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ORIGINAL ARTICLE

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Work and power outputs determined from pedalling and flywheel friction forces during brief maximal exertion on a cycle ergometer

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Abstract Work and power outputs during short-term, maximal exertion on a friction loaded cycle ergometer are usually calculated from the friction force applied to the flywheel. The inertia of the flywheel is sometimes taken into consideration, but the effects of internal resistances and other factors have been ignored. The purpose of this study was to estimate their effects by comparing work or power output determined from the force exerted on the pedals (pedalling force) with work or power output determined from the friction force and the moment of inertia of the rotational parts. A group of 22 male college students accelerated a cycle ergometer as rapidly as possible for 3 s. The total work output determined from the pedalling force (TW_p) was significantly greater than that calculated from the friction force and the moment of inertia (TW_f). Power output determined from the pedalling force during each pedal stroke (SP_p) was also significantly greater than that calculated from the friction force and the moment of inertia. Percentage difference (%*diff*), defined by $\%diff = \{(TW_p - TW_f)/TW_f\} \times 100$, ranged from 16.8% to 49.3% with a mean value of 30.8 (SD 9.1)%. It was observed that %*diff* values were higher in subjects with greater TW_p or greater maximal SP_p. These results would indicate that internal resistances and other factors, such as the deformation of the chain and the vibrations of the entire system, may have significant effects on the measurements of work and power outputs. The effects appear to depend on the magnitudes of pedalling force and pedal velocity.

Key words Cycle ergometer · Power output · Moment of inertia · Strain gauge

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Introduction

Friction loaded cycle ergometers have been widely used to determine work and power outputs during short-term, maximal exertion (supramaximal exercise). Work and power outputs have usually been calculated from the friction force applied to the ergometer flywheel. The moment of inertia of the flywheel has sometimes been taken into consideration (Lakomy 1986; Bassett 1989), but the effects of resistances within the ergometer system (internal resistances) and other factors, such as mechanical deformations and vibrations, have always been ignored. To the best of our knowledge, it has not been shown that their effects on the measurements of work and power outputs during supramaximal exercise are negligible.

In cycle ergometry, work and power outputs can also be determined from the force exerted on the pedals (pedalling force), which has frequently been measured using strain gauges bonded to the crank shafts (Hoes et al. 1968; Dally and Cavanagh 1976; Sargeant et al. 1978). If the pedalling force is completely transmitted to the flywheel via the chain transmission system, then the work and power outputs calculated from the pedalling force would agree with those calculated from the friction force and the force required to accelerate the ergometer. It seems, however, that the internal resistances and other factors could affect significantly the transmission of the pedalling force during supramaximal exercise.

In the present study, the total amount of work done (total work) during 3-s supramaximal exercise was calculated in four ways:

1. From the friction force applied to the flywheel (TW_{fric});
2. From the pedalling force (TW_p);
3. From the force required to accelerate the ergometer (TW_{acc});
4. As the sum of TW_{fric} and TW_{acc} (TW_f).

Similarly, the power generated during each pedal stroke (stroke power output) was calculated in four ways:

1. From the friction force (SP_{fric});
2. From the pedalling force (SP_p);
3. From the force required to accelerate the ergometer (SP_{acc});
4. As the sum of SP_{fric} and SP_{acc} (SP_f).

It was our main interest to estimate to what extent the internal resistances and other factors would affect the measurements of work and power outputs during supramaximal exercise by comparing TW_p with TW_f and comparing SP_p with SP_f for each pedal stroke.

Methods

Cycle ergometer

A standard, mechanically braked Monark cycle ergometer was modified to construct a constant-load cycle ergometer with a loading mechanism designed by Williams et al. (1988). The loading mechanism consisted of an electric load cell (A35967, 100 kg; Shinko-tushin-kogyo, Japan), steel plates of calibrated mass, the flywheel resistance strap, and two pulleys. These components were arranged as shown in Fig 1A. The ergometer was fitted with a racing saddle, racing handlebars, toe clips, and stirrups.

Measurement of pedal stroke time

The time taken for each one eighth pedal stroke to be completed ($t_{1/8}$) was measured using a system similar to that used by Hoes et al. (1968). The system consisted of eight small magnets and a magnetic switch (Fig. 1B). The magnets were placed equidistant from each other on a plastic board fixed to the pedal sprocket, and the magnetic switch was mounted on the ergometer frame. The switch generated a brief, square-wave pulse when each magnet passed over the switch. The pulses generated were stored on cassette tapes by a data recorder (MR-10/30; TEAK, Japan). A computer program (A-D Board Input and Analysis; Takei Co., Inc., Japan), which was run on a personal computer (NEC 9801VX), read stored data via the A-D board (ANALOG PRO; Canopus Electronics, Japan), and computed $t_{1/8}$ from pulse-to-pulse intervals by referring to the computer's internal clock. The time taken for a pedal stroke to be completed (t_{st}) was determined by adding the eight $t_{1/8}$ values obtained during a pedal stroke.

Calculation of flywheel velocity and acceleration

The one-eighth-stroke average of pedal angular velocity was calculated by dividing pedal angular displacement ($\pi \cdot 4\ \mathrm{rad}^{-1}$) by $t_{1/8}$.

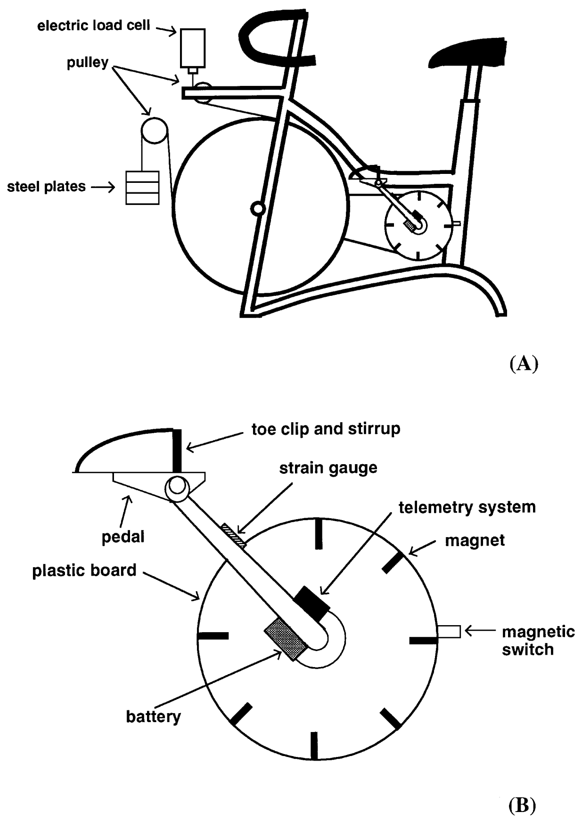

Fig. 1 **A** Modified cycle ergometer. **B** Setup for the measurements of force exerted on the pedals and time taken for each one-eighth pedal stroke to be completed

Then, the one-eighth-stroke average of flywheel angular velocity was determined as the product of the one-eighth-stroke average of pedal angular velocity and the gear ratio (52:14). Calculated one-eighth-stroke averages of flywheel angular velocity were fitted to a function of the form:

$$V_f(t) = V_m\{1 - exp(-\lambda t)\}$$

where V_m and λ are positive constants to be determined by means of the method of least squares. The values of these constants were used to calculate $dV_f(t)/dt$ given by:

$$\frac{dV_f(t)}{dt} = \lambda V_m exp(-\lambda t)$$

The value of $dV_f t/dt$ at the time of the midpoint of each pulse-to-pulse interval was used as the one-eighth-stroke average of flywheel angular acceleration.

Measurements of pedalling force and friction force

To measure the force exerted on the pedals (pedalling force), a strain gauge was glued to the trailing edge of each crank shaft, 10 cm from the crank axis (Fig. 1B). In previous studies (e.g. Sargeant et al. 1978), two strain gauges have usually been glued to each pedal-crank shaft, one on the leading edge and the other on the trailing edge, probably in the hope that using two strain gauges would cancel out the effects of traction and compression. In our preliminary studies, however, we found that pedalling force measured with two strain gauges was not significantly different from that measured with one strain gauge glued on the trailing edge.

The strain gauge was statically calibrated by suspending steel plates of masses 25 kg, 50 kg, 75 kg, and 100 kg from the pedal while the crank shaft was held horizontally. A linear regression equation was obtained to determine the torque acting on the pedal from the output of the strain gauge. We also suspended steel plates with masses of 50 kg and 75 kg from the pedal while maintaining the crank shaft at various angles. The outputs of the strain gauge yielded reasonable measures of the perpendicular component of the forces applied to the pedal. The differences between the values calculated from the outputs and those computed using trigonometry were less than 3%.

The outputs from the strain gauges during supramaximal exercise were fed to a telemetry system (Telemetry Transmitter NK-76900, NEC, Japan), and then transmitted to the data recorder, where they were stored on cassette tapes. The computer program A-D Board Input and Analysis read stored data via the A-D board, and then determined pedalling force using the regression equation. The program calculated the one-eighth-stroke average of pedalling force using $t_{1/8}$ as the averaging period.

The friction force applied to the flywheel was computed as the difference between the average force registered by the electric load cell and the pull of the suspended steel plates. The methods for storing and digitizing the outputs from the load cell were the same as in the case of the outputs from the strain gauges. The same computer program read stored data and calculated the one-eighth-stroke average of friction force using $t_{1/8}$ as the averaging period.

Calculation of moment of inertia

The moment of inertia of the rotational parts was measured with respect to the flywheel axle. The moment of inertia was used to determine the force (acceleration force) required to be applied tangentially to the flywheel to accelerate the rotational parts. In order to measure the moment of inertia, the ergometer was placed over two tables, as shown in Fig. 2. The resistance strap was removed from the flywheel to hook a wire from a pin fixed to the rim of the flywheel. Steel plates of calibrated mass were suspended from this wire, and the flywheel was initially held so that the steel plates would not fall. The flywheel was then set in motion by allowing the steel plates to fall from the suspended position. The motion of the flywheel was filmed with a 16-mm high speed camera to determine flywheel angular acceleration using a motion analyser (Sportias 200; Nac, Japan). We calculated the moment of inertia from the flywheel angular acceleration using the equation of motion for a rotating disk.

The equation of motion for the rotating flywheel provided the relationship between the angular momentum (J) of the rotating flywheel (i.e. the product of the moment of inertia, I, and flywheel angular velocity, ω) and the torque (T) acting on the flywheel

$$\frac{dJ}{dt} = T$$

Thus, we have the following relationship among I, T, and flywheel angular acceleration $\alpha\,(d\omega/dt)$:

$$I = \frac{T}{\alpha}$$

It is clear from Fig. 2 that T can be expressed as:

$$T = rm(g - \alpha r)$$

where r is the radius of the flywheel (0.26 m), m is the mass of the suspended steel plates, and g is the gravitational constant ($9.81\,\mathrm{m \cdot s^{-2}}$). Therefore, I is given by:

$$I = \frac{rm(g - \alpha r)}{\alpha}$$

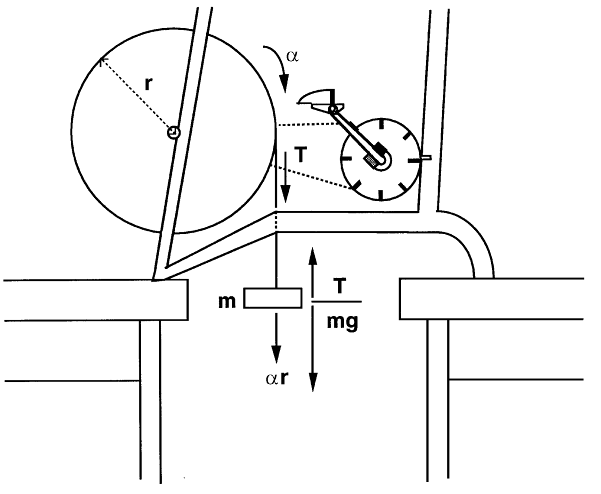

Fig. 2 Setup for the measurement of the moment of inertia. T net torque acting on the flywheel, r radius of the flywheel, m mass of suspended steel plates, g gravitational constant ($9.81\,\mathrm{m \cdot s^{-2}}\alpha$) flywheel angular acceleration

The rotation of the flywheel was initiated by dropping the steel plates of five different masses (0.4 kg, 0.6 kg, 0.8 kg, 1.0 kg, and 1.2 kg). For each mass, I was calculated from the above equation. It should be noted that the rotation of the flywheel resulted in rotating the crank and the other rotational parts because the ergometer chain was not removed. Thus, I determined in this study was of all rotational parts.

Calculation of acceleration force

The one-eighth-stroke average of acceleration force (F_{acc}) was calculated from

$$F_{acc} = \frac{1}{r} I dV_f/dt,$$

where dV_f/dt is the one-eighth-stroke average of flywheel angular acceleration. The F_{acc} is the force required to be applied tangentially to the flywheel in order to achieve acceleration dV_f/dt.

Calculation of work output

Work output was calculated for each one-eighth pedal stroke during 3-s supramaximal exercise in four ways:

1. As the product of the friction force and the distance (D, 0.75 m) travelled by the flywheel during one-eighth pedal stroke (W_{fric});
2. As the product of the pedalling force and the distance (0.13 m) travelled by the pedal during one-eighth pedal stroke (W_p);
3. As the product of F_{acc} and D (W_{acc});
4. As the sum of W_{fric} and W_{acc} (W_f).

The amount of work done during each pedal stroke (stroke work output) was calculated as the sum of eight one-eighth-stroke work output values. Stroke work outputs SW_{fric}, SW_p, and SW_f were calculated as the sum of the eight W_{fric}, W_p, and W_f values, respectively. The total amount of work done during 3-s supramaximal exercise (total work) was calculated as the sum of all one-eighth-stroke work output values. Total work determined from W_{fric}, W_p, and W_f were denoted respectively by TW_{fric}, TW_p, and TW_f.

Calculation of power output

The one-eighth-stroke average of power output was calculated during 3-s supramaximal exercise in three ways:

1. As the quotient $W_{fric}/t_{1/8}$ (P_{fric});
2. As the quotient $W_p/t_{1/8}$ (P_p);
3. As the quotient $W_f/t_{1/8}$ (P_f).

Stroke power output was determined from stroke work output. We divided stroke work outputs SW_{fric}, SW_p, and SW_f by t_{st} to determine stroke power outputs SP_{fric}, SP_p, and SP_f, respectively. Thus, SP_{fric} is stroke power output determined from the friction force applied to the flywheel, SP_p is stroke power output determined from the pedalling force, and SP_f is stroke power output determined from the friction force and F_{acc}.

Calculation of percentage difference

To evaluate the relative difference between TW_p and TW_f, we calculated %*diff*, which was defined by:

$$\%diff = \frac{TW_p - TW_f}{TW_f} \times 100$$

Subjects

A group of 22 healthy male college students participated in this study. The mean values for their age, height, and body mass were 21.0 (SD 2.8) years, 172.8 (SD 4.8) cm, and 71.1 (SD 7.3) kg. The procedures used in this study were explained in detail to each subject. All the subjects gave their informed consents prior to their inclusion in this study.

Test protocols

Each subject was seated on the ergometer saddle, the height of which was so adjusted that he could bend his knee slightly when the pedal was at its lowest position. All the subjects assumed the same starting position by having the right pedal forward, 45° above the horizontal position. They were instructed to accelerate the pedals from the starting position as rapidly as possible for 3 s, and not to stand on the pedals while pedalling. The friction loads administered to the subjects were standardized with respect to their body masses by suspending from the resistance strap steel plates with masses corresponding to 10% of their body masses. To help the subjects remain seated during exercise, a 150-kg steel weight was placed on the floor and connected by wires to a belt worn by the subjects around their waist. Two exercise tests were given to each subject on the same test day. The two tests were at least 5 min apart. To examine the test-retest reliability of the methods used in this study, t values were calculated with respect to stroke power output values obtained in test 1 and test 2.

Results

All the subjects completed the two tests. They managed to overcome the assigned friction loads and accelerated the pedals without difficulty. During a 3-s supramaximal exercise session, all the subjects made at least five pedal strokes. The test-retest reliability of the methods used in this study was examined with respect to stroke power outputs of the first five pedal strokes. The reliability was confirmed, as calculated t values indicated that there was no significant difference between the mean values of stroke power output obtained in test 1 and test 2 for each of the five pedal strokes. The level of significance was established as $P < 0.05$. In this report, the results from test 1 are given.

Moment of inertia

The analysis of the film revealed that the flywheel was accelerated at a constant rate by the falling steel plates (Fig. 3A) and that α was proportional to T; the constant of proportion was 0.440 (Fig. 3B). The mean of the five values of the moment of inertia was 0.441 (SD 0.012) $kg \cdot m^2$ in test 1 and 0.441 (SD 0.016) $kg \cdot m^2$ in test 2. We used the value 0.441 $kg \cdot m^2$ to compute F_{acc}.

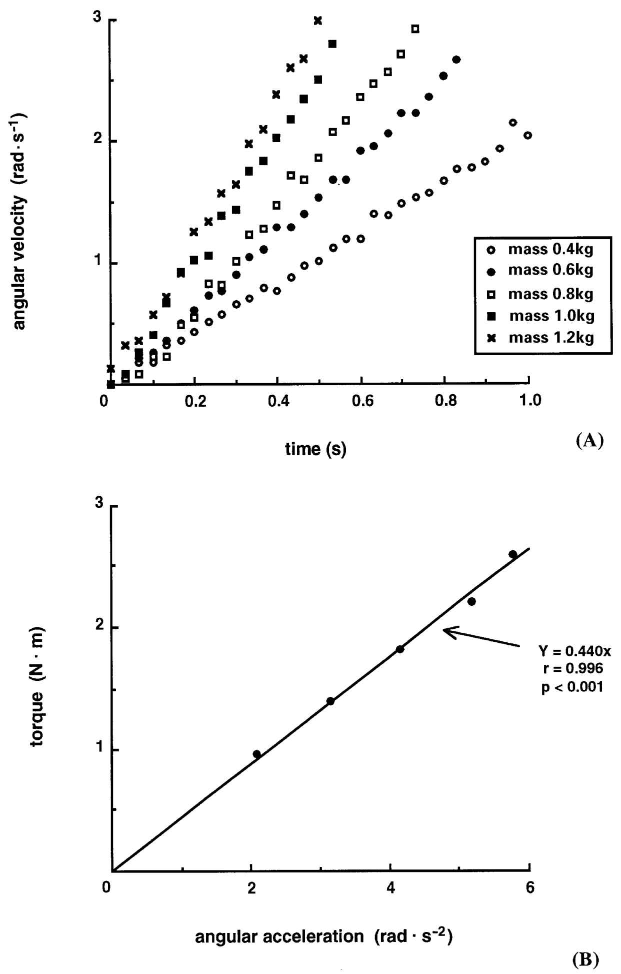

Fig. 3 A Changes in flywheel angular velocity caused by the fall of steel plates of five different masses **B** The relationship between net torque acting on the flywheel and flywheel angular acceleration

Analogue data

A typical display of analogue data provided by the computer program, A–D Board Input and Analysis, is shown in Fig. 4. From the top are shown the magnetic switch signals (SIGNAL), the force exerted on the right pedal (R. FORCE), the force exerted on the left pedal (L. FORCE), and the friction force applied to the flywheel (D. FORCE).

Pedal velocity

Figure 5 shows typical temporal changes in pedal velocity during 3-s supramaximal exercise performed in this study. The one-eighth stroke averages of pedal angular velocity were computed from the magnetic switch signals shown in Fig. 4, and were plotted versus the midpoints of pulse-to-pluse intervals. The fitted curve and its equation are also given in Fig. 5. In all the subjects, the calculated velocity values showed only minor oscillations during 3-s supramaximal exercise and fitted well to the exponential function.

Stroke power output

The one-eighth stroke averages of power outputs P_p, P_{fric}, P_{acc}, and P_f were calculated from the force data shown in Fig. 4, and were plotted in Fig. 6 versus the midpoints of pulse-to-pulse intervals. The power curves shown in Fig. 6 are the representatives of those obtained from the subjects. The P_p curve is characterized by the large oscillations resulting from the intrastroke variations in pedalling force. The P_{fric} values increased gradually throughout the 3-s period, showing small oscillations during the last second. The P_{fric} curve reflects the temporal changes in pedal velocity, because the friction force applied to the flywheel remained constant during the supramaximal exercise (Fig. 4). During the first pedal stroke, P_{acc} was greater than P_{fric}. After the initial rapid increase, P_{acc} gradually declined as pedal velocity approached its maximal value. The P_f value reached its maximal level within a second, whereas it took a few pedal strokes for peak P_p to attain its maximal value.

The differences in the way P_p, P_{fric}, and P_f changed resulted in significant differences among SP_p, SP_{fric}, and SP_f. Figure 7 shows the mean and SD values of SP_p, SP_{fric}, SP_f for the first five pedal strokes. The difference between SP_f and SP_{fric} corresponds to SP_{acc}. For each pedal stroke, SP_p was significantly greater than SP_f ($P < 0.05$) . Also, SP_f was significantly greater than SP_{fric} for each pedal stroke ($P < 0.05$).

Total work

The mean values of TW_{fric}, TW_f, and TW_p were 1213.0 (SD 220.8) J, 1999.5 (SD 252.6) J, and 2936.9 (SD 530.5) J, respectively. These three mean values were significantly different from each other ($P < 0.05$).

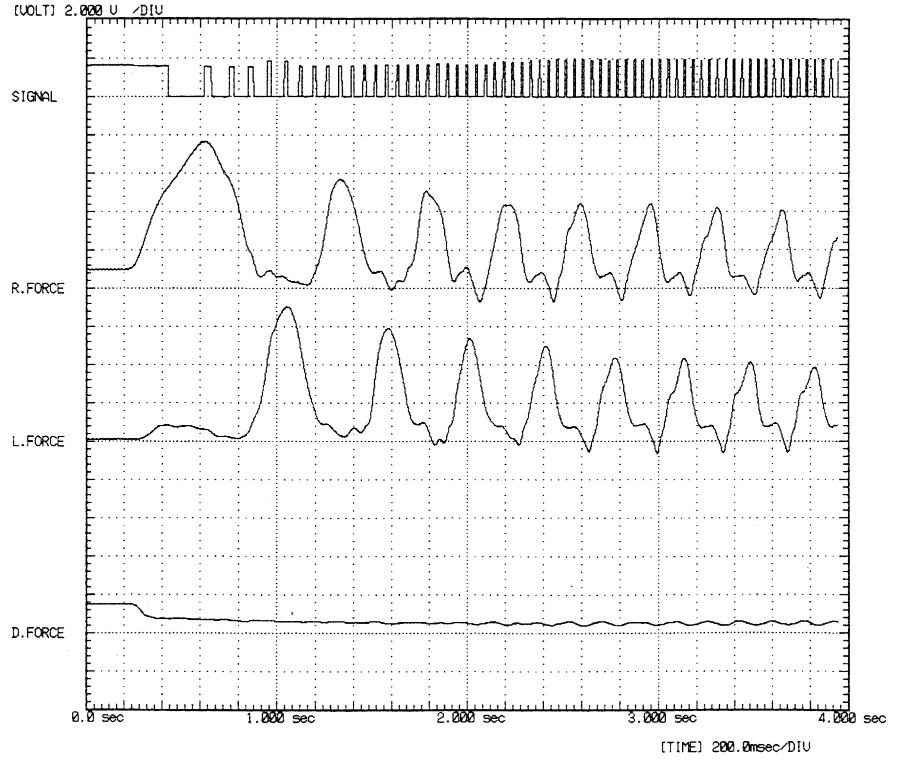

Fig. 4 Typical display of analogue data provided by A–D Board Input and Analysis

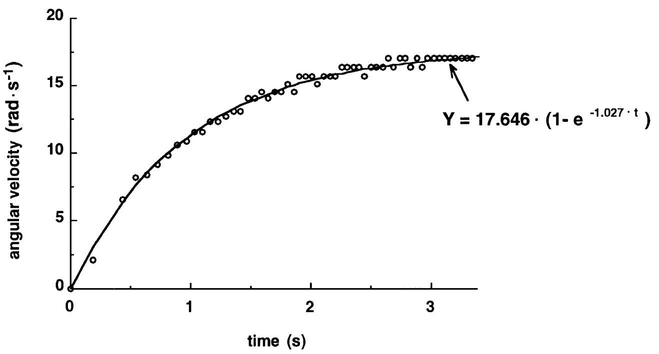

Fig. 5 Temporal changes in one-eighth-stroke average of pedal angular velocity

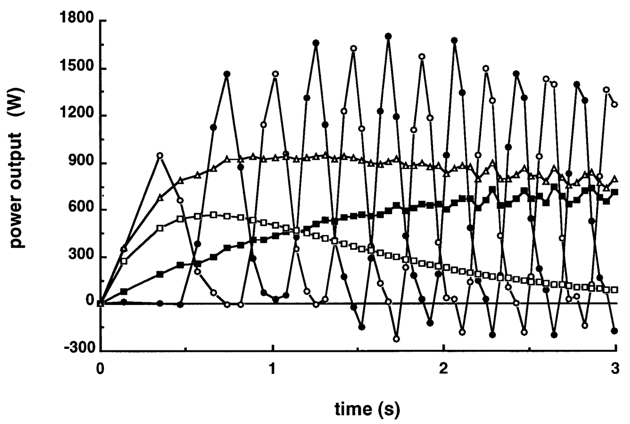

Fig. 6 Changes in one-eighth-stroke averages of power output calculated from force exerted on the right pedal (—○—) and the left pedal (—●—), from friction force applied to the flywheel (—■—), from acceleration force (—□—), and from friction force and acceleration force (—△—) during 3-s supramaximal exercise

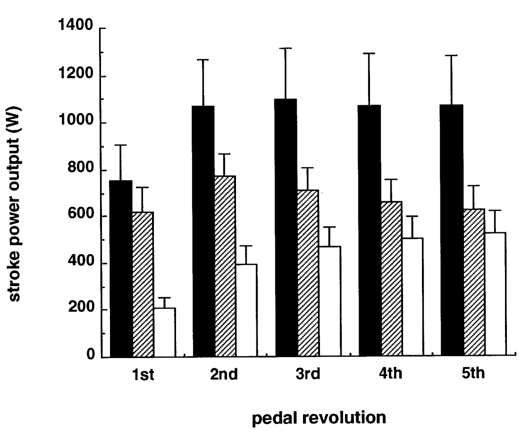

Fig. 7 Means and SD of stroke power output SP_p (■) SP_f (▨), and SP_{fric} (□) for the first five pedal strokes during 3-s maximal exertion. There were significant differences between mean values of SP_p, SP_f, and SP_{fric} ($P < 0.01$)

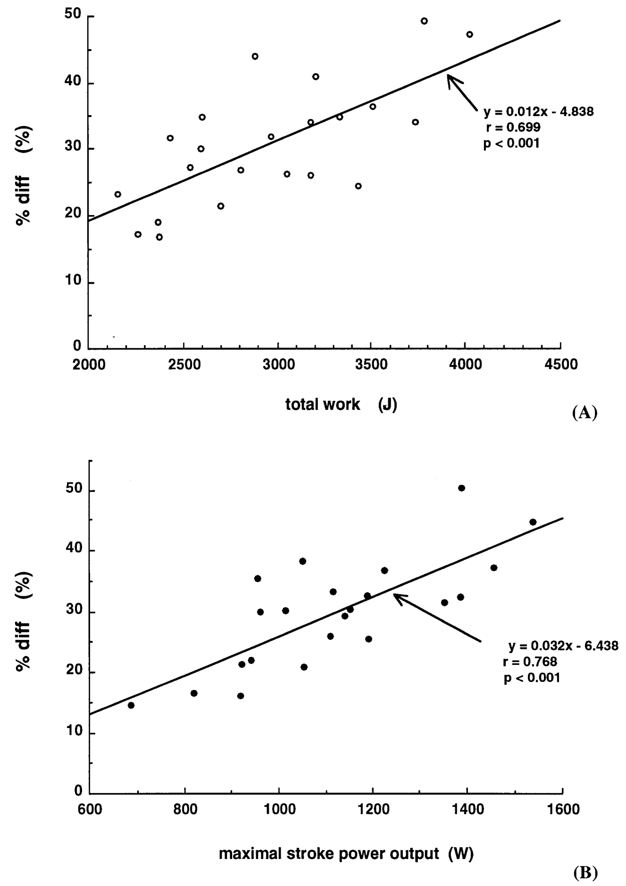

Fig. 8 The relationship between % *diff* and total work calculated from pedalling force (TW_p). **B** The relationship between % *diff* and maximal stroke power output calculated from pedalling force. For definitions in **A** and **B** see text

Percentage difference

The value of % *diff* ranged from 16.8% to 49.3% with a mean value 30.8 (SD 9.1)%. The value obtained from each subject was plotted versus his TW_p value in Fig. 8A and versus his maximal SP_p value in Fig. 8B. We found relatively strong correlations between % *diff* and TW_p ($r = 0.699$; $P < 0.001$) and between % *diff* and maximal SP_p ($r = 0.615$; $P < 0.01$).

Discussion

Friction loaded cycle ergometers have been widely used to measure power output during supramaximal exercise. Power output is usually calculated from the friction force applied to the flywheel and the number of pedal revolutions counted over fixed time intervals. In the Wingate anaerobic cycle test, for example, power output is determined during each 5-s period of 30-s supramaximal exercise. Peak power output is calculated as the highest 5-s power output, and mean power output as the average of the six values of 5-s power output; moreover, a relative or absolute measure of fatigue has also been obtained from the highest and lowest 5-s power output values (Dotan and Bar-Or 1983). It has been shown, however, that power output changes rapidly during the first 5 s of supramaximal exercise (Williams et al. 1988). Power output increased rapidly, reached its peak during the first few seconds, and then declined gradually. Thus, the initial rate of increase in power output, achieved peak power output, and the rate and magnitude of fatigue were determinants of the total amount of work done, and probably affected the performance in a short burst of maximal effort. Studying these factors by means of cycle ergometry requires that rapid temporal changes in power output be accurately recorded.

To characterize the temporal changes in power output during supramaximal exercise, it has been shown that we need to obtain a smooth power curve with an initial steep rise and a following gentle descent (Williams et al. 1988). Such smooth curves, however, may not be obtained by plotting the true instantaneous values of power output, which would be computed from analogue force and velocity signals. Lakomy (1986) has reported that averaging the friction force and flywheel velocity over fixed time intervals shorter than a pedal stroke duration often resulted in large oscillations in power output. The power oscillations may be attributed to the changes in flywheel velocity induced by the intra-stroke variations in pedalling force. In the present study, we focused on the initial acceleration period of supramaximal exercise. During the initial 3 s of supramaximal exercise performed in this study, the one-eighth stroke averages of pedal velocity did not show large oscillations (Fig. 5); therefore, we have obtained relatively smooth P_{fric}, and P_{f} curves. However, as fatigue develops, the intra-stroke variations in pedal velocity would probably increase and, as a result, the oscillations of P_{fric} and P_{f} may become more evident.

Because of the large intra-stroke variations in pedalling force, computing power output from pedalling force during each one-eighth pedal stroke yielded large oscillations in P_{p}. To obtain a smooth power curve characterizing the temporal changes in power output, we may need to determine power output either for each half pedal stroke or for each complete pedal stroke. In the present study, we determined stroke power output from stroke work output, which was computed as the sum of one-eighth stroke work outputs. If we had used a shorter averaging period (e.g. one-sixteenth pedal stroke duration), we might have obtained more precise measurements of stroke work and power outputs. However, for practical reasons, using one-eighth pedal stroke duration as an averaging period appeared to be an appropriate compromise. It seemed that the use of either one-eighth or one sixteenth pedal stroke duration would not affect the results reported in this study. Power curves can be obtained by plotting stroke power output values versus the midpoints of the corresponding pulse-to-pulse intervals. It is apparent from Fig. 7 that power curves derived from stroke power outputs SP_{p}, SP_{f}, and SP_{fric} will be smooth, but have different shapes.

During the initial acceleration period of supramaximal exercise, power is generated not only to overcome the friction force applied to the flywheel, but also to accelerate the mass of the rotational parts. Thus, the moment of inertia of the rotational parts should be taken into account when work and power outputs are determined during the acceleration period. In fact, Lakomy (1986) has demonstrated that accelerating the ergometer requires significantly more power than simply maintaining a constant speed. Lakomy's 1-s averaged peak power output was 32% higher when the excess load, i.e. the load that would be needed to prevent acceleration or removed to prevent deceleration, was added to the friction load. The results obtained in the present study were consistent with Lakomy's results. We observed that the mean value of SP_{f} of the second pedal stroke, for example, was 49.5% higher than the mean value of SP_{fric} of the second pedal stroke. We also found that the mean TW_{f} value was 39.3% higher than the mean TW_{fric} value.

In order to determine the excess load, Lakomy (1986) has allowed the flywheel to rotate at 150 rpm and applied various friction resistances to the rotating flywheel. The excess load was calculated from the relationship between the applied friction resistances and the resulting deceleration of the flywheel. Seck et al. (1995) have calculated the moment of inertia of the cycle ergometer used by Lakomy (a Monark cycle ergometer) from the relationship between the flywheel deceleration and the friction loads provided by Lakomy (1986). The calculated value was $0.365\ \mathrm{kg \cdot m^2}$, which agrees well with the value $0.346\ \mathrm{kg \cdot m^2}$ obtained by Seck et al. (1995) themselves in their similar deceleration experiments. In the present study, we calculated the moment of inertia from the relationship between the torque applied to the flywheel by the falling steel plates and the resulting acceleration of the flywheel.

The moment of inertia value obtained in the present study $0.441\ \mathrm{kg \cdot m^2}$ is comparable with the value $0.4166\ \mathrm{kg \cdot m^2}$ reported by Bassett (1989), who has determined the moment of inertia of the flywheel of a Monark cycle ergometer by considering the flywheel as a series of concentric rings around the rotational axis and computing the moment of inertia of each ring from its mass and radius. The slightly higher value obtained in this study may be explained by the fact that we have accounted for all rotational parts of the ergometer, while Bassett has dealt only with the flywheel. It is not clear why our acceleration experiments yielded a considerably higher value than the deceleration experiments employed by Lakomy (1986) and Seck et al. (1995). We adopted the acceleration experiments simply because we had to compute the power output required to accelerate the rotational parts of the ergometer. It seems that Bassett (1989) used a valid way of calculating the moment of inertia of the flywheel. His calculation was based on a well-known equation for the moment of inertia of a thin ring and a few reasonable assumptions. We have judged our moment of inertia value to be accurate by comparing it with Bassett's value.

When work and power outputs are determined from the friction force applied to the flywheel, it is tacitly assumed that the friction force is the only resistance to be overcome and that the internal resistances of the ergometer system are negligible. The present study has confirmed that the inertia of the rotational parts has significant effects on the measurements of work and power outputs, at least during the initial acceleration period of supramaximal exercise. The inertia of the rotational parts may be regarded as internal resistance, which should not be overlooked. The present study has shown, however, that there are other internal factors affecting work and power measurements during supramaximal exercise.

We found that pedalling force yielded a significantly higher value in total work (2936.9J vs 1999.5J) and in stroke power output for each of the first five pedal strokes (Fig. 7). Even though the moment of inertia of the rotational parts was taken into account, the calculation of work and power outputs based on the friction force applied to the flywheel still underestimated total work and stroke power output during supramaximal exercise. It is conceivable that the power generated during cycle ergometer exercise was expended not only to overcome the friction force externally applied to the flywheel and the moment of inertia, but also to overcome the internal resistances of the ergometer system. It is also likely that the deformation of the chain and the vibrations of the entire system resulted in significant energy losses within the ergometer system and affected the measurements of work and power outputs during supramaximal exercise. The present study cannot specify to what extent each of these factors have affected the measurements.

The present study has shown that the total amount of work done during supramaximal exercise is underestimated when calculated from the friction force applied to the flywheel and that the calculation of total work from the friction force does not account for the energy losses within the ergometer system. In the present study, the extent of the underestimation was assessed in terms of % *diff*. It should be noted that % *diff* ranged from 16.8% to 49.3% and was greater in the subjects with higher TW_p values (Fig. 8A) and higher maximal SP_p values (Fig. 8B). It would seem that the subjects with greater TW_p and maximal SP_p accelerated the ergometer more quickly and achieved higher pedal velocity. The amount of the energy losses within the ergometer system would appear to depend on the force applied to the internal mechanisms (i.e. the extent of chain deformation and vibrations) or to depend on the rotational velocity of the transmission system (i.e. the magnitude of internal resistances). When making intersubject comparisons of total work or maximal stroke power output, one needs to bear these facts in mind.

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