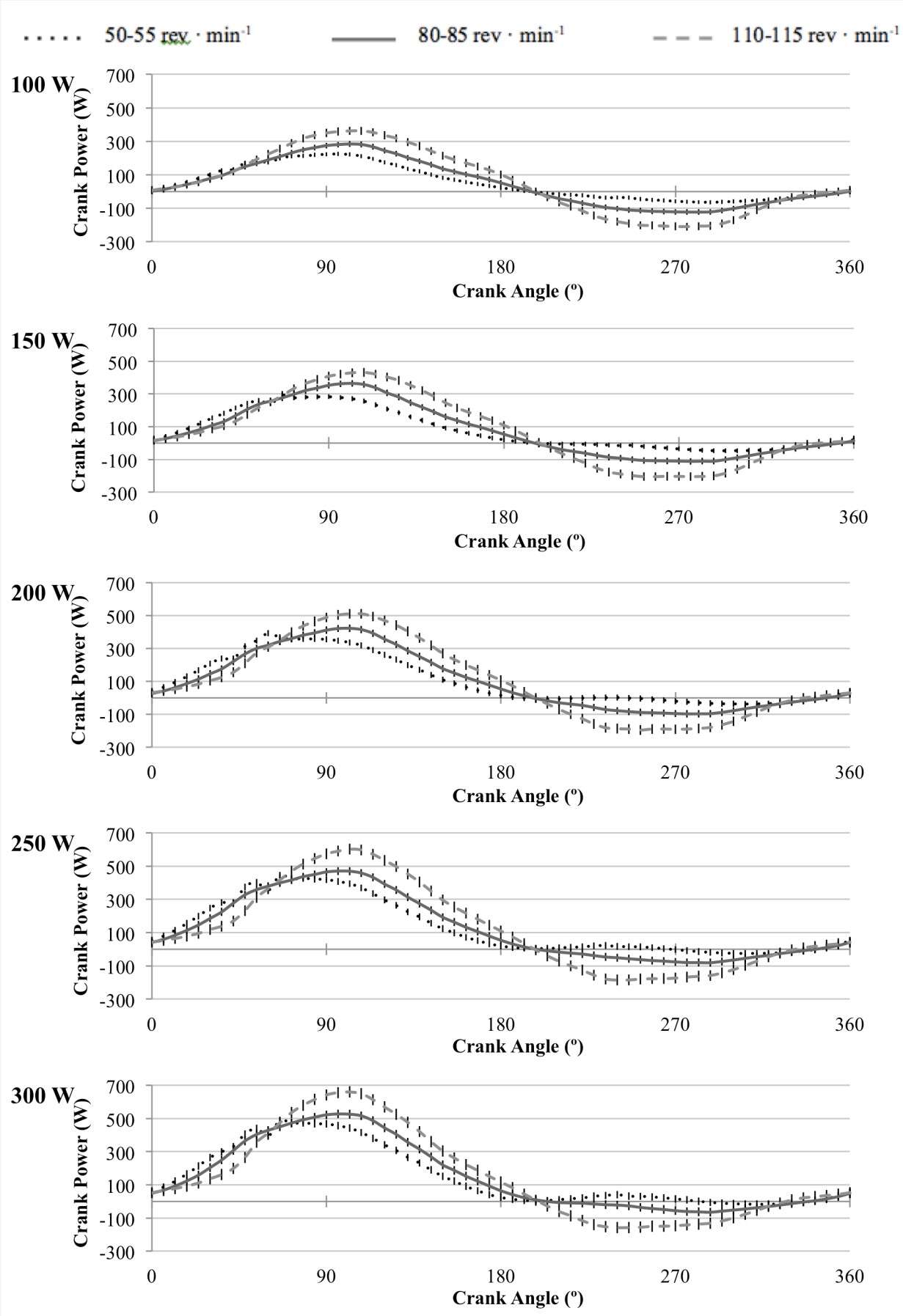

Figure 2. Mean ± SD for IP within each of the cadence ranges

Practical applications

The results of this study showed that, with the use of instrumented pedals/cranks and no change to the incremental testing protocol, more comprehensive and useful information may be obtained, including a) the delta efficiency of the cyclist; b) the estimated cost of IP and its mechanical equivalent at the cadence adopted for the test; and c) the presence of energy flow between the cyclist's feet and the pedals and cranks. Such information could allow for targeted improvements in the flow of metabolic to mechanical energy. For example, if it were possible to reduce the flow of energy to IP, more energy would be available to be used for EP, causing the cyclist to travel faster. The means by which to reduce the IP require further investigation, but might include interventions such as a change to cycling position, the use of non-circular chainrings or a modification to pedalling technique. The comparison of cadences in the current study, achieved with an updated incremental protocol that includes a multidisciplinary approach to mechanical power, demonstrate a framework that could be used by an athlete or coach to evaluate the energetic impacts of such interventions. Both acute and chronic (following a period of training) effects on mechanical power distribution could be measured with two (or more) incremental tests – one using the cyclist's current cycling position and one in which the crank is lengthened by 5 mm, or one in which the customary pedalling style is adopted compared to one in which a "pulling up" action is employed, or one using a circular chainring and the other using an elliptical chainring, for example. The intervention that offers a reduction in IP would be seen to be favourable, though it must be remembered that the reduction in IP might come only after a period of time spent training with the intervention.

In addition to this framework for assessing metabolic-mechanical energy flow, this study also yielded information about the cost of IP over a range of training- and race-specific cadences. It is normally recommended that a cycling incremental test is performed within a cadence range of 90-105 $rev \cdot min^{-1}$ (Garvican et al. 2012). However, given that the demands of cycling training and competitions require a range of cadences, administering a number of incremental exercise tests at various cadences would allow for a "cost-of-mechanical-power profile" to be developed for a particular athlete. Such a profile would assist the sport scientist or dietician to more accurately quantify and provide for the caloric needs of the athlete. This data would be invaluable to evaluating the energy expenditure in greater detail during the exercise programming and training monitoring processes.

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