The Effect of Different Calculation Methods of Flywheel Parameters on the Wingate Anaerobic Test

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Catalogue Data

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Abstract/Résumé

Researchers compared different methods of calculating kinetic parameters of friction-braked cycle ergometers, and the subsequent effects on calculating power outputs in the Wingate Anaerobic Test (WAnT). Three methods of determining flywheel moment of inertia and frictional torque were investigated, requiring “run-down” tests and segmental geometry. Parameters were used to calculate corrected power outputs from 10 males in a 30-s WAnT against a load related to body mass (0.075 kg · kg⁻¹). Wingate Indices of maximum (5 s) power, work, and fatigue index were also compared. Significant differences were found between uncorrected and corrected power outputs and between correction methods (p < .05). The same finding was evident for all Wingate Indices (p < .05). Results suggest that WAnT must be corrected to give true power outputs and that choosing an appropriate correction calculation is important. Determining flywheel moment of inertia and frictional torque using unloaded run-down tests is recommended.

Les auteurs comparent diverses méthodes de calcul des variables cinétiques au cours de l’épreuve anaérobie de Wingate pour l’évaluation de la puissance mécanique sur des ergocycles à résistance par friction. Au moyen de tests de “laisser-aller” et de géométrie segmentaire, trois méthodes de détermination du moment d’inertie du volant et du moment de force dû à la friction sont analysées. Les valeurs des diverses méthodes sont ensuite appliquées dans le calcul de la puissance mécanique corrigée chez dix hommes au cours de l’épreuve anaérobie de Wingate d’une durée de 30 s contre une résistance de 0,075 kg · kg⁻¹.

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de masse corporelle. Les indices du maximum de puissance (5 s), du travail accompli et de fatigue sont également comparés. Les auteurs trouvent une différence significative entre les valeurs de puissance corrigée et non corrigée et entre les diverses méthodes de correction (p < .05). Les ensembles d’indices sont aussi significativement différents les uns des autres (p < .05). Il faut donc apporter une correction aux valeurs de puissance obtenues au cours de l’épreuve de Wingate; la méthode de correction doit aussi être appropriée. Les auteurs recommandent de déterminer le moment d’inertie du volant et le moment de force dû à la friction au moyen de tests de laisser-aller sans charge.

Introduction

Since it was incepted by Ayalon et al. (1974), the Wingate Anaerobic Test (WAnT) has become one of the most popular methods for assessing athletes’ short-term capabilities. This test is “fast, simple, not onerous, easily adaptable for the arms or legs, can be repeated 2–3 times in the same session, and is convenient for both the laboratory or the field” (Bar-Or, 1981). The simplicity of the protocol has been the major attraction for experimenters: It requires little more than a standard friction-braked ergometer, stop-watch, and revolution counter.

In 1985, Lakomy realised that the method used to calculate power output was theoretically flawed and inaccurate when the test was performed on a friction-braked ergometer. The original protocol allowed researchers to measure power output over successive 5-s periods, using the number of pedal revolutions over each interval to calculate flywheel velocity and then multiplying this by the applied load. Lakomy recognised that ergometer acceleration and deceleration were ignored by this method, meaning that any energy stored in the flywheel was not taken into account and that power outputs would be under- and overestimated during acceleration and deceleration, respectively.

Lakomy’s correction method (Lakomy 1986, 1993) required the use of “run-down” tests of the ergometer flywheel against a range of loads applied to the friction belt. Flywheel deceleration was plotted against applied load, and an excess load required to balance any acceleration in the Wingate Test was calculated using linear regression.

Coleman et al. (1986) noted that this method gave incorrect results during flywheel deceleration due to the nonzero intercept of the regression line. They argued that correct power output should be calculated using values for the flywheel moment of inertia and frictional torque of the ergometer. These variables could be measured using run-down tests against gravity and the subsequent equating of potential and kinetic energies—a method often utilised in classical mechanics (Humphrey and Topping, 1971; Nelkon and Parker, 1987).

These quantities were then used in the following equation to calculate correct power output:

\[ P = \omega \cdot (I \cdot \alpha + L \cdot r \cdot g \cdot T_f) \]

where \( P \) = power output (W), \( \omega \) = flywheel angular velocity (rad \cdot s\(^{-1}\)), \( I \) = flywheel moment of inertia (kg \cdot m\(^2\)), \( \alpha \) = flywheel angular acceleration (rad \cdot s\(^{-2}\)), \( L \) = mass applied to friction belt (kg), \( r \) = flywheel radius (m), \( g \) = acceleration due to gravity (9.81 m \cdot s\(^{-2}\)), and \( T_f \) = frictional torque due to chainset and bearings.
Bassett (1989) measured flywheel moment of inertia using geometrical means, but this method assumed constant flywheel density. Also, the published paper contained typographical errors that gave incorrect values for the moment of inertia, and an incorrect formula was used. Frictional losses were expressed as a function of flywheel velocity squared, an empirical method that may have limited theoretical grounding.

Thus, our aim was to compare the three methods of correcting for flywheel acceleration and deceleration and to examine how they affect calculation of power outputs during the WAnT.

**Methods**

The protocol was separated into two parts: ergometer measurement and Wingate Anaerobic Tests.

**ERGOMETER MEASUREMENT**

We used 6 Monark 814E Ergomedic friction-braked devices (Monark AG, Sweden), modified by adding 90 black-white strips around the flywheel rim (Coleman et al., 1986; Lakomy and Wootton, 1981). These were then read by a photo-reflective opto-sensor connected to a microcomputer (Acorn Archimedes, England). We used this method to determine all flywheel angular displacement. Flywheel angular velocities and accelerations were then calculated using finite difference techniques (Lees, 1980). Ergometer cradle and masses, which provided variable resistance, were determined to <0.1% accuracy with a balance (Ohaus Ltd, Germany).

**LAKOMY METHOD**

We followed Lakomy’s (1986) protocol, but flywheel velocity was monitored by an opto-sensor rather than a D.C. motor. A subject accelerated the flywheel to 58.3 rad · s⁻¹ (a pedal velocity of 150 r · min⁻¹) against a friction band loaded with a known mass. The individual then ceased pedalling, and the ergometer was allowed to run-down, with the flywheel velocity monitored at 20 Hz. We used the time taken to decelerate from 40.8 rad · s⁻¹ (105 r · min⁻¹) to 0 in order to find the average flywheel deceleration. This was performed for 5 masses, and deceleration was plotted against applied load. We used linear regression to find the relationship between deceleration and applied load. A correlation coefficient (Pearson Product Moment) was also obtained (Howell, 1992). We repeated this procedure 8 times for each ergometer.

**BASSETT METHOD**

Mass of the ergometer flywheel was determined using calibrated scales (Avery Ltd, Birmingham, England), and the flywheel was then marked at 1 cm intervals from the centre. We measured the thickness at each interval using calibrated callipers and a micrometer (Mitutoyo Ltd, Japan). These measurements were used to calculate volume, mass, and moment of inertia of each segment, and hence the moment of inertia of the whole wheel. A subject-accelerated run-down test against a load of 1.0048 kg was performed to calculate frictional torque, as noted in Bassett’s
(1989) paper. This required calculating a regression coefficient constant by plotting frictional torque versus the square of the angular velocity.

**COLEMAN METHOD**

The friction belt was removed from the ergometer. We drilled a 2-mm hole in the flywheel rim and inserted a small dowel. The ergometer was placed on a balcony so that the flywheel centre was 2.52 m above the ground. The ergometer weight cradle was attached to a 2.52-m cord, and one end was attached to the dowel. We rotated the ergometer flywheel so that the string wrapped around the rim. Then, we started a specially written computer program that measured flywheel angular displacement. The weight was allowed to fall, thus accelerating the wheel. We monitored the flywheel angular displacement at 20 Hz until the wheel stopped. Wheel displacement during acceleration and deceleration were calculated and used to derive the moment of inertia of the flywheel and frictional torque (Coleman et al., 1986). This was repeated 8 times for 5 masses in random order for each ergometer.

**WINGATE ANAEROBIC TESTS**

Participants were 10 physical education and sports science students with specialisms in basketball, rugby, and soccer (mean body mass = 71.86 kg ± 11.66, height = 1.77 m ± 0.13, age = 23.2 ± 3.1 years). All students gave informed consent and completed a pretest medical questionnaire. Participants warmed up for 5 min at 60W (60 r · min⁻¹) on a calibrated cycle ergometer. During warm-up, participants were free to sprint for 2–3 s for habituation purposes. At the end of the warm-up, the ergometer cradle was supported manually, and the Wingate load (0.075 kg · kg⁻¹ body mass) was applied. Each student was told to maintain pedal frequency at 60 r · min⁻¹. After this, a 3-s countdown was given. At the end of the countdown, computer data collection was started and the Wingate load applied to the flywheel belt. Simultaneously, the subject commenced pedalling maximally and continued for 32 s. Angular displacement data from the opto-sensor were stored.

Further analysis involved smoothing the angular displacement data using a fourth-order reverse Butterworth digital filter, with the cut-off set at twice the maximum pedal frequency. Angular velocities and accelerations were then determined using finite difference techniques, and these data were combined with the kinetic variables (moment of inertia and frictional torque) resulting from the three methods of ergometer measurement. This enabled calculating power for each 0.05-s interval. Power outputs for 5-s intervals were then obtained for uncorrected, corrected (Lakomy), corrected (Bassett), and corrected (Coleman) computation methods. Wingate Indices of 5-s maximum power, work, and fatigue (power decrease/maximum power) were also determined (Bar-Or, 1981).

**STATISTICAL ANALYSIS**

We compared the 5-s power data for the four methods using a two-way analysis of variance (method × time interval), with α-level set at 0.05. Greenhouse-Geiser corrections were made to avoid sphericity problems with repeated measures tests (Thomas and Nelson, 1990). The adjusted degrees of freedom were used to determine the critical F ratio for each test. Simple effects were also computed (Howell,
1992), and pairwise comparisons were performed using post-hoc Tukey tests. Wingate Indices were compared using a one-way analysis of variance with one repeated measure, with post-hoc Tukey tests again being utilised to assess pairwise differences.

Results

ERGOMETER MEASUREMENT

The mean radii of the ergometer flywheels was 0.256 m (± 0.003). Kinetic values for the ergometers measured are shown in Table 1. Slope and intercept obtained using Lakomy's (1986) method are shown in columns 2 and 3. Moment of inertia values and frictional torques calculated using the unloaded run-down test (Coleman et al., 1986) are displayed in columns 4 and 5. Finally, moments of inertia and frictional constant (to be multiplied by the flywheel angular velocity squared) determined using Bassett's (1989) protocol are included in the last two columns.

Pearson Product Moment correlations for the run-down proposed by Lakomy (1986) ranged from 0.998 to 0.999. Ergometer number 5 (see Table 1) was then randomly chosen for subsequent Wingate tests and method comparisons.

WINGATE ANAEROBIC TEST

Results for 5-s power outputs are shown in Figure 1. Two-way ANOVA showed significant main effects for correction method \( F_{5,27} = 60.12, P = 2.84 \times 10^{-5} \) and 5-s interval \( F_{5,45} = 58.38, P = 3.19 \times 10^{-5} \) as well as a significant interaction \( F_{15,135} = 199.01, P = 5.23 \times 10^{-11} \). Simple effects showed significance \( (p < .05) \) at all time intervals. Post-hoc Tukey tests on the method main effect showed that the Coleman method was significantly \( (p < .05) \) different from the other three datasets. The Bassett correction procedure was also significantly different from Lakomy's method.

Table 1  Ergometer Kinetic Values Using Three Calculation Methods

<table>
<thead>
<tr>
<th>Ergometer</th>
<th>Lakomy method</th>
<th>Bassett method</th>
<th>Coleman method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope (rad·s⁻²·kg⁻¹)</td>
<td>Intercept (rad·s⁻²)</td>
<td>Moment of inertia (kg·m²)</td>
</tr>
<tr>
<td>1</td>
<td>2.542</td>
<td>0.312</td>
<td>0.962</td>
</tr>
<tr>
<td>2</td>
<td>2.509</td>
<td>0.281</td>
<td>0.967</td>
</tr>
<tr>
<td>3</td>
<td>2.467</td>
<td>0.206</td>
<td>0.967</td>
</tr>
<tr>
<td>4</td>
<td>2.469</td>
<td>0.247</td>
<td>0.968</td>
</tr>
<tr>
<td>5</td>
<td>2.471</td>
<td>0.249</td>
<td>0.975</td>
</tr>
<tr>
<td>6</td>
<td>2.504</td>
<td>0.250</td>
<td>0.971</td>
</tr>
<tr>
<td>M</td>
<td>2.493</td>
<td>0.259</td>
<td>0.968</td>
</tr>
<tr>
<td>SD</td>
<td>0.065</td>
<td>0.066</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Figure 1. Comparison of mean 5-s power outputs using four calculation methods.

Wingate Indices for the four methods are shown in Table 2. Maximum power data (5-s average) showed significant differences between methods ($F_{3,27} = 28.35$, $P = 0.0004$). Pairwise comparisons indicated that the uncorrected power values were significantly different from all corrected data but that no differences existed between correction methods.

Significantly different amounts of work were obtained using the four methods ($F_{3,27} = 60.81$, $P = 2.71 \times 10^{-5}$). Tukey tests showed that all pairwise comparisons were significantly different, except from that between uncorrected and Coleman-corrected data.

Fatigue values were also different ($F_{3,27} = 106.81$, $P = 2.72 \times 10^{-6}$), with post-hoc analysis indicating that uncorrected values were significantly different from all three corrected datasets and that Bassett’s calculation gave different results from the other two correction methods.

Discussion

Researchers have recognised for over 10 years that Bar-Or et al.’s (1981) WAnT is theoretically flawed because kinetic energy is stored in the flywheels of friction-braked ergometers. The search for an accurate correction method has not been straightforward, although the mechanics of the system are well understood.

We sought to compare corrected power outputs and Wingate Indices that were obtained using three correction methods. The most important finding was that uncorrected 5-s power outputs were significantly different from those obtained
Table 2  Wingate Indices Using Four Calculation Methods

<table>
<thead>
<tr>
<th>Wingate Index</th>
<th>Uncorrected</th>
<th>Lakomy</th>
<th>Bassett</th>
<th>Coleman</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$</td>
<td>$SD$</td>
<td>$M$</td>
<td>$SD$</td>
</tr>
<tr>
<td>Maximum 5-s power output (W)</td>
<td>719.3</td>
<td>96.1</td>
<td>790.6</td>
<td>103.0</td>
</tr>
<tr>
<td>Work done over 30 s (J)</td>
<td>18,626</td>
<td>2,631</td>
<td>18,983</td>
<td>2,627</td>
</tr>
<tr>
<td>Fatigue index (%)</td>
<td>27.17</td>
<td>8.53</td>
<td>37.24</td>
<td>10.34</td>
</tr>
</tbody>
</table>

using calculations that allowed for nonconstant velocity. This result agrees with conclusions from Lakomy (1986), Bassett (1989), and Coleman et al. (1986), who investigated this phenomenon, and is of crucial importance for those performing WAnTs on friction-braked ergometers.

Our second major finding was that the three correction methods gave different power outputs and Wingate Indices. This may have been for various reasons, which are discussed here.

Lakomy (1986) used a regression line to calculate an excess load required to balance deceleration. This resulted in a positive slope (related to flywheel moment of inertia) and a positive intercept (representing the deceleration obtained with no applied load, thus indicating frictional torque). When regression was used, wheel acceleration and deceleration were multiplied by a regression line with two positive coefficients. Thus, the two parts (due to moment of inertia and frictional torque) of the excess load always had the same sign (i.e., positive or negative). When the flywheel accelerates, the inertial component has the same sign as the frictional torque, but when it decelerates, the two parts have opposite signs. As a result, values obtained using Lakomy’s correction methods always underestimate the power output during flywheel deceleration.

Bassett (1989) assumed that the flywheel had a constant density, but this may not be the case. Coleman et al. (1986) found that the flywheel of one ergometer stopped at the same position during each run-down trial, requiring 0.25 kg at 0.15 m from the axle for correct balance. This would give an additional moment of inertia of 0.006 kg m$^2$—an error of 0.6%. Therefore, the flywheels that were investigated would seem to be homogenous constructions, and so Bassett’s calculations would appear theoretically sound. Unfortunately, Bassett’s original paper contained numerous typographical and calculation errors, and so the earlier values cannot be used for comparison. Thus, measuring the flywheel at 1-cm intervals may not give a true profile. In the future, greater precision should be used when measuring flywheel thickness. Frictional characteristics of the ergometer were assessed using Bassett’s single run-down test and calculation of kinetic energy to overcome friction, but no theoretical reason was given for the relationship used (constant $\times$ angular velocity squared).
The Coleman method involves using classical mechanics to measure the moment of inertia and frictional torque of the ergometer. However, there were several possible sources of error, such as the possible extension of the string used to accelerate the wheel, the low resolution of the number of black-white changes during the run-down acceleration period, and the fact that frictional torque was assumed to be independent of flywheel angular velocity. Coleman et al. (1986) examined the first two sources of error and estimated that the maximum error in the moment of inertia values would have been approximately 5%, mainly due to the second reason identified above. In our study, frictional torque increased slightly with increased velocity, but because we could find no theoretical reason for this, we provided mean values in Table 1.

The starting protocol was slightly different (Bassett, 1989; Inbar et al., 1996). Usually, cyclists pedal at maximum speed before loads are applied. When carrying out this type of test, we noticed that participants had trouble reaching peak speed against an unloaded ergometer due to coordination problems. Also, using 60 r·min⁻¹ initial velocity allowed standardisation across participants. Finally, this was the protocol used by Lakomy (1986), who applied the full load to the ergometer, with the subject pedalling at 60 r·min⁻¹. Because this paper contains the generally recognised correction method, we used this procedure. As Bassett (1989) pointed out, this would result in correction calculations giving higher power values for the first period (see Figure 1). If the load was applied when the subject reached peak speed (as in the original protocol), correction routines would result in reduced power outputs due to immediate flywheel deceleration (6.2%; lower according to Bassett, 1989). However, this fact does not obviate the need for correcting power outputs, because uncorrected data would still be erroneous.

The original test also identified differences between endurance and sprint athletes. Corrected power output data would increase these differences because sprint athletes' greater acceleration and deceleration would result in an increased inertial component. If the test protocol allowed acceleration, higher maximal power outputs would be observed, but if the test started from maximal velocity, then lower power outputs toward the end of the test would result due to greater fatigue and larger deceleration.

In conclusion, to obtain correct power output values from the WAnT, a calculation method that accounts for nonconstant flywheel velocity must be employed. Without this correction, results from the WAnT will be in error. Contrary to some scientists' beliefs, uncorrected data cannot be used for comparison purposes only (intra- or interindividuals) because accelerations may be greatly different, even though peak velocities are similar.

One of the methods that we investigated should be used to correct WAnT results. Coleman's (1986) procedure is the most theoretically sound but requires rather complex run-down tests to calculate inertial and frictional characteristics. Using Lakomy's protocol, researchers underestimate power during flywheel deceleration. However, they may be able to correct this by separating the inertial and frictional parts of the excess load. Bassett's (1989) method assumes constant flywheel density (an assumption that is validated by this study), but his frictional calculations are confusing and empirically based.

Sport and exercise scientists can no longer ignore the effect of flywheel acceleration on power outputs during the WAnT (Inbar et al., 1996). Protocols and calculation methods must be adjusted appropriately in the future.
References


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