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Crank inertial load affects freely chosen pedal rate during cycling

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Abstract

Cyclists seek to maximize performance during competition, and gross efficiency is an important factor affecting performance. Gross efficiency is itself affected by pedal rate. Thus, it is important to understand factors that affect freely chosen pedal rate. Crank inertial load varies greatly during road cycling based on the selected gear ratio. Nevertheless, the possible influence of crank inertial load on freely chosen pedal rate and gross efficiency has never been investigated. This study tested the hypotheses that during cycling with sub-maximal work rates, a considerable increase in crank inertial load would cause (1) freely chosen pedal rate to increase, and as a consequence, (2) gross efficiency to decrease. Furthermore, that it would cause (3) peak crank torque to increase if a constant pedal rate was maintained. Subjects cycled on a treadmill at 150 and 250 W, with low and high crank inertial load, and with preset and freely chosen pedal rate. Freely chosen pedal rate was higher at high compared with low crank inertial load. Notably, the change in crank inertial load affected the freely chosen pedal rate as much as did the 100 W increase in work rate. Along with freely chosen pedal rate being higher, gross efficiency at 250 W was lower during cycling with high compared with low crank inertial load. Peak crank torque was higher during cycling at 90 rpm with high compared with low crank inertial load. Possibly, the subjects increased the pedal rate to compensate for the higher peak crank torque accompanying cycling with high compared with low crank inertial load.

Keywords: Crank inertial load; Cycling; Efficiency; Freely chosen pedal rate

1. Introduction

Crank inertial load increases as a quadratic function of the bicycle gear ratio (Fregly et al., 2000). Therefore, during road cycling, conditions with low and high crank inertial load occur e.g. if a cyclist maintains the same pedal rate and work rate during uphill and horizontal cycling, respectively. The reason is that uphill cycling speed will be low and consequently require a low gear ratio, while horizontal cycling speed will be high and therefore require a high gear ratio. If, for example, a trained cyclist (70 kg) performs cycling at a predetermined work rate with 90 rpm on both a road with a steep uphill slope at 10 km h^{-1} and on a horizontal road at 50 km h^{-1}, gear ratios of 26/28 and 52/12 (chain wheel/freewheel) are required, respectively. This difference in gear ratio changes the crank inertial load from approximately 8 to 180 kg m^2 (Fig. 1).

The effect of crank inertial load on heart rate, oxygen uptake, rate of perceived exertion, and pedal forces has been studied previously (Lollgen et al., 1975; Patterson et al., 1983; Voigt and von-Kiparski, 1989). However, these studies used crank inertial loads below approximately 33 kg m^2, while so far only two studies used high crank inertial load (>100 kg m^2) that corresponds to crank inertial load during high speed horizontal road cycling (Fregly et al., 1996, 2000). In the latter studies it was reported that peak crank torque was higher during cycling at a sub-maximal work rate with high compared with low crank inertial load.

We hypothesized that an increase in peak crank torque, caused by an increase in crank inertial load,

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Nomenclature

I_D	rotational inertia of each wheel about its axis of rotation 0.1786 ($kg\,m^2$)
I_F	combined rotational inertia of the pedals, crank arms, and chain wheels about the crank axis 0.0355 ($kg\,m^2$)
I_G	rotational inertia of the freewheel 0.0003 ($kg\,m^2$)
m_B	mass of the bicycle frame[1] 6.416 (kg)[2](see footnote 2)
m_C	mass of the subject (variable, see text) (see footnote 2)
m_D	mass of each wheel 1.973 (kg) (see footnote 2)
m_F	combined mass of the chain wheels, crank arms, and pedals 1.660 (kg) (see footnote 2)
m_G	mass of the freewheel 0.317 (kg) (see footnote 2)
m_W	mass on the weight magazine (incl. the weight magazine) (variable, see text) (see footnote 2)
R_D	radius of each wheel 0.3429 (m) (see footnote 2)
R_F	number of teeth in the chain wheel (variable, see text) (see footnote 2)
R_G	number of teeth in the freewheel (variable, see text) (see footnote 2)

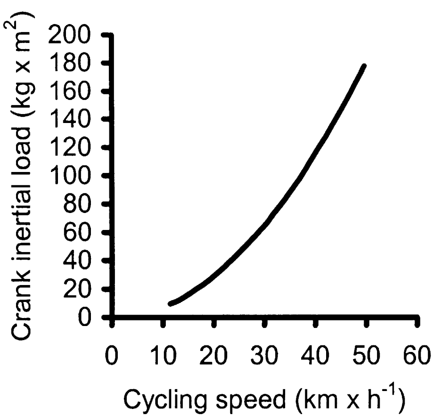

Fig. 1. Crank inertial load for a 70 kg individual performing road cycling with a constant pedal rate of 90 rpm. As cycling speed is increased higher gear ratios are required to maintain the pedal rate. The higher gear ratios cause the crank inertial load to increase.

would affect the subjects' perceived exertion that subsequently would cause the subjects to increase their freely chosen pedal rate. Increasing the pedal rate while maintaining a work rate reduces the mean and peak crank torque. However, increasing the pedal rate (above approximately 60 rpm) at a constant work rate caused the oxygen uptake to increase (Barbeau et al., 1993; Boning et al., 1984; Coast and Welch, 1985) and consequently the gross efficiency to decrease (Barbeau et al., 1993; Boning et al., 1984; Gaesser and Brooks, 1975). This is considered a disadvantage, from a metabolic point of view with regard to long duration performance.

Therefore, the two main purposes of our study were to investigate if cycling with high compared with low crank inertial load would cause the subjects to increase their freely chosen pedal rate and so decrease their gross efficiency. Our experimental set-up differed considerably from that used in the two studies by Fregly et al. (1996, 2000) that reported higher peak crank torque during cycling with high compared with low crank inertial load. Therefore, the third purpose was to investigate if a higher peak crank torque could be detected in the present study during cycling at a preset pedal rate with high compared with low crank inertial load.

2. Methods

2.1. Subjects

Nine healthy male subjects of age 24±5 years (mean±SD), height 179±4 cm, and weight 73±5 kg, volunteered and gave written consent to participate in the study which was approved by the local ethical committee. The subjects were informed about the nature, however, naive to the purposes of the study.

2.2. Procedure

Cycling conditions with low and high crank inertial load were created by having the subjects cycle on a racing bicycle with low and high gear ratios. The bicycle was placed on a motorized Woodway ELG 70 treadmill (Woodway GmbH, Weil am Rhein, Germany).

Horizontal cycling conditions with low and high crank inertial load were termed HL and HH, respectively. An uphill cycling condition with low crank inertial load was termed UL. HL and UL were performed at $11.2\,km\,h^{-1}$ while HH was performed at $30.9\,km\,h^{-1}$. Uphill cycling was performed in a sitting position since standing in the pedals affects oxygen uptake (Ryschon and Stray, 1991), crank torque profile, and muscle coordination (Caldwell et al., 1998; Li and Caldwell, 1998). The bicycle had a tire pressure of 709 kPa and it was fitted with conventional pedals with

[1] In this context the bicycle frame represents the whole bicycle minus the wheels, crank arms, and pedals.

[2] Determined in this study.

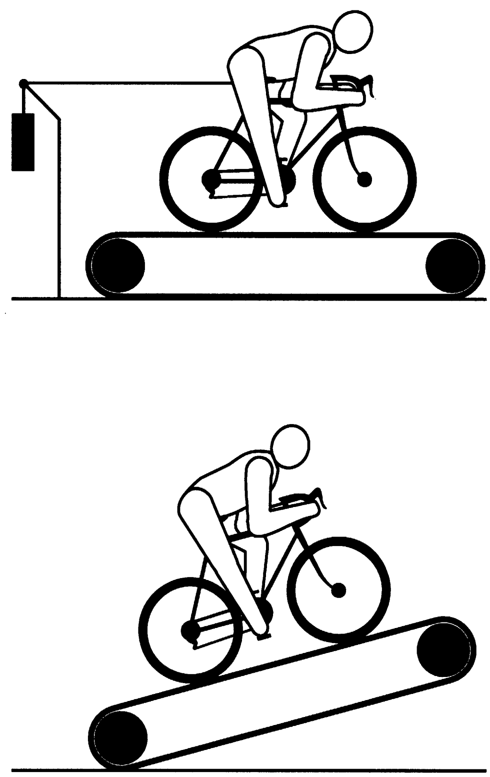

Fig. 2. Experimental set-up showing an individual performing horizontal (HL and HH) and uphill (UL) cycling conditions.

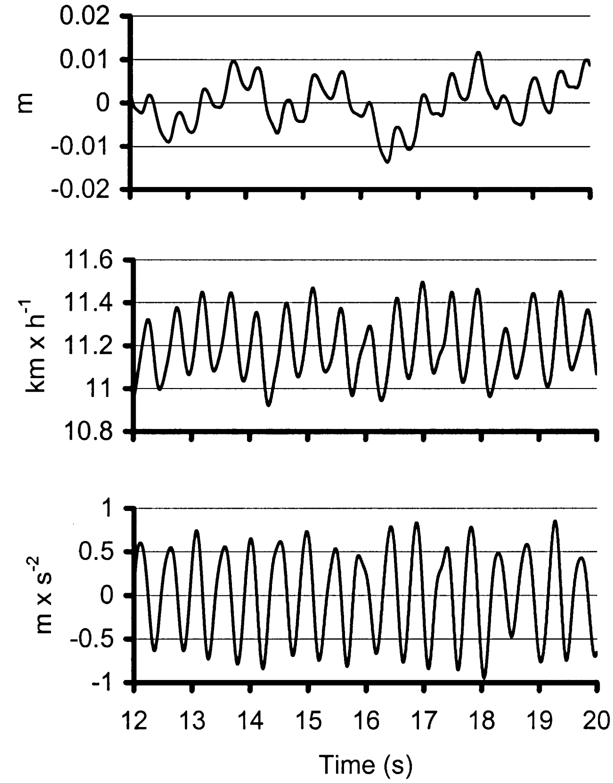

Fig. 3. A recording (8 s are shown) of the horizontal bicycle translation relative to the laboratory (top) and the calculated bicycle speed and bicycle acceleration relative to the treadmill belt (middle and bottom, respectively) from a subject performing the $UL_{250\,W}$ cycling condition in Study A.

toe clips that allowed the subjects to use sport shoes. The bicycle was fitted with a SRM crank dynamometer (Schoberer Rad Messtechnich, Jülich, Germany) that allowed measurement of work rate and the sum of the crank torque performed by right and left leg. The SRM powercontrol (a small computer) displayed work rate continuously. This allowed adjustment of work rate during horizontal cycling for each subject by changing the mass of a weight magazine, m_W, that was connected to a wire, running over a pulley placed on a tower behind the treadmill, and tied to the back of the bicycle (Faria et al., 1982) (Fig. 2). A potentiometer (Model P6501a202, $\pm 0.075\%$ linearity. Novotechnik, Ostfildern, Germany) was attached to the axis of the pulley allowing us to record the horizontal bicycle translation relative to the laboratory. This potentiometer is referred to as the tower potentiometer. Recordings from the tower potentiometer were made for 30 s at 1000 Hz and were low-pass filtered at 8 Hz (4th order Butterworth). Based on speed of the treadmill belt and first time derivatives of the bicycle translation data the bicycle speed relative to the treadmill belt was calculated. Bicycle acceleration relative to the treadmill belt was calculated as the first time derivative of the bicycle speed relative to the treadmill belt (Fig. 3). Both the bicycle speed and acceleration data were low-pass filtered at 4 Hz (4th order Butterworth). All differences between peak and nadir (lowest point) on the bicycle acceleration curve were found in each recording and averaged.

During uphill cycling, work rate was adjusted by changing the slope of the treadmill. Of interest is that in our experimental set-up the subjects needed to steer the bicycle similarly to road cycling. Further, changes in pedal rate had no effect on work rate that was determined by the rolling resistance, m_W or slope of the treadmill, and the bicycle speed.

Crank inertial load was calculated (Eq. (1))[3] using a slightly modified version of the equation reported by Fregly et al. (2000).

$$\text{Crank inertial load} = I_F + (R_F/R_G)^2[R_D^2(m_B + m_C + 2m_D + m_F + m_G + m_W)(2I_D + I_G)]. \quad (1)$$

A treadmill was chosen for our study since it provides the best approximation of road cycling within the laboratory environment. Because a treadmill approximates the loading of road cycling only to the extent that the treadmill speed remains constant (see Appendix A),

[3] Determined by Fregly (1993): I_D = rotational inertia of each wheel about its axis of rotation 0.1786 (kg m^2); I_F = combined rotational inertia of the pedals, crank arms, and chain wheels about the crank axis 0.0355 (kg m^2); I_G = rotational inertia of the freewheel 0.0003 (kg m^2).

we recorded (3 s at 100 kHz) and investigated the treadmill speed under a variety of cycling conditions: HS (high speed—30 km h^{-1} at 250 W), LS (low speed—11 km h^{-1} at 250 W), LSU (low speed uphill—11 km h^{-1} at 250 W), and LS_{max} (low speed—11 km h^{-1} at maximum effort with the bicycle fixed in relation to the laboratory). The treadmill speed during these cycling conditions was compared with the treadmill speed during freewheeling conditions at matching treadmill speeds. During freewheeling (not pedaling), the subjects maintained their balance with one hand on the handrail of the treadmill. For each time point the absolute difference between an investigated cycling condition and a freewheeling condition at matching treadmill speed was found and coefficient of variation in percent (CV) was calculated for all the differences. The CV from comparison of two freewheeling conditions at the same treadmill speed served as reference CV values. CV is presented as mean ± SD from four subjects tested at each cycling condition. The reference CV values were 0.55 ± 0.01% at high speed and 0.33 ± 0.05% at low speed. Correspondingly, CV was 0.56 ± 0.01% for HS, 0.33 ± 0.03 for LS, 0.32 ± 0.04% for LSU, and 0.47 ± 0.05% for LS_{max}. The low reference CV values demonstrated that the present treadmill maintained a highly constant speed when a subject was freewheeling on the treadmill and the similar CV values for the sub-maximal cycling conditions demonstrated that the treadmill speed was not affected when actively riding a bicycle on this treadmill in conditions similar to those used in the present study. The treadmill speed was affected at LS_{max}, however, this extreme cycling condition was not used further in this study. That justified the assumption of a constant treadmill speed for the calculations in this study.

2.3. Study A

To investigate the effect of low and high crank inertial load on freely chosen pedal rate and gross efficiency, we had the subjects performing six 5 min cycling periods in randomized order, interrupted by 5 min rest periods. Cycling conditions were $HL_{150\,W}$, $HL_{250\,W}$, $UL_{150\,W}$, $UL_{250\,W}$, $HH_{150\,W}$, and $HH_{250\,W}$. The subjects were instructed to experiment with the 8–12 available gear ratios during the initial 3 min of each condition, before finally selecting their freely chosen pedal rate i.e. their most preferred pedal rate (Table 1). Each change of gear ratio changed the pedal rate by approximately 5 rpm. The subjects were uninformed about their actual pedal rate. In a separate study we observed that freely chosen pedal rate was highly reproducible using this method (Hansen et al., submitted). Also during the initial 3 min steady state oxygen uptake was reached. Thereafter, the freely chosen pedal rate was maintained for additional 2 min, where pedal rate and work rate were measured with the SRM crank dynamometer. Oxygen uptake, pulmonary ventilation, and respiratory exchange ratio (RER) were measured with an ergo-spirometric system (AMIS 2001, Innovision, Odense, Denmark) that had previously been validated (Jensen et al., 2000). Gross efficiency was calculated from work rate and oxygen uptake, by accounting for the RER, using the same method as Coyle et al. (1992).

2.4. Study B

To investigate the effect of low and high crank inertial load on the crank torque profile, gear ratios of 26/26, 26/26, and 52/19 were used at $HL_{250\,W}$, $UL_{250\,W}$, and $HH_{250\,W}$. The combination of gear ratio and treadmill speed resulted in a pedal rate of 90 rpm during all these three cycling conditions. The subjects performed 3–4 min cycling periods at each cycling condition. At the end of each cycling period crank torque was recorded with the SRM crank dynamometer three times for each 8 s at 1000 Hz. On basis of each recording the SRM software calculated an average crank torque profile for one crank cycle. All crank torque profiles were analyzed for nadir crank torque (T_{nadir}) and peak crank torque (T_{peak}). Furthermore, the difference between T_{peak} and T_{nadir} was calculated and termed T_{delta}. T_{peak}, T_{nadir}, and T_{delta} for each subject and cycling condition were then found by averaging values from the three recordings.

Table 1
Details from the experimental set-up of Study A. The subjects could freely choose a pedal rate within the range presented in this table. Crank inertial load is calculated for a 70 kg individual cycling with a mass of 5.1, 8.2, 1.6, and 2.7 kg on the weight magazine (m_W) during the $HL_{150\,W}$, $HL_{250\,W}$, $HH_{150\,W}$, and $HH_{250\,W}$ cycling conditions, respectively

Cycling condition	Treadmill speed (km h^{-1})	Available gear ratios (chain wheel/freewheel)	Available range of pedal rate (rpm)	Range of crank inertial load (kg m^2)
$HL_{150\,W}$	11.2	36,26/19,21,23,24,26,28	47–95	9–36
$HL_{250\,W}$	11.2	36,26/19,21,23,24,26,28	47–95	9–37
$UL_{150\,W}$/$UL_{250\,W}$	11.2	36,26/19,21,23,24,26,28	47–95	8–34
$HH_{150\,W}$	30.9	52,36/12,13,14,15	56–102	56–182
$HH_{250\,W}$	30.9	52,36/12,13,14,15	56–102	57–184

Table 2
Results from Study A

Cycling condition	Resistance[a]	Work rate (W)	Crank inertial load ($kg\,m^2$)	Freely chosen pedal rate (rpm)	Pulmonary ventilation ($l\,min^{-1}$)	Oxygen uptake ($l\,min^{-1}$)	RER	Gross efficiency (%)
$HL_{150\,W}$	5.1±0.2 kg	153±5	20±7.7	69±11	52.0±2.9	2.34±0.09	0.85±0.06	19.4±1.2
$UL_{150\,W}$	6.4±0.7%	152±6	18±8.0	69±11	51.0±3.2	2.33±0.14	0.85±0.04	19.4±1.2
$HH_{150\,W}$	1.6±0.1 kg	150±4	120±35.6	75±12[b]	52.6±3.7	2.33±0.18	0.86±0.04	19.3±1.3
$HL_{250\,W}$	8.1±0.3 kg	251±7	16±4.6	74±11[c]	80.0±5.4	3.41±0.15	0.91±0.04	21.4±1.2[c]
$UL_{250\,W}$	10.3±1.0%	252±7	16±5.1	73±10[c]	79.4±6.9	3.47±0.17	0.91±0.03	21.0±1.4[c]
$HH_{250\,W}$	2.7±0.1 kg	248±8	103±28.5	82±12[c,b]	82.0±7.4	3.47±0.19	0.92±0.03	20.8±1.1[c,d]

[a] *Resistance* refers to the mass on the weight magazine (m_W) or the slope of the treadmill that was necessary to attain the target work rate.
[b] Significantly different from the HL and UL cycling conditions at same work rate.
[c] Significantly different from the similar cycling condition at 150 W.
[d] Significantly different from the $HL_{250\,W}$ cycling condition.

Table 3
Results from Study B

Cycling condition	Resistance[a]	Work rate (W)	Crank inertial load ($kg\,m^2$)	Pedal rate (rpm)	T_{nadir} (Nm)	T_{peak} (Nm)	T_{delta} (Nm)
$HL_{250\,W}$	8.3±0.4 kg	249±4	11±0.5	90.4±0.3	13.9±2.3	38.7±3.2	24.8±5.2
$UL_{250\,W}$	10.9±1.0%	251±6	10±0.6	90.4±0.3	14.4±2.7	38.1±2.2	23.8±4.7
$HH_{250\,W}$	2.8±0.1 kg	254±9	76±4.3	90.3±0.2	13.9±3.3	40.2±2.9[b]	26.3±5.9[c]

[a] *Resistance* refers to the mass of the weight magazine (m_W) or the slope of the treadmill that was necessary to attain the target work rate.
[b] Significantly different from the $HL_{250\,W}$ and $UL_{250\,W}$ cycling conditions.
[c] Significantly different from the $UL_{250\,W}$ cycling condition.

2.5. Statistics

All data are presented as mean ± SD, unless otherwise indicated. For analysis of differences between 150 and 250 W at HL, UL, as well as HH, respectively, a Wilcoxon matched-pairs signed-rank test was performed using the tables of Hinkle et al. (1994). For analysis of differences between HL, UL, and HH, at 150 as well as 250 W, an ANOVA test for repeated measures was used, followed by Fisher's PLSD test. $p<0.05$ was considered statistically significant.

3. Results

Crank inertial load was on average 6 to 8 times higher at HH compared with HL and UL at 150 as well as 250 W (Tables 2 and 3).

Study A showed that freely chosen pedal rate at $HH_{150\,W}$ on average was 6 rpm higher compared with $HL_{150\,W}$ and $UL_{150\,W}$, respectively (Table 2 and Fig. 4). Similarly, freely chosen pedal rate at $HH_{250\,W}$ was on average 8 and 9 rpm higher compared with $HL_{250\,W}$ and $UL_{250\,W}$, respectively. These differences were significant. Freely chosen pedal rates at HL and UL were similar at both 150 and 250 W. Freely chosen pedal rate was on average 7, 5, and 4 rpm higher at 250 compared with 150 W at HH, HL, and UL, respectively, these differences being significant. Gross efficiency was on average 0.6 percentage points lower at $HH_{250\,W}$ compared with $HL_{250\,W}$ (Table 2). Further, gross efficiency was on average 1.5–2.0 percentage points higher at 250 compared with 150 W at HH, HL, and UL, respectively. These differences were significant. Regarding the bicycle acceleration (Fig. 3) the difference between peak and nadir of the acceleration curve was $1.3\pm0.7\,m\,s^{-2}$ as an overall mean for three subjects tested in the six cycling conditions in Study A.

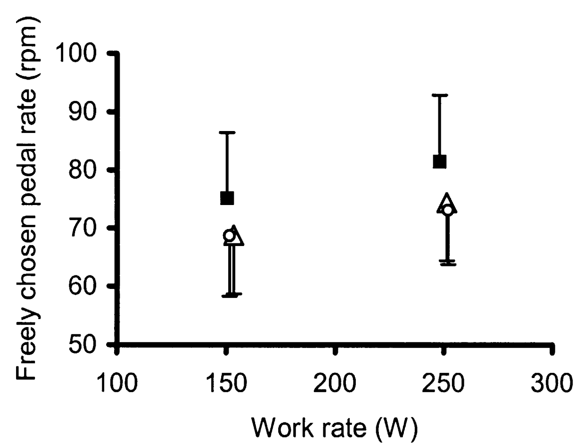

Fig. 4. Freely chosen pedal rate at 150 and 250 W. Solid squares represent the HH cycling condition while open triangles and circles represent the HL and UL cycling conditions, respectively. Note that freely chosen pedal rate is similar for the $HH_{150\,W}$, $HL_{250\,W}$, and $UL_{250\,W}$ cycling conditions.

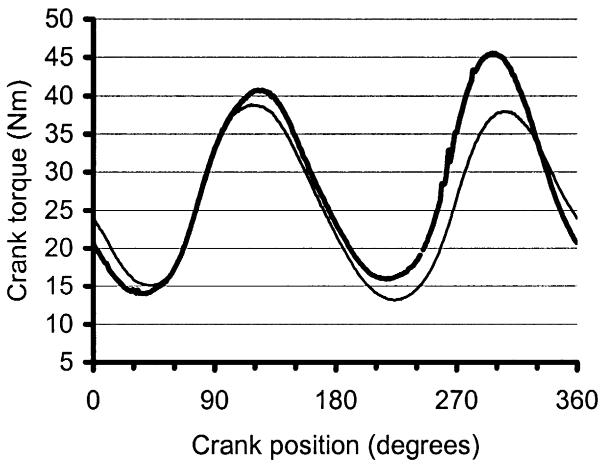

Fig. 5. Crank torque profiles from a subject, who performed the $HH_{250\,W}$ (thick curve) and the $UL_{250\,W}$ (thin curve) cycling conditions (90 rpm) in Study B. Note that peak crank torque is higher for the $HH_{250\,W}$ compared with the $UL_{250\,W}$ cycling condition.

Study B showed that during cycling with 90 rpm T_{peak} at $HH_{250\,W}$ on average was 3.4 and 5.3% higher compared with $HL_{250\,W}$ and $UL_{250\,W}$, respectively, and that T_{delta} at $HH_{250\,W}$ on average was 10.3% higher compared with $UL_{250\,W}$, these differences being significant (Table 3 and Fig. 5). Further, T_{delta} at $HH_{250\,W}$ was on average 6.1% higher compared with $HL_{250\,W}$, although this was not significant. The crank torque profiles at $HL_{250\,W}$ and $UL_{250\,W}$ were similar.

The variation in m_W and slope of the treadmill across the subjects in Studies A and B was due to the variation in body mass of the subjects which caused the rolling resistance and/or the resistance due to gravity to vary (Tables 2 and 3). The variation in crank inertial load across the subjects was due to variations in m_W and body mass of the subjects. The slightly higher crank inertial load at $HL_{250\,W}$ compared with $UL_{250\,W}$ in Study B (Table 3), despite that identical gear ratios were used, was due to the magnitude of m_W that was zero at $UL_{250\,W}$.

4. Discussion

4.1. Freely chosen pedal rate

The present study showed that freely chosen pedal rate was affected by crank inertial load. At both 150 and 250 W, freely chosen pedal rate was higher at HH compared with UL. This was in agreement with two previous studies that investigated other issues. However, both implied that freely chosen pedal rate was higher during high speed horizontal cycling compared with low speed uphill cycling. One study investigated this issue by interviewing cyclists (Hagberg et al., 1979). The other study (Caldwell et al., 1998) simulated high speed horizontal cycling and low speed uphill cycling on a Velodyne cycle ergometer where crank inertial load could be increased approximately 7 times (Fregly et al., 2000). However, these studies did not report values of the crank inertial load used. It could be speculated that the slightly changed sitting position during uphill cycling compared with horizontal cycling affected the freely chosen pedal rate. Still, our hypothesis was that the increase in crank inertial load would cause the subjects to increase their freely chosen pedal rate. Therefore, in addition to the high speed horizontal cycling condition (HH) and the low speed uphill cycling condition (UL), we also studied a low speed horizontal cycling condition (HL) where the crank inertial load was similar to UL but where the sitting position was similar to that at HH. In support of our hypothesis, our results showed that at both 150 and 250 W, freely chosen pedal rate was higher at HH compared with HL. Furthermore, freely chosen pedal rate at HL was similar to UL.

Work rate also affected freely chosen pedal rate. At 250 W freely chosen pedal rate was on average 4 to 7 rpm higher compared with 150 W at HL, UL, and HH, respectively. This result agreed with a separate study from our institute using the same experimental set-up (Hansen et al., submitted). However, it conflicted with two other studies (Marsh and Martin, 1998; Marsh et al., 2000) where a Velodyne cycle ergometer was used. The Velodyne cycle ergometer has variable crank inertial load and the authors did not specify that they controlled for crank inertial load while they increased the work rate. Work rate and crank inertial load could have counteracted each other and caused freely chosen pedal rate to be unchanged. Our results support this contention; the change in crank inertial load in the present study affected the freely chosen pedal rate as much as did the change in work rate. Correspondingly, the freely chosen pedal rate at $HH_{150\,W}$ was similar to $UL_{250\,W}$ and $HL_{250\,W}$ (Fig. 4; Table 2).

The positive relationship between freely chosen pedal rate and cycling speed during horizontal road cycling found previously was purported to arise from the increase in work rate that follows from the increase in cycling speed (Pugh, 1974; Sargeant and Beelen, 1993). However, crank inertial load also increases when cycling speed increases, since the gear ratio increases (provided that a constant pedal rate is maintained). From our results, we suggest that the positive relationship between freely chosen pedal rate and cycling speed during road cycling resulted from the increase in both crank inertial load and work rate.

4.2. Gross efficiency

The present study showed a lower gross efficiency during cycling with freely chosen pedal rate at HH_{250}

compared with HL_{250}. The difference was on average 0.6 percentage point and it could be explained by the on average 8 rpm higher freely chosen pedal rate at $HH_{250\,W}$ compared with $HL_{250\,W}$. A decrease in gross efficiency with increased pedal rate above approximately 60 rpm has been a common observation (Barbeau et al., 1993; Boning et al., 1984; Gaesser and Brooks, 1975). It is interesting to observe that an increase in crank inertial load causes the subjects to freely choose a higher pedal rate, which per se reduces gross efficiency. When gross efficiency is reduced the limited energy stored in the muscles is assumed to be used faster, which is considered a drawback in relation to e.g. long duration performance. Gross efficiency was similar at $HH_{250\,W}$ and $UL_{250\,W}$ despite a difference in freely chosen pedal rate between these two cycling conditions that was similar to the difference between $HH_{250\,W}$ and $HL_{250\,W}$. The reason possibly was that uphill cycling changed the sitting position slightly and that this required additional muscular activity e.g. in upper body muscles compared with horizontal cycling. No differences in gross efficiency were observed between $HL_{150\,W}$, $UL_{150\,W}$, and $HH_{150\,W}$. The reason possibly was the smaller differences in freely chosen pedal rate (on average 6 rpm) between these cycling conditions compared with the corresponding cycling conditions at 250 W. The gross efficiency was higher at 250 compared with 150 W at HL, UL, and HH, respectively. The reason possibly was that resting metabolism accounted for a smaller part of the total metabolism at higher work rates and the result was in agreement with several earlier studies (Boning et al., 1984; Gaesser and Brooks, 1975; Seabury et al., 1977). However, of interest is that in all these earlier studies, cycling was performed with preset pedal rates, while in our study, cycling was performed with freely chosen pedal rates. As a result, in the present study, gross efficiency was higher at 250 compared with 150 W despite a 4 to 7 rpm higher pedal rate at 250 compared with 150 W.

4.3. Crank torque

Even if cycling is performed steadily with a constant average pedal rate, variations occur in cycling (and crank) acceleration within each crank cycle (Fig. 3). The reason is that crank positions near 90 and 270 degrees are more optimal for crank torque production compared with the rest of the crank cycle (Redfield and Hull, 1986). Performing these bicycle (and crank) accelerations with different crank inertial loads will result in different crank torque profiles.

Our study showed that during cycling with 90 rpm T_{peak} was higher at $HH_{250\,W}$ compared with $UL_{250\,W}$ and $HL_{250\,W}$. Further, T_{delta} was higher at $HH_{250\,W}$ compared with $UL_{250\,W}$ and $HL_{250\,W}$, although only significant between $HH_{250\,W}$ and $UL_{250\,W}$. These results agreed with an earlier study by Fregly et al. (1996). They found slightly higher increases in T_{peak} and T_{delta} (7 and 13%, respectively) during cycling with high compared with low crank inertial load. However, they increased crank inertial load 20 times (from 6.5 to 130 kg m^2) compared with 6 to 8 times in the present study.

It is speculated that the higher T_{peak} and T_{delta} resulted in an increased stimulation of mechanoreceptors in the legs and that the higher T_{delta} called for increased rate of force development to be performed by the active muscles. In combination this possibly induced an increase in muscle activity and a change in muscle fiber recruitment from slow twitch fibers towards more fast twitch fibers as well as an increase in perceived exertion. In response the subjects possibly increased the pedal rate to reduce the mechanical load, since pedaling faster at a given work rate reduces the mean and peak crank torque. In this context it should be mentioned that the increase in pedal rate reduced the T_{peak} and T_{delta} in two ways: One from the increased pedal rate per se that also reduced the mean crank torque, and another from the reduced crank inertial load, caused by the lower gear ratio. For example, a gear ratio of 46/14, resulting in 74 rpm at 30.9 km h^{-1} causes the crank inertial load to be 106 kg m^2 for a 70 kg individual. Alternatively, a gear ratio of 36/12, resulting in 82 rpm at 30.9 km h^{-1} causes the crank inertial load to be 88 kg m^2 for the same individual.

4.4. Crank inertial load

One of the implicit assumptions of this study was that treadmill cycling could be used to achieve crank inertial loads comparable to those of road cycling in the same gear ratio. Since the results of the study were valid only to the extent that this was true, evaluation of this important assumption was warranted. Such an evaluation based on engineering mechanics is outlined in the Appendix A. The primary conclusions of this evaluation were that the assumption was reasonable for the low crank inertial load cases and less reasonable for the high ones. Consequently, for the low crank inertial load cases, the calculated crank inertial load values were close to the values experienced by the subjects. For the high crank inertial load cases, the calculated values were likely lower than that experienced by the subjects, since reduced forward accelerations of the bicycle due to large backward accelerations of the treadmill belt would make the perceived crank inertial load seem larger than the calculated value. However, additional analyses (see Appendix A) suggest that our high crank inertial load values were at least as large as, and probably not excessively larger than, our calculated values.

In conclusion, freely chosen pedal rate was higher during cycling with high compared with low crank inertial load. Interestingly, the change in crank inertial load affected the freely chosen pedal rate as much as the 100 W increase in work rate. Higher crank inertial load resulted in higher peak crank torque at a constant pedal rate that via increased mechanoreceptor stimulation possibly induced an increase in perceived exertion. This in turn possibly caused the subjects to increase their pedal rate, since both mean and peak crank torque was thereby reduced. However, an increase in pedal rate may reduce the gross efficiency and subsequently the long duration performance. It is therefore important to account for crank inertial load when investigating cycling performance.

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Appendix A

This appendix evaluates the assumption that treadmill cycling can be used to achieve crank inertial loads comparable to those of road cycling in the same gear ratio.

From an engineering mechanics perspective, a treadmill simulates the drive system dynamics of road cycling to the extent that the treadmill speed remains constant. This statement is supported by the concept of a secondary Newtonian reference frame. Let N be a Newtonian (or inertial) reference frame fixed to the Earth, B a reference frame moving with the treadmill belt, P a point fixed on the bicycle frame, and $\bar{B}$ a point fixed on the treadmill belt but coincident with P at the instant under consideration. Then since reference frame B is only translating, rigid body kinematics provides the following relationship between the acceleration of point P in reference frames N and B (Kane and Levinson, 1985):

$$^{N}\mathbf{a}^{P} = {}^{N}\mathbf{a}^{\bar{B}} + {}^{B}\mathbf{a}^{P},$$

where $^{N}\mathbf{a}^{P}$ = acceleration of point P in reference frame N, $^{N}\mathbf{a}^{\bar{B}}$ = acceleration of point $\bar{B}$ in reference frame N, $^{B}\mathbf{a}^{P}$ = acceleration of point P in reference frame B.

For the bicycle drive system dynamics to be the same on the treadmill as on the road, we must have $^{N}\mathbf{a}^{P} = {}^{B}\mathbf{a}^{P}$, which will be true if and only if $^{N}\mathbf{a}^{\bar{B}} = 0$. In reality, the acceleration of the treadmill belt will not be zero, and it becomes necessary to define how close to zero is close enough. To answer this question, one can investigate the ratio $|^{N}\mathbf{a}^{\bar{B}}|/|^{N}\mathbf{a}^{P}|$. If this ratio is close to zero, then the treadmill belt can be treated as a secondary Newtonian reference frame, and the treadmill provides a good representation of the crank inertial load experienced during road cycling. Note that the Earth is the most common example of a secondary Newtonian reference frame, since the Earth moves with respect to the Sun, yet we can still treat it as an inertial frame for movements performed close to the surface of the Earth.

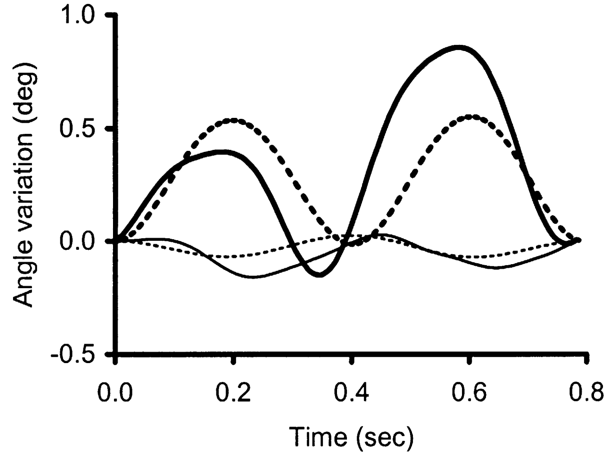

Fig. 6. Comparison of crank angle and scaled tower potentiometer variations between the present study and that of Fregly et al. (2000). Trials with similar experimental conditions were chosen for comparison (see Appendix A). The thick curves represent the crank angle variations, while the thin curves represent the tower potentiometer variations scaled by gear ratio times wheel radius. Solid curves represent the present study, while dashed curves represent the study of Fregly et al. (2000).

The ratio defined above was calculated for the three subjects for whom the bicycle translation with respect to the laboratory was measured with the tower potentiometer. To estimate $|^{N}\mathbf{a}^{\bar{B}}|$, we differentiated the measured treadmill speed variations assuming they were sinusoidal with two cycles per crank revolution. To estimate $|^{N}\mathbf{a}^{P}|$, we differentiated the tower potentiometer data twice with respect to time. We found that for the high crank inertial load conditions, the ratio varied between 0.5 and 1.25, while for the low crank inertial load conditions, it varied between 0.06 and 0.17. Consequently, the treadmill belt can be regarded as a secondary Newtonian reference frame only for the low crank inertial load conditions.

As a check on our calculated crank inertial load values, we analyzed whether the measured crank angle variations from each cycling condition were consistent with these values. Fregly et al. (2000) showed that if the pedal rate is above a certain critical value, then the intracycle variations in crank angle should be in phase with the crank torque. They provided a theoretical equation for this critical pedal rate, which requires an effective drive system stiffness and crank inertial load as inputs. We assumed an effective stiffness of 3000 Nm rad^{-1} in all cases (Fregly et al., 2000) and used our calculated crank inertial load values in this equation. We found that for all trials, the freely chosen pedal rate was above the critical pedal rate, and furthermore, that the intra-cycle variations in crank angle were consistent with this finding. Thus, for all cycling conditions, the crank inertial load was likely *at least* as large as the calculated values.

To evaluate further our crank inertial load values, we compared the intra-cycle variations in crank angle and tower potentiometer data with similar data generated from Fregly et al. (2000). The comparison was made using one high crank inertial load experimental trial (i.e., 76.4 rpm, 257 W and $112.9\,\mathrm{kg\,m^{-2}}$) that was extremely similar to conditions used in Fregly et al. (2000) (i.e., 75 rpm, 225 W and $101.6\,\mathrm{kg\,m^{-2}}$). However, while we used a treadmill, Fregly and co-workers used a stationary ergometer with a geared-up flywheel. As shown in Fig. 6, the variations in crank angle (thick curves) and tower potentiometer (thin curves - scaled by gear ratio times wheel radius) data were extremely similar between the two studies. This suggests that our high crank inertial load values may not have been excessively greater than the calculated values.

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