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ORIGINAL ARTICLE

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Assessment of peak power and short-term work capacity

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Abstract The purpose of this study was to evaluate conditions for conducting a 30 s Wingate test such as load selection, and the method of starting the test (stationary or flying start). Nine male and four female athletes volunteered to be tested on four laboratory visits. Tests were performed on a modified Monark cycle ergometer (Varberg, Sweden) equipped with force transducers on the friction belt and an optical encoder for velocity measurement. Power was calculated with the moment of inertia (*I*) of the flywheel taken into consideration. One laboratory visit was used to determine individualized optimal resistance conditions. The other three visits were for performance of one of three Wingate tests: a flying start with 0.834 $N \cdot kg^{-1}$ [85 $g \cdot kg^{-1}$ body weight (BW)] resistance (FLY-0.8); a stationary start with 0.834 $N \cdot kg^{-1}$ BW resistance (ST-0.8), or a stationary start with optimal resistance (ST-OPT). FLY-0.8 gave a lower ($P < 0.05$) value for short-term work capacity [19,986 (827) J] than either ST-OPT [23,014 (1,167) J] or ST-0.8 [22,321 (1075) J]. Peak power output per pedal revolution was lower ($P < 0.005$) for FLY-0.8 [833 (40) W] than for either ST-0.8 [974 (57) W] or ST-OPT [989 (61) W]. The results of this study demonstrate that higher values for peak power and short-term work capacity are obtained with a test from a stationary start. It is apparently not necessary to use an individualized optimal resistance when *I* is considered in a Wingate test initiated from a standstill.

Keywords Wingate test · Cycle ergometry

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Introduction

The Wingate test was developed in the 1970s as a method to evaluate supramaximal (above maximal oxygen uptake) capabilities of athletes (Bar-Or et al. 1977; Inbar et al. 1976; Inbar et al. 1977). The test is widely used, is simple to administer, and has the further advantage that it uses equipment that is typically available in standard Exercise Physiology laboratories. The test is a substitute for direct measurement of the capability to provide energy from non-aerobic sources (Vandewalle et al. 1987b). The Wingate test has potential utility and has been adopted worldwide. However, some problems have been identified with the way in which the test is administered. There are three problems in particular that need to be addressed, the first of which is that moment of inertia (*I*) must be taken into consideration (Lakomy 1986). This issue has been clearly demonstrated, yet is rarely given the consideration it deserves. The second problem concerns the selection of the appropriate resistance to permit the subject's highest possible power output. It is clear that an optimal resistance for peak power output (PPO) is an individual characteristic, but it is not clear that this optimal resistance will permit the greatest total work in 30 s. The third problem is that the test is traditionally conducted with a flying start. This may not be appropriate, but the issue has not been systematically evaluated.

In its original form, the Wingate test simply required the subject to cycle at maximum effort for 30 s against a resistance that was set proportional to body weight, BW (75 $g \cdot kg^{-1}$ or 0.74 $N \cdot kg^{-1}$). This recommended resistance was later revised to 0.834 $N \cdot kg^{-1}$ BW (85 $g \cdot kg^{-1}$) for adults (Bar-Or 1987). The instrument of choice was the Monark cycle ergometer, a pendulum-loaded friction ergometer. Setting resistance on these ergometers requires that the flywheel be in motion, so the test was conducted with a "flying start". The flying start also permitted the subject to accelerate the flywheel prior to application of the resistance, thereby presumably minimizing the impact of not considering *I*. During the 30 s of the test, pedal revolutions were counted, and the total work in 30 s was calculated as the product of the average velocity and the resistance that was set with the pendulum device. A modest advance in methodology was electronic counting of the pedal revolutions. This was done with a pen-chart recorder and removed the need for an assistant (usually a graduate student) to count the pedal revolutions during the test.

The permanent record of pedal revolutions has traditionally been divided into six consecutive blocks of time, 5 s each, and average power was calculated across each block (see Fig. 1). These measurements permitted calculations of the average power across 30 s, an estimate of peak power (usually the first 5 s), and a measure of fatigue (the difference between peak power and the lowest 5 s average power expressed as a percent of the peak power). The average power over the 30 s duration of the test can also be presented as total work, which is the short-term work capacity (STWC).

The utility of the Wingate test relies on the test conditions allowing each subject to achieve the highest possible power output and STWC. This is because the efficiency of cycling at this high intensity cannot be known with certainty. If the purpose of testing is to compare individuals then it would be inappropriate to arrive at the conclusion that one individual has a lower PPO or STWC than another if the reason for the lower power output was due to inappropriate (less than optimal) test conditions. The problems identified above are quite likely to impact on the ability of the test to permit the highest PPO and STWC. In addition, dividing the test results into 5-s blocks ignores the possibility that there may be a 5-s period with greater power output that begins at some time between these designated 5-s intervals.

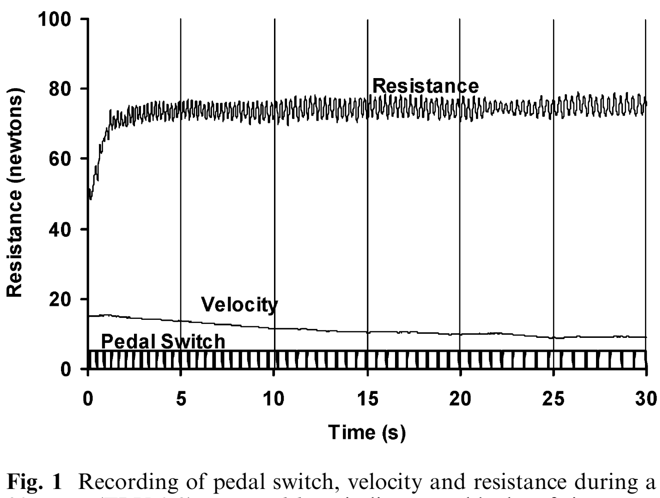

Fig. 1 Recording of pedal switch, velocity and resistance during a 30-s test (FLY-0.8). *Vertical lines* indicate 5-s blocks of time over which power is traditionally measured. Note that for this subject, the greatest amount of work in 30 s included a portion of the time when resistance was still being increased to the target level. This recording also shows that resistance oscillates with each pedal stroke

Several attempts have been made to improve the method of selecting the resistance that is appropriate for an individual (Dotan et al. 1983; Evans et al. 1981; Lowensteyn et al. 1991; Rodgers et al. 2000; Vandewalle et al. 1985). Of the several approaches that have been tried, one stands out as having a sound theoretical basis for selecting the resistance that will permit the highest PPO for an individual. This approach is based on the observation that there is a linear relationship (with a negative slope) between resistance and the velocity that can be achieved with a given resistance. This is illustrated in Fig. 2. Since power is the product of resistance and velocity, the linear resistance–velocity (*R*–*v*) relation yields an inverted U-shaped relationship between resistance and power (as shown in Fig. 2). There is a unique resistance (optimal resistance) at which power is the highest that it can be for constant velocity pedaling. This method of selecting the appropriate resistance does not take *I* into consideration because, at the peak velocity of each trial, there is no acceleration of the flywheel and, therefore, the measured velocity and resistance represent the total power output. Arsac and colleagues (Arsac et al. 1996; Hautier et al. 1996) have used a similar approach

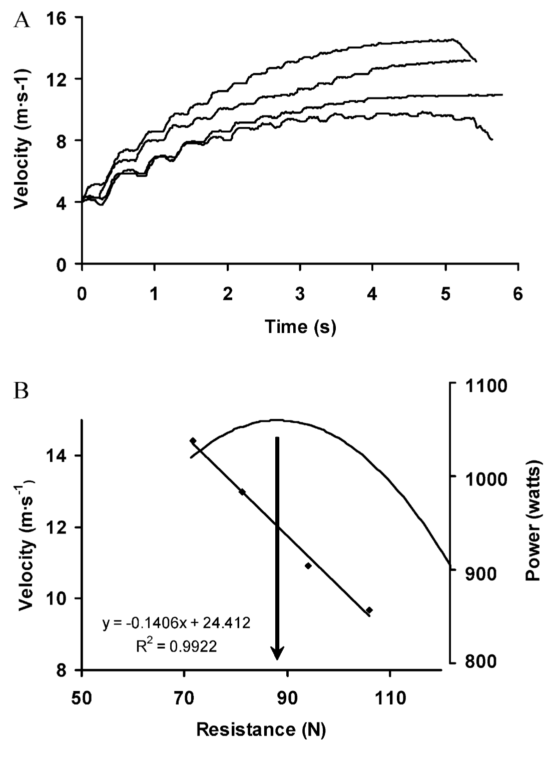

Fig. 2 **A** Recordings of velocity during four resistance-velocity (*R*–*v*) trials. Resistance (N) for each trial corresponds with the value plotted in B. The oscillations in velocity early in each trial represent individual pedal strokes (two per crank revolution) **B** Peak velocity (averaged over a complete pedal revolution) and corresponding resistance (*diamonds*). Linear regression for this subject yielded apparent optimal resistance of 86.5 N. The power–resistance relationship derived from the regression line shows peak power occurs at a unique resistance (optimal resistance, *vertical arrow*) and a unique velocity (optimal velocity) corresponding with the *intersection of the vertical arrow* on the regression line

to determine the optimal conditions for PPO, while taking I into consideration. This approach yields an optimal torque at peak power, but it is not clear if this can be used to set a resistance.

The primary purpose of this study was to compare the PPO and STWC results obtained from three different methods of conducting a Wingate test consisting of 30 s of maximum-effort cycling. The first method was the traditional test with resistance set at 0.834 $N{\cdot}kg^{-1}$ BW during a flying start; the second was with a stationary start using 0.834 $N{\cdot}kg^{-1}$ BW preset resistance; the third test was also from a stationary start, but with the resistance optimized for PPO according to individual *R–v* relationships (MacIntosh et al. 1997; Vandewalle et al. 1987a). Power output was calculated in various ways [consecutive 5-s blocks, per pedal revolution (ppr), best 5 s during the test]. It was hypothesized that PPO and STWC would be highest for the modified Wingate test conducted with the individualized optimal resistance. In all tests and methods of calculating power and work, I was taken into consideration. To permit acknowledgement of the impact of this on our calculations, values without considering I are also presented.

Methods

Subjects

Nine male and four female athletes volunteered to be tested on four different laboratory visits within a 4-week period. The subjects were recruited from a number of competitive sports including track and road cycling, mountain biking, and long-track speed skating. All subjects signed an informed consent form prior to their participation. Procedures were approved by a Research Ethics Board of the University of Calgary. All subjects maintained their habitual level of physical activity during the study and were instructed to avoid strenuous exercise during the 24 h prior to each testing session.

Measurements

Tests were performed on a modified Monark cycle ergometer (Varberg, Sweden), which was equipped with force transducers on the friction belt, an optical encoder for velocity measurement, and a pedal switch. The ergometer was bolted to the floor. Resistance was measured as the difference in tension between the force transducers mounted at each end of the friction belt,and these were calibrated with weights of known mass. Velocity was measured with a light emitting/detecting diode directed at a precision-machined metal encoder, center-mounted on the hub of the flywheel. The oscillating voltage signal from the diode was converted to a continuous voltage proportional to the frequency of oscillations. This voltage was calibrated in $m{\cdot}s^{-1}$ by simultaneously collecting this signal and the pedal switch signal while cycling over a range of constant velocities. Actual velocity was determined from the pedal switch and the duration for several complete crank revolutions (6 $m{\cdot}rev^{-1}$) at constant velocity. The relationship between voltage and velocity ($m{\cdot}s^{-1}$) was linear.

Data were collected at 50 Hz using the Easy LX program (Keithly, ASYST, Taunton, Mass.) then exported to Excel (Microsoft, Redmond, Wa.) for further analysis. Power was calculated by two methods: (1) $R{\cdot}v$,and (2) $T\omega + I\alpha\omega$; where R is the resistance in newtons (N), v is velocity of a point on the perimeter of the flywheel in $m{\cdot}s^{-1}$, T is torque in newton meters(N m) applied to the flywheel, I is the moment of inertia of the flywheel in $kg{\cdot}m^2$, α is the angular acceleration in $rad{\cdot}s^{-2}$, and ω is the angular velocity in $rad{\cdot}s^{-1}$. For this investigation, a series of repeated spin-down trials were conducted to determine the moment of inertia of the flywheel as per the procedure of Lakomy (1986). This value was determined to be 0.827 $kg{\cdot}m^2$.

Procedures

All subjects made a total of four visits to the laboratory for testing with a minimum of 24 hr separating visits. Of the four laboratory visits, one was used to determine the individualized *R–v* relation for calculation of optimal resistance (MacIntosh et al. 1997). On each of the other three visits, subjects performed one of three Wingate tests: a traditional flying start test with a resistance of 0.834 $N{\cdot}kg^{-1}$ BW (FLY-0.8); a modified Wingate test from a stationary start with a resistance of 0.834 $N{\cdot}kg^{-1}$ BW (ST-0.8), and a modified Wingate test from a stationary start with optimal resistance according to the *R–v* relation for each subject (ST-OPT). The order in which the three tests were performed was randomized. The only stipulation in the order of test performance was that the *R–v* test had to be completed prior to ST-OPT.

The Monark cycle ergometer used for all procedures was modified for interchangeability of the two resistance setting systems (pendulum and electronic). For the FLY-0.8 test, a standard pendulum system was installed on the ergometer. The pendulum used was double the weight of a standard Monark pendulum, requiring re-labeling and calibration of the pendulum scale. For the *R–v* trials and stationary start tests, a fixed-end electronic load application system was used to apply tension to the belt prior to starting the test. The system consisted of two brackets mounted to the front supports of the ergometer with a small stepper motor connected to a lever. The lever was attached to the front of the resistance belt. Resistance was preset for all tests that used this system.

For all tests, subjects were instructed to stay seated to standardize body position. Seat height was adjusted at the first session for each subject such that there was a slight bend at the knee at the bottom of the pedal stroke. This seat height was used for all tests for that subject. Subjects were allowed to wear either running shoes or cycling shoes, and each subject wore the same footwear for all tests. For those wearing running shoes, toe clips and straps were used, and those with cycling shoes used clipless pedals.

Warm-up

Subjects were required to perform a 10-min warm-up before all tests. They were asked to ride at 80–90 rpm against a low resistance resulting in 75–100 W power output. At the beginning of the 7th, 8th, and 9th min they performed a brief sprint (approximately 5 s) against the same resistance. After the warm-up, subjects were given a 3-min rest period before the test began.

R-v trials

The *R–v* relation was determined for each subject for estimation of optimal resistance. Each subject performed four or five maximum-effort sprints on the cycle ergometer (Fig. 2). All *R–v* trials were conducted from a stationary start. Each trial was between 4 and 7 s in duration, depending on the time taken to accelerate to peak velocity. At least 3 min were permitted for recovery between trials, which is sufficient to prevent fatigue from affecting the outcome (Blonc et al. 1998). During the recovery period, subjects were allowed to pedal lightly against a low resistance. Resistance settings for *R–v* trials were chosen in random order to give a range of peak pedaling velocities between 90 and 160 rpm as this range has been shown to permit estimation of optimal conditions for PPO (Vandewalle et al. 1987a). The highest average velocity for a complete pedal revolution was determined, and the corresponding resistance was calculated. Resistance was calculated as the average difference between the front and rear tension transducers. For each trial, the average resistance and velocity for the highest velocity pedal revolution were plotted and linear regression was used to estimate optimal resistance (R_{opt}), the resistance at which PPO was predicted to occur (MacIntosh et al. 1997). It should be noted that I was not considered in the determination of R_{opt}. This is because it was assumed that peak velocity was maintained for at least two pedal revolutions, so no work was done to accelerate the flywheel at this time. Under these conditions, the torque applied to the flywheel by the subject should be equal to the torque applied to the flywheel by the resistance belt.

Wingate testing protocols

In each Wingate test, subjects were instructed to maintain maximum effort for 31 s to ensure that a full 30 s of data were collected. At the conclusion of each test, the resistance was decreased, and subjects completed a 10-min active recovery period.

Flying start (FLY-08). The resistance for this test was set at 0.834 N·kg^{-1} BW. After completing the standardized warm-up procedure, subjects were asked to pedal at a moderate pace with light resistance. A 15-s count-down was then started with the subject bringing their cadence to a high level (140–160 rpm) when the test administrator reached the "zero" mark. The resistance was increased as quickly as possible during the final 2–4 s of this count-down to the appropriate value with the pendulum device. Once the resistance was set, a stopwatch was started to record the cumulative test time. All subjects were verbally encouraged to maintain maximal effort throughout the test.

Stationary start with 0834 N·kg^{-1} BW (ST-08). Once the load (0.834 N·kg^{-1} BW) was preset, the subject's feet were fixed to the pedals. They were then given a 5-s count-down and began to accelerate the flywheel with maximal effort. Maximal effort was sustained for the 31-s duration.

Stationary start test with optimal resistance (ST-OPT). The resistance for this test was equivalent to the calculated R_{opt} from the *R–v* trials. Once the resistance was preset on the ergometer, the subject's feet were fixed to the pedals. They were then given a 5-s count-down and began the test with maximal effort. Maximal effort was sustained for the 31-s duration.

Data analysis

Each data file, containing signals from the front transducer, rear transducer, velocity sensor, and pedal switch, was exported from Easy LX, and analyzed in Excel (Fig. 3). The STWC was calculated as the greatest amount of work that was done in 30 consecutive seconds. As previously mentioned, all tests were conducted for 31 s to ensure that a full 30 s of data were collected. STWC was calculated both with and without accounting for I of the flywheel.

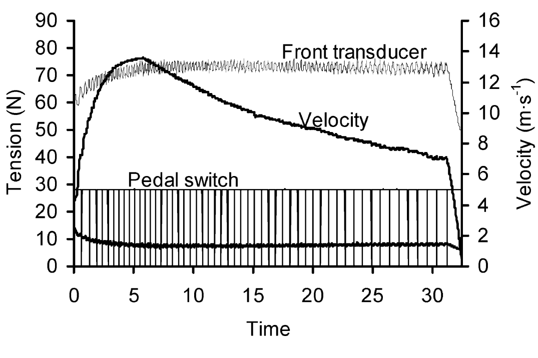

Fig. 3 Raw data from a single 30-s trial (ST-0.8). Force transducer output is plotted on the *left* ordinate (*lower* unlabeled trace is rear transducer). Velocity and pedal switch signals are plotted on the *right* ordinate. Resistance, calculated as the difference between the front and rear transducers, increases during acceleration

When I was taken into account, angular acceleration was calculated by differentiating the velocity signal (by finite difference). Instantaneous power was calculated according to the equation: Power $= I\omega\alpha + \omega T$, (as defined above). The torque was calculated as the difference in tension between the front and back transducers (N) multiplied by the distance from the axis of rotation to the point on the periphery where resistance was applied (0.26 m). Work was calculated by integration of the resulting power.

PPO was measured in a variety of ways. These included: the PPO over any 5-s window (PPO 5 s), the greatest average power of the consecutive 5-s blocks of time (PPO 5 s block), and PPO_{ppr}. The corresponding low power output for each of these methods of measurement was also determined, in order to calculate the percentage decrement in power output during the test, i.e., the fatigue index (FI).

Statistics

All means are presented with standard error of the mean as calculated with Statistica (Release 5, Statsoft, Tulsa, Okla.). Linear regression was done on all *R–v* values using Excel to determine optimal resistance. All additional statistical analyses (a priori comparisons) were conducted with Statistica. Paired *t*-tests were used for each measurement condition to see if accounting for I had an effect on the outcome parameters (STWC, PPO 5 s, block, ppr). Repeated measures one-way ANOVA was used to compare PPO, STWC and FI values across the three test conditions, but only for the values that did consider I. Sheffé post hoc analyses were used when significant differences were evident from the ANOVA. Differences were considered significant for $P < 0.05$.

Results

Subjects who volunteered for this study were 23.5 (1.0) years of age, 177.5 (1.7) cm in height, and 76.1 (1.6) kg in mass.

Resistance

There were two methods used for setting the resistive load in this investigation. In the FLY-0.8 test condition, resistance was set manually during the test by a traditional pendulum system. In both the ST-0.8 and ST-OPT test conditions, the resistance was preset with an electronic load application system. The tension transducers on the flywheel belt permitted continuous measurement of resistance during the test. The intended and actual resistance settings for FLY-0.8 were both 63.4 (1.3) N. The resistance was 66.4 (1.7) N for ST-0.8 and 93.1 (4.2) N for ST-OPT. The resistance for ST-0.8 was slightly higher than the intended resistance, due to the method of presetting the resistance by applying tension to the belt. The setting is based on an assumed peak velocity but, if the subject exceeds that velocity, the resistance will be greater, because the flywheel pulls more on the belt as velocity increases (Fig. 3).

It should be noted that the resistance obtained for the ST-OPT condition was considerably greater (by 46.8%) than the body mass-dependent test condition (FLY-0.8). The resistances obtained for the three conditions when expressed relative to body mass were 0.83 (0.007), 0.87 (0.012), and 1.22 (0.052) N·kg^{-1} BW for the FLY-0.8, ST-0.8, and ST-OPT conditions respectively.

Short-term work capacity

The total work in 30 s was calculated in each test condition, with and without accounting for *I*. Values are presented in Table 1. When *I* was not considered, STWC for FLY-0.8 was greater, and for ST-0.8 it was less. Repeated measures ANOVA detected a significant difference between test conditions ($P < 0.002$). FLY-0.8 was significantly lower than the other two conditions, and the other two were not different from each other.

Peak power output

PPO was calculated three different ways in each of the three test conditions, and each of these ways was done with and without accounting for *I*. Each part of Fig. 4 presents one test condition, and the three methods of peak power measurement with and without accounting for *I*. In all cases except one (ST-OPT, PPO_{ppr}, $P > 0.68$), accounting for *I* resulted in a significantly different ($P < 0.03$) value for PPO. In the case of the flying start, PPO was less when *I* was considered. Otherwise, PPO was greater when *I* was taken into account.

Statistical evaluation was conducted to detect significant differences between test conditions for a given method of measuring PPO. In general, ST-OPT gave higher values for PPO, but these were not significantly different from the corresponding power measurement for ST-0.8. FLY-0.8 gave values for PPO that were significantly lower than the corresponding values for ST-0.8 and ST-OPT.

Time to reach peak power

Test condition and method of measurement had a significant effect on the time at which PPO was detected. These values are presented in Table 2. This measurement (time at which peak power was detected) helps to explain why the various measurements of PPO were different. Notably, the best 5 s and the complete pedal revolution with the highest PPO occurred later for FLY-0.8 than for the modified tests. This would appear to be due to the fact that it took several seconds for the velocity to slow to an optimal velocity for PPO. A typical modified test is illustrated in Fig. 5 to show when PPO was detected by the various measurements.

Table 1 Mean (SEM) short-term work capacity

Test condition	STWC (J)	STWC *I* (J)
FLY-0.8	20,270 (831)	19,986 (827)*
ST-0.8	22,257 (1079)	22,321 (1075)*
ST-OPT	23,015 (1170)	23,014 (1167)
Between conditions:	$P < 0.002^a$	$P < 0.001^a$

* Indicates a significant impact of accounting for moment of inertia ($P < 0.005$)

[a] FLY-0.8 was significantly different from the other two but ST-0.8 was not significantly different from ST-OPT

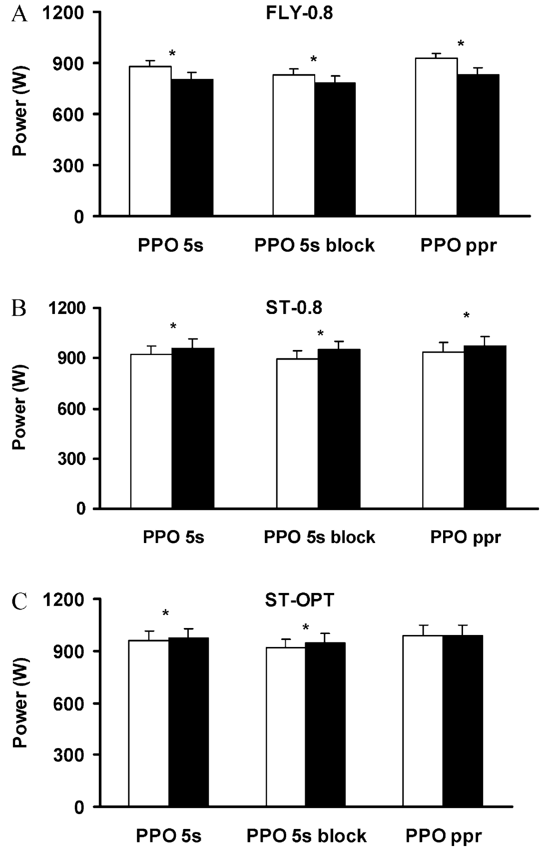

Fig. 4 Mean and SD for peak power output (*PPO*) values with and without accounting for moment of inertia (*I*) for **A** flying start 0.834 N·kg^{-1} BW condition; **B** stationary start 0.834 N·kg^{-} and; **C** stationary start with optimal resistance. *Asterisks* indicate significant difference between measures with (*black*) and without (*white*) accounting for *I*

Table 2 Time to reach peak power output(s)

Measurement	*P* value	FLY-0.8	ST-0.8	ST-OPT
Best 5 s *I*	<0.0001	5.30 (1.28)*	3.24 (0.13)	3.85 (0.29)
5 s Block *I*	>0.35	3.27 (1.88)	2.50 (0.00)	3.27 (0.52)
ppr *I*	<0.001	5.63 (1.83)*	3.34 (0.37)	3.79 (0.26)

* Significantly different from other two in row

Fatigue index

The results for the calculation of the FIs for each of the test conditions are presented in Fig. 6. The FI for FLY-0.8 was significantly less than that for ST-0.8 and ST-OPT ($P < 0.005$), but there were no differences between ST-OPT and ST-0.8 ($P > 0.4$), regardless of the measurement method.

Discussion

The primary purpose of this study was to compare the PPO and STWC results obtained from three different

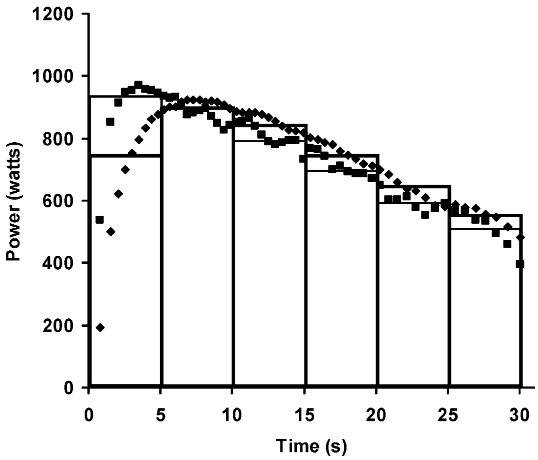

Fig. 5 Power output, as measured for 5-s block, and per pedal revolution (ppr) with (*squares*) and without (*diamonds*) accounting for *I*. This graph illustrates more than the difference in the time at which peak power was reached. Although not shown directly, the position and magnitude of the best 5 s (with and without considering *I*) can be located by considering the best 5 s of individual pedal revolutions. Clearly, the time at which PPO occurred depended on the manner in which this power was determined

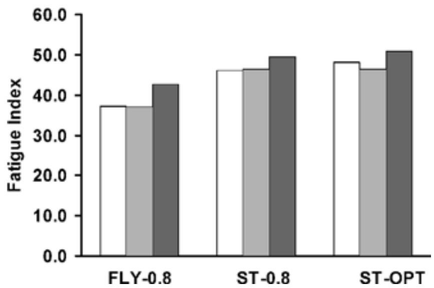

Fig. 6 Mean and SEM of fatigue index for: flying start with resistance 0.834 $N{\cdot}kg^{-1}$ BW; stationary start with 0.834 $N{\cdot}kg^{-1}$ BW and stationary start with optimal resistance. Three *columns* in each test type represent best 5 s, 5-s block, and PPO_{ppr} from *left to right* respectively. Significant difference ($P < 0.05$) between FLY-0.8 and the other two tests

methods of conducting a Wingate test consisting of 30 s of maximal-effort cycling. The first method was the traditional test with resistance set at 0.834 $N{\cdot}kg^{-1}$ BW during a flying start; the second was from a stationary start using 0.834 $N{\cdot}kg^{-1}$ BW preset resistance; the third was also from a stationary start, but with the resistance individually optimized for PPO. This is the first time that comparison has been made between the traditional Wingate test and a modified test initiated from a standstill.

The key findings of this study include the following: (1) the traditional Wingate test consistently underestimated STWC and PPO; (2) taking *I* into consideration is necessary, for all three tests; (3) it is unnecessary to determine an optimal resistance according to the *R*–*v* relation when the test is started from a stationary condition, when *I* is taken into consideration, and (4) test protocol will affect the FI.

Comparison of the three tests when *I* was considered revealed that the traditional test underestimated STWC and PPO. These measures were not different between the two modified tests. The major difference between the modified tests and FLY-0.8 was that FLY-0.8 required considerable effort prior to the period of measurement. Measurement was initiated within two to three crank revolutions of the start for the modified test. It seems reasonable to assume that FLY-0.8 yielded lower values for peak power and STWC due to the energy expenditure during the acceleration phase, prior to initiation of measurement. If it is assumed that the average velocity during the 15-s wind-up phase of FLY-0.8 was 12 $m{\cdot}s^{-1}$, it can be estimated that 8,100 J of mechanical work was done (assuming, on average, a resistance of 45 N). In addition, accelerating the flywheel from 8 $m{\cdot}s^{-1}$ to 16 $m{\cdot}s^{-1}$ could account for an additional 1,200 J of mechanical work. The energy expenditure that was required to generate this work (approximately 46.5 kJ, assuming 20% efficiency) apparently detracted from the ability to generate mechanical power during the subsequent 30 s. Considering that the amount of energy expended during this wind-up phase could vary between subjects, or between trials for the same subject, the impact of this on the test outcome could vary. Some investigators have attempted to minimize the impact of this wind-up phase by regulating the starting velocity (Lakomy 1986; Reiser et al. 2000). This can be done when a rapid load application system is used, but caution should be exercised with these as well (MacIntosh et al. 2001).

The mechanical work generated while riding on a cycle ergometer is the sum of the work done in overcoming the resistance, and the energy transferred to the flywheel. This means that not considering *I* in the calculation will give erroneous values for peak power, STWC and fatigue (Bassett 1989; Lakomy 1986; Reiser et al. 2000). The magnitude of this error will vary considerably. The error obtained by not taking *I* into account when calculating STWC depends on whether the angular velocity of the flywheel at the end of the test is greater than or less than that at the start of the test. The traditional Wingate test began with a flying start, and the angular velocity decreased throughout the test. Therefore, not taking *I* into consideration would overestimate STWC and PPO, regardless of the duration over which the measure was made (single pedal revolution, 5 s or 30 s). This is consistent with observations reported by Bassett (1989) who estimated a difference in STWC of 621 J (less work when *I* was considered) in a test with a flying start (150–200 rpm). That study was done with an aluminum flywheel, which has an *I* which is about half that of the steel flywheel used in the current study (see MacIntosh et al. 2001). This approach (FLY-0.8) also resulted in peak power being reached later when *I* was considered. This is because the test begins at a velocity that is greater than the optimal velocity for PPO. Peak power is reached only when velocity slows down. This, of course was related to fatigue or inability to sustain that velocity with the higher resistance. Fatigue resulting from the wind-up phase or from the early part of the test before optimal conditions are achieved can explain why the values for PPO were lower for the traditional test.

In contrast, when the test began from a stationary condition, angular velocity increased during the first several seconds. Not considering *I* would underestimate PPO. This is similar to what others have observed (Lakomy 1986; Reiser et al. 2000). When resistance was 0.834 N·kg^{-1}, the final velocity was greater than the initial velocity, so STWC was lower when *I* was not considered. This is in contrast with Lakomy (1986) who found no difference in STWC with and without accounting for *I*. Apparently in that case, there was no difference in the initial and final velocity. Lakomy (1986) had his subjects begin the test at 70 rpm. This lack of effect of considering *I* will only give the correct value for STWC if the velocity at the end of the test is the same as that at the start of the test. Since this cannot be guaranteed prior to the test, this observation of a lack of significant effect should not be construed as evidence for not considering *I* in the calculation of STWC.

It was initially surprising that both PPO and STWC were not significantly different for the two modified tests when *I* was considered. In spite of the fact that the resistance that was estimated to permit PPO was 46.7% greater than the resistance that was 0.834 N·kg^{-1} BW, PPO was not different. In retrospect, this absence of a difference can be explained by the fact that taking *I* into account permits detection of a relationship between torque applied to the flywheel and the angular velocity. This has been demonstrated by others (Arsac et al. 1996; Linossier et al. 1996; Martin et al. 1997). When the resistive load is less than optimal, the subject passes through the optimal torque–angular velocity combination on the way to peak velocity.

The traditional Wingate test is analyzed by dividing the 30 s effort into six 5-s blocks. Current technology permits easy determination of the work per crank revolution and the average power during each crank revolution. This permits greater resolution in finding peak power. Furthermore, if it is considered desirable to find the highest average power over 5 s, then dividing the test into 5-s blocks clearly does not identify the best 5 s of the test.

It is customary to calculate a FI for the Wingate test. The results of this study confirm that the value obtained for the FI is dependent on the test protocol. The greater FI obtained with the modified tests results from the greater PPO, rather than lower power output at the end of the test. This is surprising in the case of the ST-OPT test since the resistance was quite high, and a greater decrease in peak velocity was anticipated. It is known that fatigue results in a shift in the optimal condition (lower resistance and lower velocity) for maximum power output (Buttelli et al. 1996). Further research is needed to quantify this shift during the 30 s of a Wingate test.

The results of this study permit specific recommendations. First, this study reconfirms the necessity to consider *I* when conducting the Wingate test. Secondly, the test is most effectively conducted from a stationary start and lastly, a resistance of 0.834 N·kg^{-1} BW is adequate to permit the highest PPO and STWC. The flying start is unnecessary when *I* is considered, and avoiding the flying start limits the energy expended prior to the actual test period. This early energy expenditure compromises the peak power and the STWC associated with the flying start. Finally, multiple trials for determination of optimal conditions for PPO are not needed when *I* is taken into consideration. However, it is likely that the optimal condition for PPO changes during the test, and it cannot yet be known with certainty that any constant resistance permits the greatest STWC.

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