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ORIGINAL ARTICLE

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Maximal power and torque-velocity relationship on a cycle ergometer during the acceleration phase of a single all-out exercise

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Abstract Seven subjects pedalled on a Monark cycle ergometer as fast as possible for approximately 7 s against four different resistances which corresponded to braking torques (T_B) equal to 19, 38, 57 and 76 N·m at the crank level. Exercise periods were separated by 5-min recovery periods. Pedal velocity was recorded every 50 ms by means of a disc with 360 slots fixed on the flywheel, passing in front of a photo-electric cell linked to a microcomputer which processed the data. Every 50 ms, the time necessary to perform half a pedal revolution ($t_{1/2}$) was computed by adding the 50-ms periods necessary to reach 669 slots (the number of slots corresponding to half a pedal revolution). To measure $t_{1/2}$ to an accuracy better than 50 ms, this time was computed by a linear interpolation of the time-slot number relationship. Power (P) was averaged during $t_{1/2}$ by adding the power dissipated against braking torque and the power necessary to accelerate the flywheel. The torque-velocity (T–v) relationship was studied during the acceleration phase of a sprint against a single T_B by computing every 50 ms the relationship between v and T (N·m), equal to the sum of T_B and the torque necessary to accelerate the flywheel at the same time. The T–v relationships calculated from the acceleration phase of a single all-out exercise were linear and similar to the previously described relationships between peak velocity and braking force. These relationships can be expressed as follows: $v = v_{0,acc}(1 - T/T_{0,acc})$ where v is pedal velocity, T the torque exerted on the crank and $T_{0,acc}$ and $v_{0,acc}$ have the dimensions of maximal torque and maximal velocity respectively. Based on this model, maximal power ($P_{max,acc}$) is calculated as $0.25\, v_{0,acc}\, T_{0,acc}$. Maximal power $P_{max,acc}$ measured with the acceleration method was independent of braking torque T_B and slightly higher than P_{max} calculated from the relationship between peak velocity and T_B.

Key words Exercise · Power · Anaerobic testing Cycling

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Introduction

A linear relationship between the braking force (F) exerted on the circumference of the flywheel of a friction loaded ergometer and the corresponding peak pedal velocity (v_{peak}) has been found during short-duration all-out exercise for resistances corresponding to v_{peak} ranging between 100 and 210 rpm (Nadeau et al. 1983; Nakamura et al. 1985; Pérès et al. 1981; Vandewalle et al. 1985, 1987). Similar linear relationships have also been found on isokinetic cycle ergometers (McCartney et al. 1983; Sargeant et al. 1981). The relationship between F (in newtons) and v_{peak} (in revolutions per minute) can also be expressed by the following equations (Vandewalle et al. 1985, 1987):

$$v_{peak} = v_0(1 - F/F_0) \quad \text{or} \quad F = F_0(1 - v_{peak}/v_0)$$

where v_0 and F_0 are parameters which have the dimensions and the meanings of the maximal value of v_{peak} and maximal F respectively. Based on this model, maximal power (P_{max}) has been calculated as $0.25\, v_0 F_0$. Such a linear relationship does not mean that the classic force-velocity relationship does not apply to muscle acting during cycling. Even if F acting on the flywheel were perfectly constant, the magnitude and direction of the force exerted on the pedal vary during a revolution. Consequently, the linear relationship between F and v is equivalent to a relationship between v and the average value of the perpendicular force component of the crank force, i.e. equivalent to a relationship between the average value of the corresponding torque exerted at the crank level (T_B) and v.

The relationship between F and v can be transformed into an equivalent relationship between the braking torque T_B (N · m) exerted at the pedal level and v_{peak} (radians per second) with T_0 as the T_B corresponding to zero velocity:

$$v_{peak} = v_0(1 - T_B/T_0) \quad \text{or} \quad T_B = T_0(1 - v_{peak}/v_0)$$

Based on this model, P_{max} may be calculated as $0.25\, v_0 T_0$.

Unfortunately, the total duration of this kind of test is rather long since subjects must recover for 5 min between the exercise periods corresponding to the different T_B. At v_{peak}, T corresponds to T_B necessary to move the flywheel against the braking force. During the acceleration phase, the subjects have to produce a supplementary torque (T_k), necessary to accelerate the flywheel of the cycle ergometer and to increase its kinetic energy. If the subjects exert a maximal effort, T ($T = T_B + T_k$) would be the maximal T corresponding to v at that time. Consequently, it should theoretically be possible to determine the T–v relationship on a cycle ergometer during a single all-out exercise against a small T_B, provided that the subjects exert a maximal effort from the very beginning (v equal to zero) to the end of the acceleration phase (v around 21 rad · s^{-1}, i.e. around 200 rpm). In the present study we have tried to ascertain whether the relationship between T and v is similar to the relationship between v_{peak} and T_B and can be expressed as follows:

$$v = v_{0,acc}(1 - T/T_{0,acc}) \quad \text{or} \quad T = T_{0,acc}(1 - v/v_{0,acc})$$

where $v_{0,acc}$ and $T_{0,acc}$ are parameters which have the dimensions and the meanings of maximal v and maximal T. Based on these models, maximal power ($P_{max,acc}$) was calculated as $0.25\, v_{0,acc} T_{0,acc}$. In the present study, we have compared the values of P_{max}, v_0 and T_0 (calculated from the relationship between v_{peak} and T_B) with the different values of $P_{max,acc}$, $v_{0,acc}$ and $T_{0,acc}$ (calculated from the acceleration phase) corresponding to different T_B.

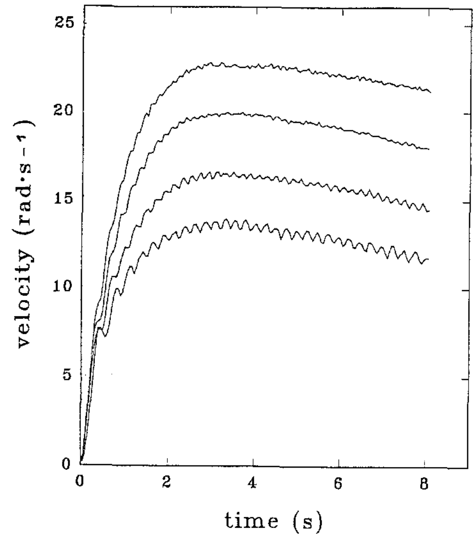

Fig. 1 Time-velocity curves during short sprints on cycle ergometer against different braking torques (19, 38, 57, 76 N · m). Velocity oscillations correspond to half a pedal revolution

Methods

Protocol

Seven subjects pedalled on a Monark cycle ergometer (model 864), which enabled a given T_B to be set before cycling. They were encouraged to cycle as fast as possible during the test until the end of the exercise (approximately the 7th s). The first T_B corresponded to a 19 N · m torque at the crank level. The T_B was increased by 19 N · m increments and the subjects performed the same exercise after 5 min recovery up to the last T_B equal to 76 N · m. Thereafter, the two first exercises (against 19 N · m and 38 N · m) were repeated again.

Measurement of pedal velocity

The v (Fig. 1) was recorded every 50 ms using a disc fixed on the axis of the flywheel of the cycle ergometer. This disc presented 360 slots which passed in front of a photo-electric cell. Given that the crank wheel and the sprocket of the flywheel consisted of 52 and 14 teeth respectively, one pedal revolution corresponded to a 1337.143 slot deplacement of the flywheel disc (669 slots for half a pedal revolution). The electric cell was linked to a PC XT microcomputer which counted the slot number every 50 ms. The relationship between angular v (in radians per second) and the angular velocity of the flywheel v_f (in radians per second) was:

$$v = 14\, v_f/52$$

The T exerted on the pedal and power-output (P) varied within a pedal revolution showing two peaks corresponding to the power exerted by each leg (for example, see data presented by Sargeant et al. 1981) and the time-velocity curve (Fig. 1) presented oscillations which corresponded to half a revolution of the crank. Consequently, the average T and P could vary even at constant v if the average did not correspond to an integer value of pedal revolutions (or half revolution). Therefore, to compute average T and P, our v were not averaged according to time but according to pedal motion (half a revolution) by computing the time necessary to perform half a pedal revolution ($t_{1/2}$). Every 50 ms, $t_{1/2}$ was computed by adding the 50-ms periods necessary to reach 669 slots. To measure $t_{1/2}$ with an accuracy better than 50 ms, this time was computed by a linear interpolation of the time-slot number relationship.

Torque computation

When F (in newtons) is acting on the circumference of the flywheel which has a radius r (0.262 m), the braking torque exerted on the flywheel (T_F) is:

$$T_F = F \cdot r$$

The T_B which is exerted on the crank would not be equal to T_F but would be given by the following equation:

$$T_B = 52\, T_F/14$$

When T_{kf} is the average torque exerted on the flywheel and necessary to accelerate it and to increase its kinetic energy during half a revolution, T_{kf} would be calculated as equal to the product of flywheel inertia (I) and angular velocity difference between the beginning and the end of each half a revolution and divided by $t_{1/2}$.

$$T_{kf} = I(v_{f,end} - v_{f,beginning})/(t_{1/2})$$

where $v_{f,beginning}$ and $v_{f,end}$ were the value of flywheel angular velocity at the beginning and the end of the half revolution. The $v_{f,beginning}$ and $v_{f,end}$ corresponded to the value of v_f computed from the value of $t_{1/2}$ at the beginning and the end of the half revolution. The value of the corresponding torque at the crank level was equal to:

$$T_k = 52\ T_{kf}/14$$

The T exerted on the pedals was calculated by adding T_B and T_k

$$(T = T_B + T_k).$$

T–v relationship

The T–v relationships of the acceleration phase refer to the relationship between v (computed every 50 ms from the calculated values of $t_{1/2}$) and T (in N·m), equal to the sum of T_B and T_k at the same time. The individual T–v relationships were calculated from all the T and v data, computed every 50 ms from the second half of a pedal revolution up to v_{peak}.

In addition, we calculated the relationship between T_B and v_{peak}. To compare the results of the T–v relationship during the acceleration phase with the results obtained from a protocol close to that of the "force-velocity test" which we had used in previous studies (Vandewalle et al. 1985, 1987), v_{peak} corresponded to the peak value of the moving average calculated from 20 consecutive measurements (i.e. 1 s). The relationship between T_B and the corresponding v_{peak} did not take into account the first trials at 19 and 38 N·m because they were considered as warming-up and learning exercises (Vandewalle et al. 1985, 1987).

The values of v_0 and T_0 were calculated from the linear T_B–v_{peak} relationships as follows:

$$v_{peak} = a - bT_B = a(1 - bT_B/a) = v_0(1 - T_B/T_0)$$

$v_{0,acc}$ and $T_{0,acc}$ were similarly calculated from the linear relationship between the values of v and T computed every 50 ms during the acceleration phase.

$$v = a - bT = a(1 - bT/a) = v_{0,acc}(1 - T/T_{0,acc})$$

The different linear relationships between v and T (or T_B and v_{peak}) were calculated according to the least squares method.

Power output computation

The P was averaged during half a pedal revolution by adding the power dissipated against T_B (P_B) and the power necessary to accelerate the flywheel and to increase its kinetic energy (P_k). The value of P_k was calculated as equal to the difference of kinetic energy between the beginning and the end of half a pedal revolution, divided by the time necessary to perform half a revolution ($t_{1/2}$).

$$P = P_B + P_k = vT_B + 0.5I(v_{f,end}^2 - v_{f,beginning}^2)/t_{1/2}$$

Maximal power-output computation

Maximal power-output (P_{max}) was calculated according to three different methods:

1. P_{max} from the relationship between v_{peak} and T_B ($P_{max} = 0.25\ v_0 T_0$);
2. Peak P_{max} corresponding to the highest power output during the acceleration phase. For each subject, four peak P_{max} corresponding to the four different T_B were calculated from the time-power output curves during the acceleration phases (peak P_{max} = peak value of P for a given T_B);
3. For the four T_B, $P_{max,acc}$ were calculated from the values of $T_{0,acc}$ and $v_{0,acc}$ given by the linear relationship between T and v during the acceleration phases corresponding to a given T_B ($P_{max,acc} = 0.25\ T_{0,acc} v_{0,acc}$).

Measurement of I

If the resistances located in cranks, chain-wheel, chain, gear and ball-bearings are considered as negligible, the F applied to the circumference of the flywheel are the only cause of the acceleration or deceleration in the absence of power exerted on the pedals. In this case, the relationship between F (in newtons) acting on the circumference of the flywheel, the angular acceleration or deceleration of the flywheel (dv_f/dt in radians per second squared) and I (in kilograms per metre squared) was:

$$I\ dv_f/dt = F \cdot r = T_F$$

$$I = T_F/(dv_f/dt)$$

Therefore, it was possible to measure I by determining the deceleration induced by a calibrated T_B in the absence of power exerted on the pedals. A subject cycled against different T_F (equivalent to T_B equal to 14.5 to 57 N·m at the crank level) up to a high pedalling frequency (between 10 and 15 rad·s^{-1}, i.e. approximately 100 and 150 rpm) and thereafter stopped cycling and took his feet off the pedals. Velocity was measured during the deceleration phases due to the different T_F acting on the flywheel. The I could be calculated from the slope of the experimental linear relationship between flywheel deceleration (in radians per second squared) and T_F (in newton metres) acting on the flywheel:

$$dv_f/dt = aT_F + b$$

Indeed, provided that the value of b was very close to 0, we could write:

$$I = T_F/(dv_f/dt) = T_F/(aT_F + b) = 1/a$$

The slope a of this relationship was equivalent to the proportionality coefficient between acceleration and the force necessary to accelerate the flywheel as proposed in the study by Lakomy (1986).

Check of the v and the computing programs

The accuracy of the measurement of v and the calculation of T and P could be estimated by feeding the data processing programs with the data corresponding to the procedure for I measurement. Indeed, in the absence of power exerted on the crank, computed P and T should be equal to 0 if there were no error in v measurement and P or T computing and no mechanical flaw.

Results

Value of I

The relationship between flywheel deceleration (dv_f/dt in radians per second squared) and T_F (in newton metres) acting on the flywheel was:

$$dv_f/dt = 2.89\ T_F + 0.0463 \qquad r = 0.99$$

Whence

$$I = (1/2.89)\,\text{kg}\cdot\text{m}^2 = 0.346\ \text{kg}\cdot\text{m}^2$$

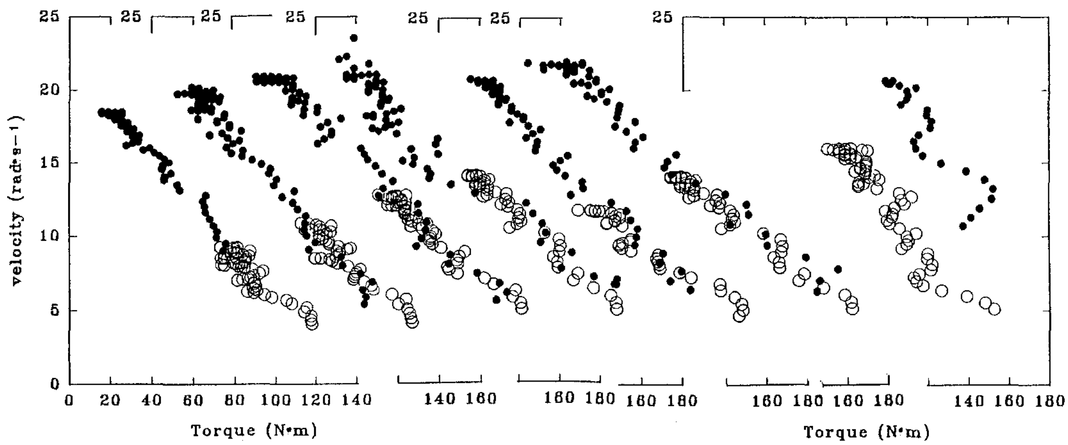

Fig. 2 Individual relationships between velocity and total torque equal to braking torque + kinetic torque during the acceleration phase of the sprints against 19 N.m (*black dots*) and 76 N·m (*unfilled circles*) braking torques in the seven subjects. Note that the different individual relationships have been shifted to the right so that they may be displayed in the same figure without being superimposed

T–v relationships

The T–v relationship measured during the acceleration phase was linear between 4 and 20 rad·.s^{-1}. Data collected during the exercises corresponding to T_B equal to 19 and 76 N·m are presented in Fig. 2. Similar linear T–v relationships were observed for 38 and 57 N·m. Parameter v_0, calculated from the relationship between T_B and v_{peak}, was not significantly different from the values of $v_{0,acc}$ corresponding to the various T_B (Table 1). But $v_{0,acc}$ for 76 N.m was significantly different from the other values of $v_{0,acc}$.

The $T_{0,acc}$ for 76 N·m (Table 2) was significantly different from the T_0 (calculated from the relationship between T_B and v_{peak}) only ($P < 0.05$).

Maximal power output

The P_{max} was significantly correlated with peak P_{max} for the different T_B ($0.001 < P < 0.02$). Nevertheless, P_{max} was significantly lower than all the values of peak P_{max} ($P < 0.05$ for 19 and 38 N·m and $P < 0.01$ for 57 and 76 N·m) (Table 3).

On the other hand, there was no statistical difference between the different peak P_{max} values measured during the acceleration phases against the four T_B (Table 4).

The P_{max} and $P_{max,acc}$ for 76 N·m were significantly lower than the values of $P_{max,acc}$ for 19 N·m ($P < 0.05$). $P_{max,acc}$ for 76 N·m was also significantly lower than $P_{max,acc}$ for 38 N·m (Table 3).

At a given braking T_B, peak P_{max} was higher than $P_{max,acc}$ for 76 N·m only.

The higher the T_B, the longer was the time to peak P_{max} (mean ± SD): 0.59 ± 0.15 s (19 N·m), 1.00 ± 0.42 s (38 N·m), 1.48 ± 0.73 s (57 N·m) and 2.01 ± 1.04 s (76 N·m).

Time to v_{peak} (mean ± SD = 3.53 ± 0.33 s for all the exercises) was independent of T_B and much longer than time to peak power at low T_B.

Table 1 Values of parameters which have the dimensions and the meanings of maximal peak velocity and maximal pedal velocity (v_0 and $v_{0,acc}$ in radians per seconds) for the different braking torques (19 to 76 N·m)

Subject	$v_{0,acc}$ 19 N·m	38 N·m	57 N·m	76 N·m	v_0
1	23.7	23.5	22.1	18.8	24.9
2	23.7	23.9	24.0	23.7	22.1
3	23.0	22.6	20.9	19.6	23.1
4	24.0	22.9	25.0	22.1	24.5
5	23.7	28.2	23.0	21.7	22.9
6	21.5	20.8	22.0	16.8	21.8
7	38.0	25.4	24.7	29.1	21.8
Mean	25.4	23.9	23.1	21.7	23.0
SD	5.6	2.3	1.5	4.0	1.3

Table 2 Values of parameters which have the dimensions and the meanings of maximal torques a zero velocity (T_0 and $T_{0,acc}$ in N·m) for the different braking torques (19 to 76 N·m)

Subject	$T_{0,acc}$ 19 N·m	38 N·m	57 N·m	76 N·m	T_0
1	169	189	196	202	148
2	202	191	184	190	191
3	143	141	155	165	139
4	210	224	242	214	180
5	172	150	170	181	172
6	142	155	141	159	137
7	220	212	188	172	259
Mean	180	180	182	183	175
SD	31	32	32	20	42

Check of the v measurement and the computing programs

The time-velocity relationships corresponding to the different T_B in the deceleration experiments were not perfectly linear; small v oscillations were observed.

Table 3 Comparison between maximal power, P_{max} (equal to 0.25 v_0T_0) and $P_{max,acc}$ (equal to 0.25 $v_{0,acc}T_{0,acc}$) for exercise at the different braking torques (19 to 76 N · m)

Subject	$P_{max,acc}$ 19 N · m	38 N · m	57 N · m	76 N · m	P_{max}
1	999	1104	1079	951	923
2	1191	1136	1105	1124	1051
3	829	801	809	811	809
4	1263	1286	1508	1177	1100
5	1021	1053	980	979	986
6	764	808	777	668	746
7	2082	1350	1166	1250	1409
Mean	1164	1077	1061	994	1003
SD	409	197	228	192	219

Table 4 Comparison between maximal power, P_{max} and peak power (peak P_{max}) for different braking torques (19 to 76 N · m)

Subject	Peak P_{max} 19 N · m	38 N · m	57 N · m	76 N · m	P_{max}
1	1060	1078	1162	1029	923
2	1215	1232	1242	1226	1051
3	903	897	876	936	809
4	1357	1306	1242	1249	1100
5	1100	1062	1008	1027	986
6	832	851	862	780	746
7	1277	1375	1439	1432	1409
Mean	1106	1114	1119	1097	1003
SD	193	200	213	219	219

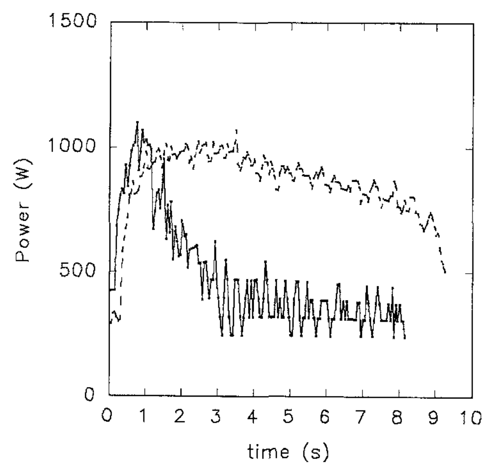

Fig. 3 Time-power output curve for braking torques equal to 19 N · m (*solid line*) and 76 N · m (*dashed line*) in the same subject

When the data were fed into the computing programs, P and T were not equal to 0 but oscillated around this value (Figs. 4, 5). For each T_B, the amplitudes of P oscillations were small and were less than $\pm$ 10 W, which corresponded to approximately 1% P_{max} in the present study. The maximal amplitude of the oscillations in computed T were close to ± 4 N · m in some cases,

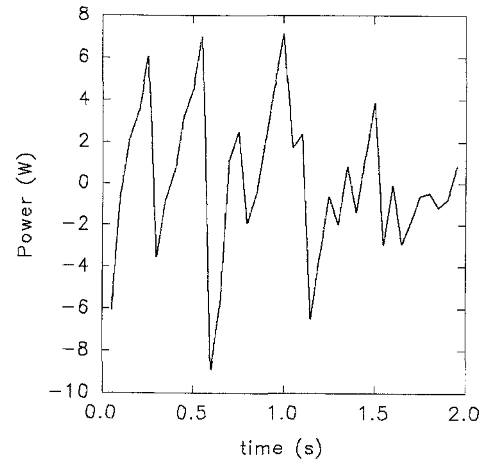

Fig. 4 Errors in computed power-output as a function of time in the deceleration experiment with a 15 N braking force exerted on the circumference of the flywheel

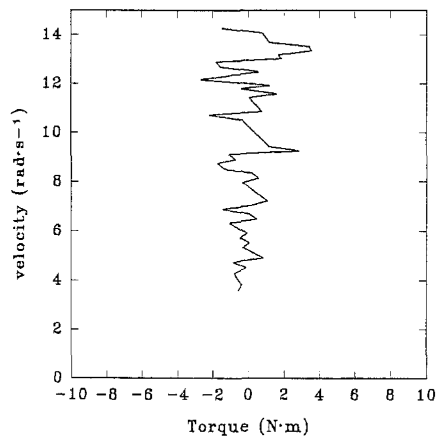

Fig. 5 Errors in computed torque as a function of velocity in the deceleration experiment with a 15 N braking force exerted on the circumference of the flywheel. Flywheel velocity is expressed as its pedal velocity equivalent (radians per second)

which was not neglible as it was approximately equal to $\pm$ 2% T_0 in the present study. As shown in Fig. 5, the higher the v, the larger were the computed T oscillations.

Discussion

The validity of the calculation of P and T depends on the accuracy of the I value. Bassett (1989) has found a 20% higher inertia (0.4166 kg · m^2) from calculations based on the mass and shape of the flywheel instead of deceleration experiments. Lakomy (1986) has presented a relationship between pedal deceleration expressed in revolutions per minute per second and braking force at the flywheel level (F expressed in kilograms), in the absence of power exerted on the pedals:

$$dv/dt = 18.1\,F + 4.1 \qquad r = 0.99$$

Our equation between T_B (newton metres) and pedal deceleration (radians per second squared) can be transformed and presented with the same units as in the Lakomy equation (F in kilograms and dv/dt in revolutions per minute per second):

$$dv/dt = 19.094\,F + 0.119 \qquad r = 0.99$$

This equation is quite close to the relationship presented by Lakomy (1986). The Lakomy equation corresponds to an I 5.5% higher than the calculated value in the present study (0.365 vs 0.346 $kg \cdot m^2$). However, the intercept with the deceleration axis is higher in the Lakomy relationship (4.1 vs 0.119), which would suggest either that the v measurement was less accurate or that forces other than T_B (for example frictional forces in ball-bearings, chain, chain wheel and gear) were not negligible at low F in the study by Lakomy. It is likely that the inertia of the ergometer in the present study was very close to that of the Lakomy ergometer as the calculated values for the deceleration are similar for medium F (equality between the Lakomy equation and our equation corresponds to 3.98 kg) and slightly different at high F (for example 149 vs 153 $rpm \cdot s^{-1}$ for 8 kg).

Origins of the oscillations

In spite of data processing according to the moving average method, there were large oscillations in computed T (Fig. 3). The origins of these oscillations could be either biological (due to the subjects) or methodological. Differences between the right and left legs and revolution-to-revolution fluctuations in muscle activation (Vandewalle et al. 1991) are possible biological causes of oscillations in T and P. Biological causes of oscillations should interact with biomechanical factors as the degrees of freedom of cycling exercise. There are at least two degrees of freedom for cycling exercise: the same pedal rotation can be produced by different combinations of knee and ankle extensions. Variations in the position on the saddle add a third degree of freedom. Moreover, pelvis movements could modify the efficiency of hip extensor and rectus femoris muscles. In theory, if the activation of all the agonistic and antagonistic muscles which exert their actions on the knee and the ankle are given and if the position of the pelvis is constant, there should be only one degree of freedom for cycling exercise. But if there are small fluctuations in the activation level of the muscles acting on the knee, the same activation levels of the muscles acting on the ankle joints correspond to different movement amplitudes of this joint and vice versa for variations in the activation of the ankle muscles. Small variations in leg muscle activation could induce larger P oscillations when combined with variations in the position on the saddle and movements of the pelvis.

The magnitude of the oscillations depends on the period of the moving average process as illustrated in Fig. 6 A and B. The oscillations were clearly smaller when the moving average was calculated on a revolution instead of half a revolution. However, the method of data processing and the period of the moving average are probably not the only causes of the oscillations. The relationship between P and flywheel motion (instead of the power output-time curve) demonstrated that the number of large oscillations was approximately equal to the number of revolutions for the half-a-revolution moving average. This result suggests that a biological factor (for example a revolution-to-revolution variation in muscle activation level) explains in part the oscillations in P. For the one-revolution moving average (Fig. 6B), the large oscillations almost disappeared, which revealed smaller oscillations whose

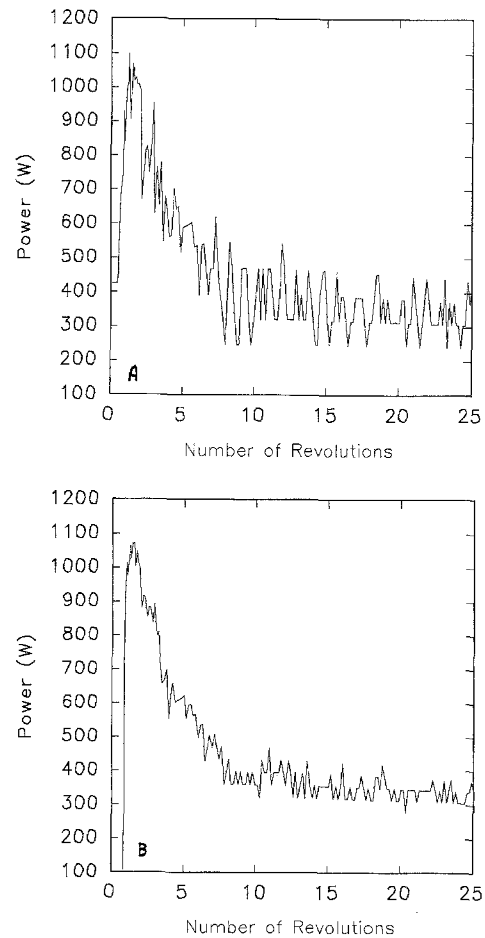

Fig. 6A,B Relationship between power output and the number of flywheel revolutions for the same subject as in Fig. 3. Power output was averaged for one revolution in **B** instead of half a revolution in **A**

frequency was higher. The number of oscillations in Fig. 6B is approximately twice the revolution number, i.e. the number of half-revolutions, which suggests that differences between the right and left legs in part explain the oscillations.

As explained in Methods, the importance of the methodological causes of fluctuations can be estimated by feeding the data processing programs with the data corresponding to the I measurement experiment. Indeed, computed P and T should be equal to 0 if there were no methodological errors. As shown in Figs. 4 and 5, the methodological causes of the oscillations in computed P and T are not negligible.

It is likely that fluctuations are partly the result of computing approximations and errors in v measurement. The sensitivity of the flywheel-motion transducer is equal to 1°. Consequently, at constant velocity, a 1° difference between two consecutive measurements is possible and the computed v can alternate between a low value and a 1° higher value. These variations are computed as equivalent to accelerations at the transitions from low to high values. These artefacts would induce oscillations in computed T and P which are not negligible for a 0.346 $kg \cdot m^2$ I. A 1° fluctuation would correspond to a 0.15% fluctuation in v as computations corresponded to half a revolution average (669 slots). For example, at 20 $rad \cdot s^{-1}$ the fluctuations of T and P_k would be equal to ± 0.993 N·m and $\pm$ 21 W, respectively. Moreover, there is a fluctuation in friction dissipated power equal to $\pm$ 0.15% as the computed $t_{1/2}$ varies. These T and P artefacts would be larger with the heavier flywheels available on some recent friction-loaded ergometers.

Mechanical flaws are other causes of the P oscillations. If the centre of mass of the flywheel does not exactly coincide with its rotation axis, this flaw would be the cause of a torque which must be added to or substracted from the computed T when the centre of mass goes up or down, respectively. For our ergometer, we have measured a torque due to this flaw approximately equivalent to a 0.5 N·m T_B. For a 10-kg flywheel, this torque corresponds to a very small shift (approximately 1.25 mm) of the centre of mass. This flaw induces a fluctuation in the computed T equal to $\pm$ 0.5 N·m. Likewise, this flaw corresponds to a fluctuation in P equal to $\pm$ 10 W at 20 $rad \cdot s^{-1}$ and around $\pm$ 6 W at peak P_{max}. Again, the heavier the flywheel is, the higher the possible torque and the magnitudes of these fluctuations would be. For example, we have measured a torque equivalent to a 2.5 N·m torque at the crank level for the 18-kg flywheel for another kind of cycle ergometer.

Finally, an underlying assumption of the present study was that T_B was constant within a flywheel revolution, which should be verified. For example, it is possible that the belt tension varies significantly within a flywheel revolution if the flywheel is not perfectly round and centred.

T–v relationship

The present study does not agree with some previous experiments which have found curvilinear relationships between T and v (McCartney et al. 1985; Sjogaard 1978). One subject excepted (subject 7) T–v relationships between T and v was apparently linear between 4 $rad \cdot s^{-1}$ and v_{peak} with a 19 $N \cdot m^{-1}$ T_B (Fig. 2). It was not possible to measure the T–v relationship for lower v because 4 $rad.s^{-1}$ was generally reached within half a revolution for the low T_B. The T–v relationship did not present the slight downwards inflection which is generally observed at high resistances in the T_B–v_{peak} relationship (Vandewalle et al. 1987). One subject excepted (subject 7), the T–v relationships corresponding to the 19 and 76 $N \cdot m^{-1}$ T_B were superimposed (Fig. 2), although there were slight differences between the values of $T_{0,acc}$ and $v_{0,acc}$ (Tables 1, 2). In subjects 6 and 7, who were never habituated to cycling exercise, the correlation coefficient between T_B and v_{peak} was lower than 0.99 and, consequently, their values of v_0 and T_0 were probably inaccurate. In subject 7, the values of $v_{0,acc}$ and $T_{0,acc}$ were probably as inaccurate as his values of v_0 and T_0, which could explain why the differences between the two methods were rather large (Tables 1–3) for this subject.

The studies of the F–v relationship of an isolated muscle (Fenn and Marsh 1935; Hill 1938) have shown that maximal muscular power is produced at an optimal force and, consequently, at an optimal velocity which depends on muscle fibre typology. The fact that peak P_{max} was independent of braking torque suggests that P_{max} can be measured with low and high resistances, provided that the subject exerts a maximal effort. This result does not disagree with the isolated muscle experiments: v progressively increases and P_{max} is produced when optimal velocity is reached. Thereafter, P decreases at higher v. Therefore, the only necessary condition is that the braking torque must be equal to or lower than the T_B corresponding to a v_{peak} equal to optimal v.

The following reasons could explain why peak P_{max} for the different T_B were higher than P_{max} calculated from the linear relationship between T_B and v_{peak}:

1. Time to v_{peak} was significantly longer than time to peak power and a fatigue phenomenon could slightly lower P_{max};
2. Peak P_{max} corresponded to a half-a-revolution average instead of a 1-s average for P_{max} and, consequently, peak P_{max} represented: (a) the peak of an oscillation; (b) the performance of the most powerful leg instead of an average of both legs;
3. The slight downwards inflection (Vandewalle et al. 1987) of the relationship between T_B and v_{peak} at high resistances (for example 76 N·m) diminished the values of T_0 (computed according to the least squares method) and P_{max} ($P_{max} = 0.25\, v_0 T_0$).

Conclusions

The T–v relationships calculated from the acceleration phase of a single all-out exercise were similar to the relationship calculated from the v_{peak} corresponding to different T_B, provided that the subjects exert a maximal effort. The values of maximal power measured with the acceleration method ($P_{max,acc}$ or peak P_{max}) are independent of T_B but slightly higher than P_{max} calculated from the relationship between v_{peak} and T_B. Time to v_{peak} was clearly longer than time to P_{max}, especially for the small T_B.

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