Accurate assessment of work done and power during a Wingate anaerobic test

Kathryn L. Franklin, Rae S. Gordon, Julien S. Baker, and Bruce Davies

Abstract: A Monark cycle ergometer is used in physiological studies to measure work done and power. In this paper, the accuracy of a Monark rope-braked cycle ergometer was examined for a Wingate anaerobic test (WAnT). The traditional method of determining brake torque fails to take into account rope-brake theory and, as the brake torque is used to determine the moment of inertia of the flywheel, a second error is introduced into the calculation to determine the work done or power. In this study, the rope tensions were measured to determine the actual brake torque. A deceleration test was carried out to determine the moment of inertia of the system. The work done by subjects of different masses was calculated for various accelerations and it was found that the traditional calculations overestimate work done and power by between 12% and 14.7%.

Key words: cycle ergometer, inertia, rope-brake, brake torque.

Résumé : Dans des études en physiologie de l'activité physique, on utilise l'ergocycle Monark pour la mesure du travail et de la puissance. Dans cet article, nous analysons la précision de l'ergocycle Monark servant au test de puissance anaérobie de Wingate Test (WAnT) ; dans ce test, la résistance au pédalage provient d'une courroie tendue sur la jante. Dans la méthode traditionnelle de la mesure du moment de force du frein, on ne tient pas compte de la théorie du frein au moyen d'une courroie ; de plus, comme on utilise le moment de force du frein pour évaluer le moment d'inertie du volant cinétique, on introduit une deuxième erreur dans le calcul du travail accompli ou de la puissance développée. Dans cette étude, nous mesurons la tension sur la courroie afin d'évaluer le moment réel du frein. De plus, nous effectuons un test de décélération pour évaluer le moment d'inertie du système. Par la suite, nous calculons le travail accompli par des sujets de masse corporelle différente qui ont effectué diverses accélérations. Nous observons en fin de compte une surestimation des valeurs de travail accompli et de puissance développée de 12 % et 14,7 % respectivement lors de l'utilisation de la méthode traditionnelle.

Mots clés : ergocycle, inertie, courroie de freinage, moment du frein.

[Traduit par la Rédaction]

Introduction

The first useable bicycle ergometer was developed by von Döbeln (1954). Earlier ergometers used two spring balances, connected to either side of a brake band to measure the difference in tension and hence obtain the brake torque. This method was often inaccurate, as it was difficult to obtain reliable spring balances. This shortcoming was overcome by von Döbeln (1954), who used a device called a sinus balance. This device is commonly used in weighing machines. The sinus balance consists of a pulley to which the two ends of the brake band are connected. A gear mechanism connects the pulley to a pendulum arm. As the tension in the brake band changes, the pulley is displaced, thus causing the pendulum arm to move. This provides a measurement of brake torque.

As the use of bicycle ergometers increased, a growing number of experiments or protocols were developed by physiologists and sports scientists. The sinus balance mechanism proved to have a number of limitations, such as the inability to apply an instantaneous load (a requirement for tests such as the Wingate anaerobic test (WAnT)). To overcome these limitations the sinus mechanism was replaced by a rope-brake system and the brake force applied by means of a suspended mass. For a Monark rope-braked ergometer (Vansbro, Sweden) the work done is calculated as the force, due to the basket mass, multiplied by the distance moved (flywheel moves through 6 m for 1 revolution of the pedals (Åstrand 1988)). The power is then the pedal cadence multiplied by the force due to the basket mass. This fails to take into account rope-brake theory, which gives the transmission of the forces from the pulley to the flywheel.

The WAnT comprises a subject initially pedalling the ergometer at a fixed speed against no resistance. The resistance (determined using the mass of the subject) is then applied and the subject has to pedal at a maximal level for a period of between 10 and 30 s. The WAnT is subject to a number of different variations, such as the method used to calculate the resistance, the speed at which the subject initially pedals, etc.

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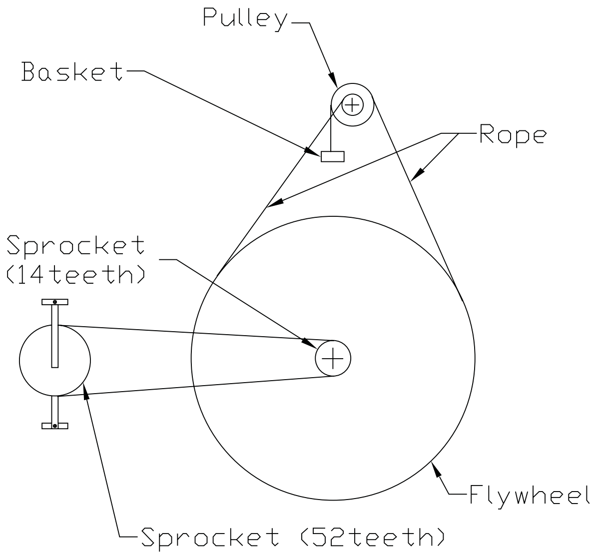
Fig. 1. Layout of ergometer pedals and the brake mechanism.



Lakomy (1986) was the first to consider the inertial work done by the rider in accelerating the flywheel. Although often credited with being the first to determine the moment of inertia of the ergometer flywheel system, Lakomy (1986) did not actually publish a value. He suggested that a look-up table, based on the flywheel deceleration against a series of known brake loads, be used to correct the results for work. It was argued that the brake load required to decelerate the flywheel would be equal to the load required to accelerate the flywheel at the same rate. Hence, the "actual" brake load is determined by examining the acceleration and taking the value of brake load to effect a similar deceleration. It was found that the work done by the rider was 36% more when the inertia of the flywheel system was considered.

Bassett (1989) determined the actual moment of inertia of the flywheel mathematically, by measuring the flywheel and breaking the geometry down into a series of rings. He pointed out that the rider should not be credited with work to overcome the brake load while the flywheel was decelerating. The work done by the subject was determined to be the total work minus the work done by the flywheel; this would assume that the subject was pedaling at a maximal rate prior to the start of the WAnT and that no acceleration takes place over the period of the test. It was found that the peak power values were lowered by 6.2%.

Coleman and Hale (1998) compared the Lakomy and Bassett methods of determining the flywheel moment of inertia with a classical mechanics approach using suspended masses to accelerate the flywheel. The results presented showed that the moment of inertia calculated using Bassett's procedure was similar to the experimental values obtained using Coleman's method.

Reiser et al. (2000) determined the moment of inertia of the ergometer flywheel using three experimental methods and a geometrical approximation (computer-aided design). The three experimental methods were the deceleration test proposed by Lakomy (1986), a physical pendulum, and a torsional pendulum. The moment of inertia was reported to be 0.91 kg·m^2 (standard deviation (SD) 0.021), with good agreement between each method. Unfortunately, Reiser et al. (2000) gave no details of the experiments or even the individual results for the moment of inertia. It would be expected that there would be some difference between the results.

Gordon et al. (2004*a*) determined the moment of inertia of a Monark (Model 824E) ergometer flywheel using the method outlined in the British and European Standard BS EN 957-5(3). This was then compared with the values obtained using the Cranlea Wingate correction system. The Cranlea system gave a moment of inertia of 1.18 kg·m^2 (SD 0.233), whereas the British Standard procedure gave a value of 0.8 kg·m^2 (SD 0.0085).

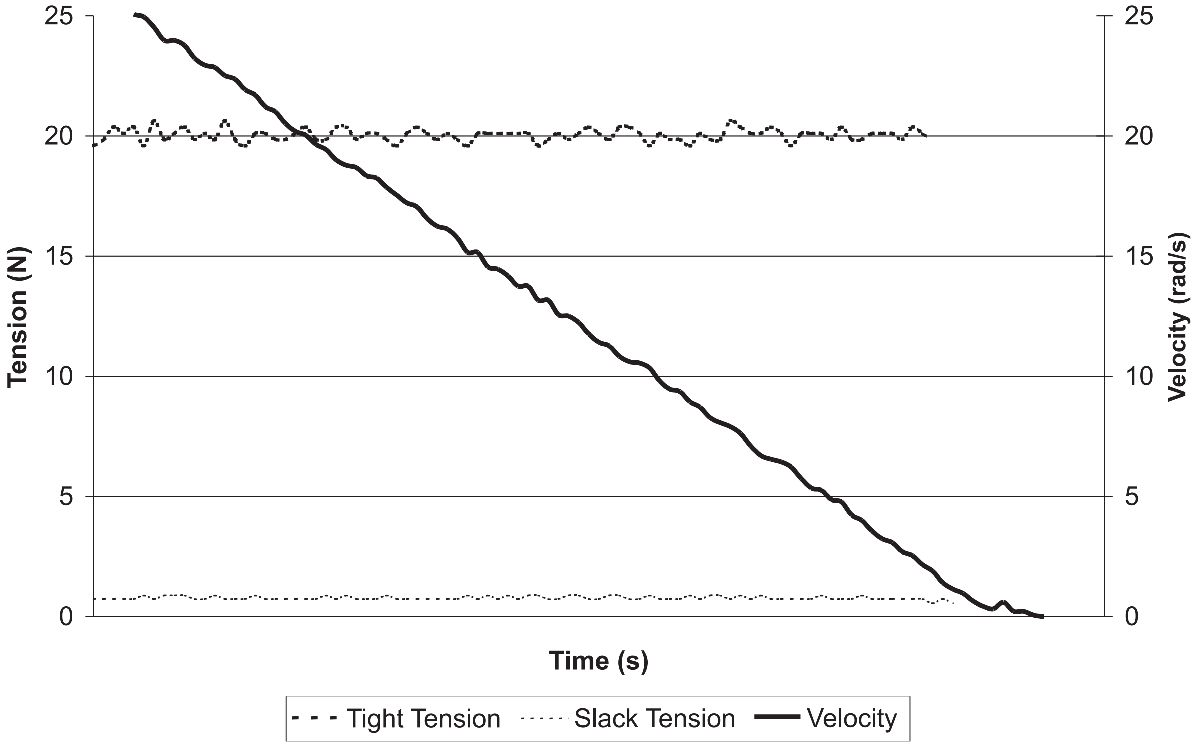
A number of researchers have tried to measure the brake load using a variety of techniques. Lakomy (1993) measured the input torque by connecting the chain of the pedal sprocket to a torque meter, the output of which was then connected via another sprocket to the flywheel. He then compared this torque with one calculated from the speed of the flywheel. Significant differences between the input and frictional torque were found at 2 (15.8%) and 3kg (17.7%) loads. Lakomy (1993) attributed these differences to the additional friction in the chains used in the intermediate step between the pedals and the flywheel. Generally, a chain-drive system connected between shafts on bearings is assumed to be highly efficient, in the order of 98% (Burges (1998)) on a well-setup system, although the efficiency decreases if the ergometer is not reasonably maintained (Maxwell et al. 1998).

Hibi et al. (1996) compared the torque applied to the pedals with the frictional torque of the flywheel system. A load cell was used to measure the slack side tension and the tight side tension was the suspended mass. However, Hibi et al. (1996) modified the brake system of the ergometer and the results are not applicable to a standard system. Hibi et al. (1996) made no comment about any difference being observed in the brake load that was measured and that found using the weight of the suspended mass.

MacIntosh et al. (2001) used buckle gauges to directly measure the tension in the brake rope of a Monark ergometer (Model 834E). It was found that the front and rear rope had measured tensions equivalent to 95.5% (SD 0.8%) and 6.17% (SD 0.8%) of the load applied to the basket, respectively. These results, however, do not provide rotational equilibrium at the pulley and this must call them into question. (This can be checked using eq. 2 and the values r_1 = 71 mm and r_2 = 32 mm for the physical measurements of the pulley.) The measured brake torque was 12% less than that generally assumed using the basket mass alone. The moment of inertia was found to be 0.77 kg·m^2, which is in good agreement with Franklin and Gordon (2002), but 21.6% less than the value suggested by Reiser et al. (2000); however, each casting of flywheel may be individual.

MacIntosh et al. (2001) stated that the slack side rope tension varies with the rotational speed of the flywheel. Rope-brake theory suggests that this is not the case, as the tension is independent of the speed (see eq. 1). If MacIntosh et al. (2001) are correct, this would have major consequences for all tests that involved any variation in speed and for the WAnT in particular. If the brake force varies with speed, then the deceleration test for determining the moment of inertia would not be valid. A graph of the flywheel velocity against basket load would be non-linear, as the brake load would be increasing as the flywheel decelerates. This has

Fig. 2. Flywheel velocity as the flywheel decelerates from a pedal speed of 70 r·min^{-1} and the tight and slack side rope tensions during deceleration.



never been observed in any of the work done to date (other in the special case where no brake load is applied Franklin and Gordon 2002). MacIntosh et al. (2001) did not explain any of these results.

Gordon et al. (2004*b*) provided the theoretical analysis of the actual rope-brake tensions and measured these directly. There was good agreement between the two sets of results. There was a difference between the theoretical results and that suggested by Monark of 10.8%. The moments applied to the pulley were checked and found to be in equilibrium.

The aim of this paper is to determine the total the work done (or power) during the acceleration phase of a WAnT, by direct measurement of the brake torque for determining the system moment of inertia and for the WAnT.

Rope-brake theory

Since the earliest machines, rope has been used both to transmit power and as a brake material. The derivation of the tension in the rope can be found in many machine design textbooks (e.g., Spotts and Shoup (1998)). The ratio of the tensions is given by,

$$[1] \qquad \frac{F_1}{F_2} = e^{\mu\varphi}$$

where F_1 (measured in Newtons (N)) is the tight side tension, F_2 (N) is the slack side tension, μ is the coefficient of friction and φ (radians) is the angle between the lap rope and the flywheel.

In the case of the Monark ergometer (model 824E), one end of the rope brake is attached to the outer radius of a pulley, which is held in a bracket above the flywheel. The pulley is free to rotate. The rope is then wound around the flywheel approximately 1.65 times and then attached to the pulley in a machined recess, i.e., at a smaller radius than the other end of the rope. The end of the rope attached to the outer radius is the tight side and the other end is the slack side. The brake load is applied to the outer radius of the pulley by webbing straps that are independent of the rope. The system is designed to be self-calibrating. The configuration of the ropes and pulley is shown in Fig. 1.

The pulley is in equilibrium (i.e., stationary when the ergometer is in use) and therefore the moments resulting from the loads must balance. This gives,

$$[2] \qquad P \cdot r_1 = F_1 r_1 - F_2 r_2$$

where P (N) is the load due to the basket mass, r_1 (m) is the outer radius of the pulley, and r_2 (m) is the inner radius of the pulley.

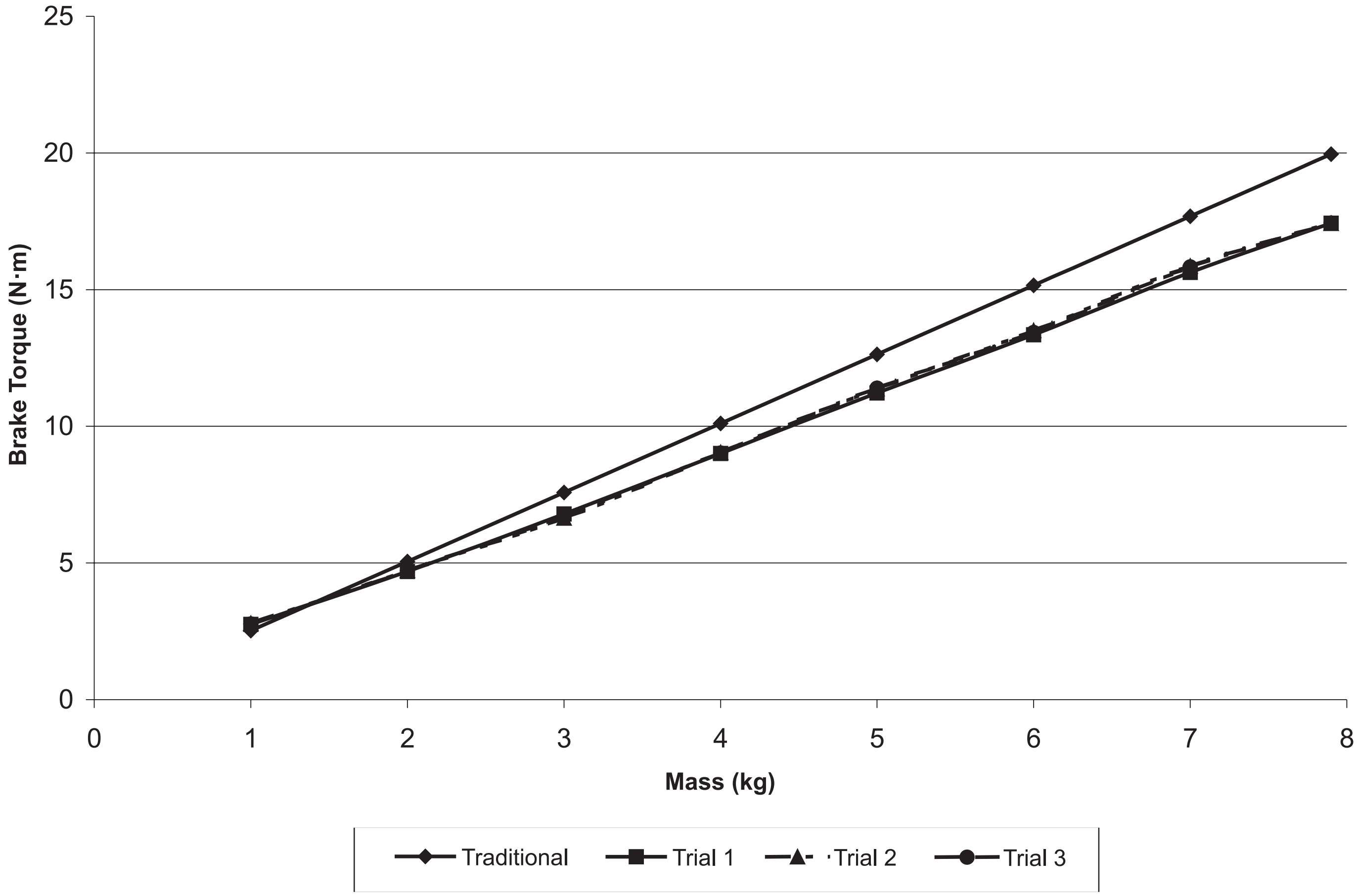
From eqs. 1 and 2 the theoretical rope tensions can be determined given the coefficient of friction between the rope and the flywheel. The coefficient of friction between the rope and flywheel can be determined experimentally (Gordon et al. 2004*b*), but this is not a practical solution for physiologists, as it would need to be carried out before any testing. It is more practical to measure the rope tensions directly. It should be noted that the coefficient of friction will vary with time as the rope wears or becomes contaminated by dust, salt, temperature, etc.

The brake torque is therefore,

$$[3] \qquad T = (F_1 - F_2)r$$

where T (N·m) is the brake torque and r (m) is the flywheel radius.

Fig. 3. A comparison of the manufacturer's assumed brake torque applied to the flywheel and that measured directly from the tension in the rope brake at a series of different basket masses.



Moment of inertia

The work done in rotating the flywheel is considered to have two main components: the work done in overcoming the brake load and the work done in accelerating the flywheel. (In some cases a frictional component is included, but this has not been validated, as experimental work is not in agreement with the theory.) The work can be written as

$$[4] \qquad W = T\theta + I\alpha\theta$$

where W is the work done (J), T is the brake torque (N·m), θ is the angular distance through which the flywheel rotates (rad), I is the moment of inertia of the flywheel (kg·m^2), and α is the angular acceleration (or deceleration) (rad/s^2).

During deceleration (i.e., negative acceleration) there is no work done, thus eq. 4 can be rewritten as

$$[5] \qquad \alpha = \frac{T}{I}$$

This equation provides the basis of the deceleration test for determining the moment of inertia of the flywheel system. The deceleration is measured for a number of different brake torques; when plotted, the slope is the inverse of the moment of inertia.

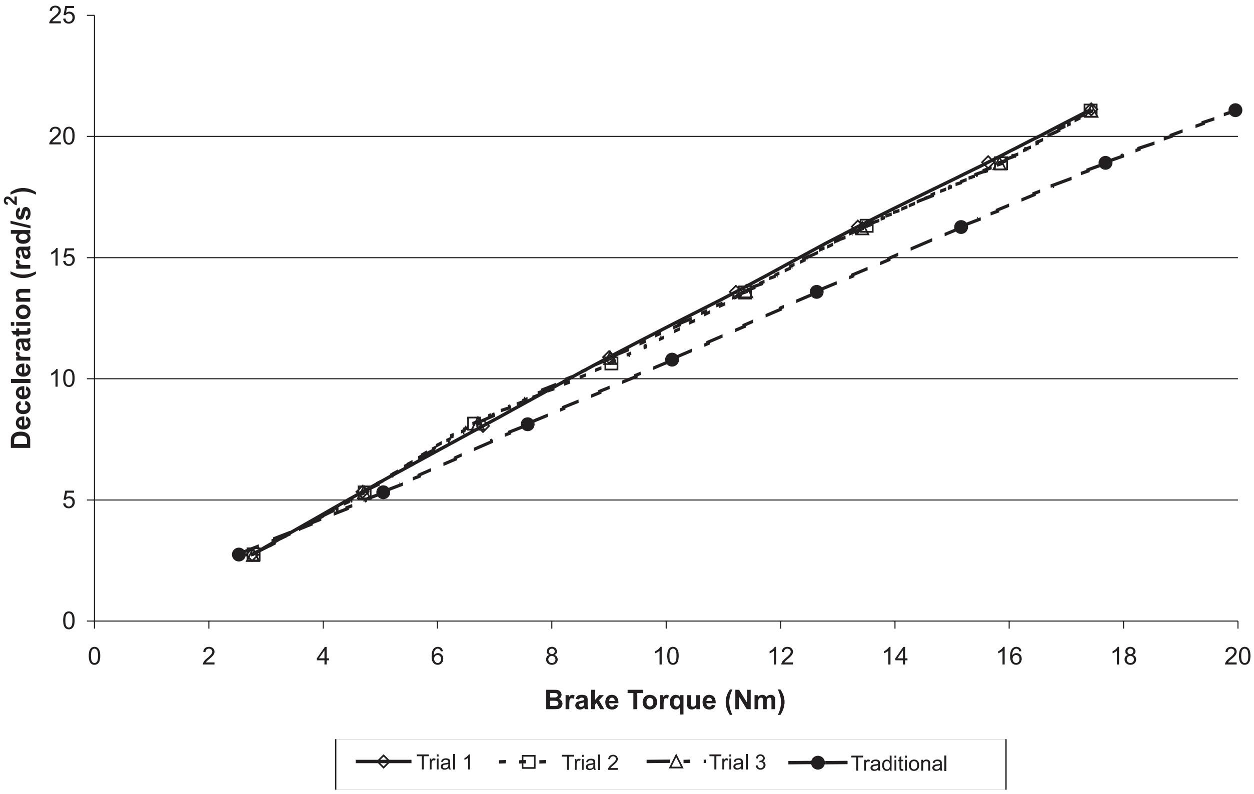
Materials and methods

To determine the actual brake load applied to the flywheel of the cycle ergometer (Monark 824E), the tension in the rope for both the tight and slack side must be obtained. The measurement system used could not change the basic setup of the ergometer or alter any of the parameters in the analysis. To this end, load cells were designed and tested to measure the rope tension. The load cells consisted of a small beam arrangement with three rollers. The rope was fed over–under–over the rollers, effectively putting the beam into three point bending when tension was applied to the rope. Two duel in-line strain gauges were fitted to the load cell to measure the strain in the beam (Franklin et al. 2006). The load cells were calibrated using dead weights. A load cell, that had a mass of 16 g was attached to the brake rope on both the tight and slack sides. The outputs from the strain gauges were connected to a full Wheatstone bridge circuit. This was in turn connected to a National Instruments PC16023C data acquisition card connected to a PC. The load cells were calibrated using a spare ergometer rope and a series of weights, which were weighed using calibrated scales.

The flywheel speed was measured using a Greenbank Tachometer (model No. RE1001). This was also attached to the National Instruments PC16023C data acquisition card. The transducer measurements were then recorded with a virtual instrument created using National Instruments LabView software. The sampling frequency was 50 Hz.

A subject was asked to pedal a Monark Ergometer (model

Fig. 4. A comparison of the flywheel deceleration for three run-down tests at varying brake torques measured from the rope tensions and using the manufacturer's figures. The gradient of the resulting curves is equal to $1/I$, where I is the moment of inertia of the flywheel system.



824E) against different resistances. The basket and each of the weights used as resistance were weighed on calibrated scales (GEC Avery, Smethwick, UK, model RB153-CA4Z-H10AA 1.5 kg × 0.001 kg) before the commencement of each trial. Initially the subject pedaled against the weight of the basket, nominally 1 kg. The pedal cadence has no effect on the tension in the rope (eq. 1) and the subject was asked to pedal at a comfortable speed. The tight and slack side tensions were measured. The subject ceased pedaling and the flywheel was allowed to decelerate to rest. The resistance was increased by 1 kg, which was gently placed on the basket to prevent any shock loading of the rope. The subject pedaled against resistances varying from 1 to 7 kg in 1 kg increments with the tight and slack tension measurements being taken in each case along with the velocity of the flywheel. A final basket mass of 7.9 kg was applied for the test. The procedure was repeated three times.

Results

Figure 2 shows typical results for a deceleration test, the total time for the flywheel to come to rest from a pedal speed of 70 $r \cdot min^{-1}$ was 4.65 s with a mass of 2 kg suspended from the basket. The rope tensions for both tight and slack side are given.

The traditional method of calculating the brake torque for a WAnT using a Monark rope-braked ergometer is to take the product of the brake mass, the flywheel radius (0.2575 m), and the gravitational acceleration due to gravity (9.81 $m \cdot s^{-2}$). This was done for each of the loads used in the test and is compared with the measured brake torque obtained from the rope tensions and using eq. 3 in Fig. 3.

The results from the three deceleration trials at the different levels of measured brake torque are shown in Fig. 4 and are compared with the values derived using the traditional brake torque. The slope of these lines is the inverse of the moment of inertia of the flywheel system.

The average value for moment of inertia from the three tests where the rope tension was directly measured was 0.807 $kg \cdot m^2$ (SD 0.006) compared with a value of 0.94 $kg \cdot m^2$ determined using the traditional method.

During the initial stage of a WAnT the flywheel is accelerated by the subject as they apply maximal effort against a resistance. The pedal cadence can increase from 60 to 140 $r \cdot min^{-1}$ in the first 5 s. This would represent an increase in pedal cadence of 16 $r \cdot min^{-1} \cdot s^{-1}$. Using the equations of angular motion the flywheel would travel through 26.44 $rad \cdot s^{-1}$ with acceleration of 6.23 $rad \cdot s^{-2}$. For a subject weighing 70 kg, a resistance of 0.075 kg·kg body $mass^{-1}$ would result in a basket mass of 5.25 kg and the measured brake torque would be 11.53 N·m compared with the traditional brake torque of 13.26 N·m. The work done by the subject can be calculated using eq. 4. The traditional values of brake torque results in 505.4 J of work being done; this compares with a value of 437.7 J using the measured brake torque. Table 1 shows the difference in work between that traditional and direct torques for a range of scenarios. As all the calculations for work done were based on an acceleration over a time step of 1 s, the figures also represent the values for power.

Table 1. Monark and direct results of work done for a range of subjects of different body mass over a range of accelerations for a 1 s period.

Subject body mass (kg)	Basket mass (kg)	Monark torque (N·m)	Direct torque (N·m)	Initial pedal rate (r·min^{-1})	Final pedal rate (r·min^{-1})	Monark work (J)	Direct work (J)	Error (%)
50	3.75	9.47	8.52	60	65	274.72	245.3	11.99
50	3.75	9.47	8.52	60	70	331.93	294.79	12.60
50	3.75	9.47	8.52	60	75	392.69	347.34	13.06
50	3.75	9.47	8.52	60	80	457.01	402.93	13.42
50	3.75	9.47	8.52	60	90	596.32	523.28	13.96
55	4.125	10.42	9.33	60	65	297.75	264.92	12.39
55	4.125	10.42	9.33	60	70	355.88	315.20	12.91
55	4.125	10.42	9.33	60	75	417.57	368.53	13.31
55	4.125	10.42	9.33	60	80	482.80	424.91	13.62
55	4.125	10.42	9.33	60	90	623.95	546.83	14.10
60	4.5	11.37	10.14	60	65	320.78	284.55	12.73
60	4.5	11.37	10.14	60	70	379.83	335.61	13.18
60	4.5	11.37	10.14	60	75	442.44	389.72	13.52
60	4.5	11.37	10.14	60	80	508.60	446.89	13.81
60	4.5	11.37	10.14	60	90	651.58	570.38	14.24
70	5.25	13.26	11.75	60	65	366.84	323.79	13.29
70	5.25	13.26	11.75	60	70	427.73	376.42	13.93
70	5.25	13.26	11.75	60	75	492.18	432.11	13.90
70	5.25	13.26	11.75	60	80	560.18	490.84	14.12
70	5.25	13.26	11.75	60	90	706.85	617.47	14.48
80	6	15.16	13.36	60	65	412.89	363.04	13.73
80	6	15.16	13.36	60	70	475.63	417.24	13.99
80	6	15.16	13.36	60	75	541.92	474.49	14.21
80	6	15.16	13.36	60	80	611.76	534.80	14.39
80	6	15.16	13.36	60	90	762.12	664.57	14.68

Note: The total work done is assumed to be the work done in overcoming the brake load and the inertial work done in accelerating the flywheel for both cases.

Discussion

Figure 2 shows the results for a typical deceleration test. If, as stated by MacIntosh et al. (2001), there is a decrease in slack side tension with an increase in flywheel speed, then this would result in a change in the brake torque. If this were the case, then as the flywheel decelerates the slack side tension would increase, the brake torque would be reduced, and the deceleration would not be constant. Figure 2 shows that both the tight and slack side tensions are constant during deceleration and thus the brake torque is constant. It can also be seen that the deceleration is linear and therefore constant. MacIntosh et al. (2001) drew their conclusion about the slack side tension reducing with flywheel speed using a linear velocity (m·s^{-1}) instead of an angular velocity (rad·s^{-1}), which would be more relevant for a rotating system. It should also be noted that the range of the slack side tension, reported by MacIntosh et al. (2001), was between approximately 4.3 N and 4.6 N. This is a very small load and difficult to measure accurately, particularly when the transducer has a range from 0 to at least 98.1 N (from the calibration information given). This would suggest that the conclusion reached by MacIntosh et al. (2001) was incorrect. It should be pointed out that if MacIntosh et al. (2001) were correct, then the deceleration test that they subsequently used to obtain the moment of inertia would not be valid, as the value obtained would be a function of the starting pedal cadence. The deceleration method for determining the moment of inertia of the flywheel system is based on constant deceleration.

Figure 3 shows a comparison of the traditionally assumed brake torque and the directly measured brake torque for each of the three tests carried out. It can be seen that there is very good agreement between the three sets of measured torques with the greatest discrepancy at the 6 kg brake mass, where the average torque is 13.45 N·m (SD 0.043 N·m). The larger the brake mass, the larger the difference between the assumed and measured brake torques. The error ranges from 6.77% at the 2 kg brake mass to 12.65% at the 7.9 kg brake mass.

Figure 4 shows the results from the series of deceleration tests and the traditionally assumed values. Once again, there is good correlation between the measured results for each test. The greatest discrepancy between the three sets of measured results was at the brake torque of 9.02 N·m (equivalent to a brake mass of 4 kg) with the mean deceleration being 10.79 rad·s^{-2} (SD 0.14 rad·s^{-2}). The inverse of slope of these lines gives the moment of inertia of the flywheel system. This was calculated to be 0.807 kg·m^2 (SD 0.006 kg·m^2) compared with a value of 0.941 kg·m^2 obtained using the traditional calculations. This represents an error of 14.2%.

The accuracy of the results for a WAnT is subject to two errors, the first due to the inaccuracy of the brake load and the second due to the subsequent error in the value for the moment of inertia of the flywheel system. The overall effects of these two sources of error must be determined. The effect of these two sources of error on the work done was calculated for hypothetical subjects, weighing between 50 and 80 kg, and for accelerations from an initial pedal cadence of 60 $r \cdot min^{-1}$ to a final pedal cadence of between 65 and 90 $r \cdot min^{-1}$. The results are shown in Table 1. It can be seen from Table 1 that the difference between the traditional values of work and the measured values increases both with an increase in the brake mass and an increase in the acceleration. The difference between the work done over a 1 s period for the examples given range from 11.99% to 14.98%. For a 50 kg subject the difference between work done overcoming the brake load using Monark's value and the direct value is 11.17%. The difference in the inertial work done between the Monark value and the direct value is constant over the range of accelerations at 14.15%. However, the difference in the total work done increases as the acceleration increases. At an increase in pedal cadence from 60 to 65 $r \cdot min^{-1}$ the difference in total work done is 11.99% and this increases to 13.96% when the pedal cadence increases from 60 to 90 $r \cdot min^{-1}$. At the lower level of acceleration (5 $r \cdot min^{-1} \cdot s^{-1}$) the inertia element of work only contributes 15.56% of the total work, but this increases to 52.5% at the highest acceleration (30 $r \cdot min^{-1} \cdot s^{-1}$). The contribution of the inertial error increases with the increasing rate of acceleration.

As the resistance is increased, the error between the Monark and directly measured results also increases. This is consistent with the results shown in Fig. 3.

MacIntosh et al. (2001) concluded that the power obtained using direct measurement was always less than that calculated by their Monark ergometer. This is consistent with the results found in this study. It is difficult to compare the results between the two studies, as different models of ergometers were used and because of the inconsistency in the tensions (given as percentages) measured by MacIntosh et al. (2001).

The calculations for work done in a WAnT presented in this study are based on the method of calculation presently used by physiologists. Further work needs to be carried out to apply these findings to a WAnT in a physiological study; however, experimental observations show that the actual data generated by the WAnT are complex and need close examination.

It should be noted that the mechanical efficiency of the ergometer has not been accounted for in the calculations presented. This could account for an additional 2% to 12% of work being done by the subject.

Conclusions

The method currently used to determine the brake torque on a rope-braked flywheel ergometer is incorrect and overestimates the actual value. As the setup of the brake system and the level of maintenance vary between ergometers the actual amount of overestimation will also vary. This means that the current results generated a lack of accuracy and, if taken over a period of time, they will lack precision. The only accurate method to determine the brake torque is to measure the tensions in the ropes. This will provide the accuracy and precision that is currently lacking.

It has been shown that brake torque is constant during pedalling and deceleration of the flywheel. This is up to the point where there is insufficient energy in the flywheel to overcome the friction in the rope and the system goes from dynamic to static equilibrium. The fact that the brake torque is constant means that the deceleration will be constant. The constant deceleration allows the moment of inertia of the flywheel system to be determined.

The moment of inertia of the flywheel system was found to be overestimated by 14.15% in this study because of the overestimation in the brake torque being applied.

The percentage difference in the work done by the subject between the traditional method of calculation and the direct measurement of the brake torque for a WAnT increases as the load increases and also increases as the rate of acceleration increases.

References

Åstrand, P.-O. 1988. Work tests with the bicycle ergometer. Monark Exercise AB, Sweden.

Bassett, D.R., Jr. 1989. Correcting the Wingate test for changes in kinetic energy of the flywheel. Int. J. Sports Med. **10**: 446–449. PMID:2628365.

Burges, S.C. 1998. Improving cycling performance with large sprockets. *In* The engineering of sport. *Edited by* S.J. Haake. Blackwell Science, Oxford, UK. pp. 23–30.

Coleman, S.G., and Hale, T. 1998. The effect of different calculation methods of flywheel parameters on the Wingate anaerobic test. Can. J. Appl. Physiol. **23**: 409–417. PMID:9677437.

Franklin, K.L., and Gordon, R.S. 2002. A study into the work done in accelerating a rope braked flywheel ergometer. *In* The 4th International Conference on the Engineering of Sport, ISEA, Kyoto, Japan. *Edited by* S. Ujihashi and S. Haake. International Sport Engineering Association, Sheffield, UK. pp. 144–148.

Franklin, K.L., Baker, J.S., Davies, B., and Gordon, R.S. 2006. Determination of aerobic work and power on a rope-braked cycle ergometer by direct measurement. Appl. Physiol. Nutr. Metab. **31**: 392–397. PMID:16900228.

Gordon, R.S., Franklin, K.L., Baker, J.S., and Davies, B. 2004a. A study in the accuracy and precision of determining the moment of inertia of an ergometer flywheel. *In* The engineering of sport 5. Vol. 1. *Edited by* M. Hubbard, R.D. Mehta, and J.M. Pallis. International Sport Engineering Association, Sheffield, UK. pp. 529–535.

Gordon, R.S., Franklin, K.L., Baker, J.S., and Davies, B. 2004*b*. Accurate assessment of the brake torque on a rope-braked cycle ergometer. Sports Eng. **7**: 131–139.

Hibi, N., Fujinaga, H., and Kihachi, I. 1996. Work and power outputs determined from pedaling and flywheel friction forces during brief maximal exertion on a cycle ergometer. Eur. J. Appl. Physiol. **74**: 435–442.

Lakomy, H.K.A. 1986. Measurement of work and power output using friction-loaded cycle ergometers. Ergonomics, **29**: 509–517. PMID:3709505.

Lakomy, H.K.A. 1993. An indirect method for measuring the torque applied to friction loaded cycle ergometers. Ergonomics, **36**: 489–496.

MacIntosh, B.R., Bryan, S.N., Rishaug, P., and Norris, S.R. 2001. Evaluation of the Monark Wingate ergometer by direct measurement of resistance and velocity. Can. J. Appl. Physiol. **26**: 543–558. PMID:11842272.

Maxwell, B.F., Withers, R.T., Ilsley, A.H., Wakim, M.J., Woods, G.F., and Day, L. 1998. Dynamic calibration of mechanically, air- and electromagnectically braked cycle ergometers. Eur. J. Appl. Physiol. Occup. Physiol. **78**: 346–352. doi:10.1007/s004210050430. PMID:9754975.

Reiser, R.F., II, Broker, J.P., and Peterson, M.L. 2000. Inertial effects on mechanically braked Wingate power calculations. Med. Sci. Sports Exerc. **32**: 1660–1664. PMID:10994921.

Spotts, M.F., and Shoup, T.E. 1998. Design of machine elements. 7th ed. Prentice Hall, London, UK. pp. 341–342.

von Döbeln, W. 1954. A simple bicycle ergometer. J. Appl. Physiol. **7**: 222–224. PMID:13211502.