Low Sampling Rates Bias Outcomes from the Wingate Test

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Abstract
The purpose of this work was to apply a simple method for acquisition of power output (PO) during the Wingate Anaerobic Test (WAnT) at a high sampling rate (SR) and to compare the effect of lower SR on the measurements extracted from the PO. 26 male subjects underwent 2 WAnTs on a cycle ergometer. The reference PO was calculated at 30Hz as a function of the linear velocity, the moment of inertia and the frictional load. The PO was sampled at 0.2, 0.5, 1, 2 and 5Hz. Both the peak (16.03±2.22W·kg⁻¹) and mean PO (10.34±1.01W·kg⁻¹) presented lower relative values when the SR was lower. Peak PO was attenuated by 0.29–42.07% for decreasing sampling rates, resulting in different values for 0.2 and 1 Hz (P<0.001). When the SR was 0.2Hz, the time to peak was delayed by 53.81% (P<0.001) and the fatigue index was attenuated by 22.12% (P<0.001). In conclusion, due to the differences achieved here and the fact that the peak flywheel frequency is around 2.3Hz, we strongly recommend that the PO be sampled at 5Hz instead of 0.2Hz in order to avoid biased errors and misunderstandings of the WAnT results.

Introduction
Since the middle and late 1970s, the Wingate Anaerobic Test (WAnT) has been used to assess anaerobic performance and has been recognized for its reliable determination of power output (PO). The WAnT has been retested, reproduced, and modified by various researchers and has yielded reliable results [7]. The WAnT may be administered easily with a mechanically braked cycle ergometer, and it is routinely used to non-invasively extract parameters such as the peak PO (PP), mean PO (MP), and fatigue index (FI). These measures can be used to assess anaerobic fitness levels as well as the effects of anaerobic training. This performance-based test requires little equipment or experience to perform and is generally hypothesized to be a reflection of anaerobic capacity [3,9,11,21]. Some authors have suggested that the WAnT may not be the most appropriate test for assessing anaerobic power in athletes [22,32]. A common concern in these studies was the applicability of a cycle ergometer test for assessing anaerobic power in athletes who primarily perform sprinting activities. Others have studied the effects of the standing and the sitting positions [30], of the hip orientation [31], of inertia [17,34] and of the characteristics of the ergometer [29] on the interpretation of WAnT. Early studies [10,24,25] showed that the pedal acceleration and deceleration could imply either an under- or over-estimation of the PO. Nevertheless, the procedures used to measure the PO are commonly based on the original protocol [3] that aimed to measure the PO over successive 5s periods and simply used the number of pedal revolutions over each interval to calculate the flywheel velocity.

Nowadays, there is a lack of consensus on the choice of the sampling rate that is used to extract the PO parameters during the WAnT. As Table 1 shows, many different sampling rates have been used: 1Hz [4,12,21,25,30], 1.5Hz [27], 4Hz [28], 20Hz [10] and even 100–500Hz [9,26]. Nevertheless, authors often express the PO as the mean value over a 3–5s interval [9,10,26,27], following an approach similar to the original protocol [3]. Of course, since the PO is a mean value, the output will be smoother if the time-average window is wider. Given that the ergometer produces a measure of work or power expended, the accuracy and precision of the PO is essential [17]. Accordingly, early studies [23,24] examined the accuracy of the classical protocol and proposed a...
In the present work, we hypothesized that different sampling rates could produce under- or over-estimation of the parameters extracted from the WAnT. Consequently, with the other parameters that are extracted from the PO curve and, consequently, with the other parameters that are extracted from the WAnT.

In the present work, we hypothesized that different sampling rates could produce under- or over-estimation of the parameters extracted from the temporal response of the PO. Thus, we developed a simple method for acquiring the PO during the WAnT at a high sampling rate (30 Hz). In addition, in order to reproduce the results obtained from some ergometers, we simulated low sampling rates could produce under- or over-estimation of the parameters extracted from the temporal response of the PO as well as on the accuracy of each parameter extracted from the WAnT.

Materials and Methods

Subjects

26 physically active, non-athlete, young males (mean age, 21.90±5.10 yrs; mean weight, 74.03±7.09 kg; mean height, 178.08±5.70 cm; mean estimated body fat, 7.89±3.87%) volunteered for this study, which was approved by the Institutional Ethics Committee. All of the subjects were previously informed about the testing procedures and any known risks, and provided their own written informed consent. All of the procedures were in accordance with the Helsinki Declaration of 2008 and the ethical standards of the International Journal of Sports Medicine [19]. The subjects were asked not to eat within 3 h of the time scheduled for testing and to avoid strenuous exercise in the 48 h preceding the test. The experimental design consisted of a preliminary visit to the laboratory and a second visit 1 week later. During their first visit, the stature of the subjects was measured to the nearest 0.5 cm using a stadiometer (Filizola, Brazil) and the moment of inertia of the body mass (BM) of the subjects was measured to the nearest 0.1 kg using a digital scale (Filizola, Brazil). Both measurements were assessed twice and the test-retest reliability for these measurements was = 0.99 in our laboratory. During their first visit, the subjects also performed a preliminary WAnT at a mechanically braked cycle ergometer (824E, Monark Exercise AB, Varberg, Sweden). During their second visit, the subjects repeated the WAnT. The subjects performed the tests using their own cycling shoes and clipless pedals were used.

Wingate anaerobic test

Prior to each session, the subjects carried out a 5-min cycling warm-up that was administered with a frictional load of 2.0% of their body mass (BM) and at a self-selected cadence. During the warm-up period, the subjects were allowed to adjust the height and rotation of the handlebar to achieve the greatest comfort. As described elsewhere [28], saddle height was adjusted so that, with the crank position at bottom dead centre and the foot secured to the pedal with toe clips, the knee joint was almost in full extension (~180°) and the sole of the foot was parallel to the ground. The warm-up period also included three, 5 s sprints that were administered at 2, 3 and 4 min with a frictional load of 4.0% BM. A 3-min recovery followed the warm-up and preceded the beginning of the test. During the recovery period, each subject was allowed to continue cycling with zero load or to stop and stretch. At the beginning of the test, each subject was still seated. Following a standing start protocol, after a 5 s countdown, each subject started cycling for 30 s against a resistance of 8.5% BM using an all-out strategy. The subjects were required to remain seated throughout the 30 s test. After the completion of the test, the subjects were allowed to continue cycling against a light load until they recovered.

Signal processing

The angular displacement of the flywheel was monitored and sampled at 30 Hz throughout the tests using a digital camera DCR-VX2000 (Sony, USA). Afterwards, the linear velocity was calculated offline as a function of the angular velocity and of the linear displacement of each revolution. Following Lakomy [23, 24], a calibration routine for the speed and the moment of inertia of the flywheel was completed before the tests. Deceleration curves were obtained using a series of frictional loads. Given the deceleration against each load, the moment of inertia (M = 10.034 kg; r² = 0.97) was obtained by linear regression with the angular coefficient [10, 23, 26]. Finally, the PO applied to the flywheel, in Watts, which the subject gen-

<table>
<thead>
<tr>
<th>Study</th>
<th>Subjects</th>
<th>Age, yrs</th>
<th>Sampling rate, Hz</th>
<th>Absolute PPO, W</th>
<th>Relative PPO, W · kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calbet et al. [9]</td>
<td>5 A</td>
<td>18.8</td>
<td>500⁺</td>
<td>1122</td>
<td>17</td>
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<tr>
<td>Hoffman et al. [21]</td>
<td>9 A</td>
<td>17</td>
<td>–</td>
<td>1200</td>
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<tr>
<td>Coso and Mora-Rodriguez [12]</td>
<td>15 A</td>
<td>23.2</td>
<td>1</td>
<td>1268</td>
<td>17.4⁺</td>
</tr>
<tr>
<td>Bell and Cobner [4]</td>
<td>41 A</td>
<td>21.7</td>
<td>1</td>
<td>1154</td>
<td>12.9⁺</td>
</tr>
<tr>
<td>Dupont et al. [14]</td>
<td>12 A</td>
<td>22.8</td>
<td>0.2</td>
<td>1085</td>
<td>15.2⁺</td>
</tr>
<tr>
<td>Coleman and Hale [10]</td>
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<td>20⁺</td>
<td>781</td>
<td>10.9⁺</td>
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<td>24</td>
<td>4</td>
<td>931</td>
<td>12.4⁺</td>
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<tr>
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<td>1.5⁺</td>
<td>683</td>
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<tr>
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<td>22.7</td>
<td>1</td>
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<td>11.1⁺</td>
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<tr>
<td>Smith and Hill [32]</td>
<td>6 NA</td>
<td>23</td>
<td>0.2</td>
<td>819</td>
<td>11.1</td>
</tr>
<tr>
<td>Hill and Smith [20]</td>
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<td>23</td>
<td>0.2</td>
<td>1099</td>
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<tr>
<td>Esbjörnsson-Ljedahl et al. [15]</td>
<td>20 NA</td>
<td>25</td>
<td>0.2</td>
<td>860</td>
<td>11.46⁺</td>
</tr>
</tbody>
</table>

A = Athletes; NA = Non-athletes; PPO = Peak Power Output; (⁺ calculations and parameters computed throughout 5 s intervals (0.2 Hz); * estimated from mean body mass reported data).

Mean values of peak power output during the Wingate Anaerobic Test found in the literature.
Grates while pedaling the ergometer, was calculated as a function of the linear velocity and of 2 independent components: the frictional load applied to the flywheel equivalent to 8.5% BM (F) and the moment of inertia (M):

$$PO_i = (F \cdot a_g + M \cdot a_f_i) \cdot v_i$$ (1)

where $v$ is the linear velocity, $a_g$ is the acceleration of gravity, $a_f_i$ is the flywheel acceleration and $i$ corresponds to the $i$-th flywheel sample.

In order to reproduce the results obtained from some ergometers, the angular displacement originally sampled at 30 Hz, was averaged over different timeframes corresponding to the sampling rates of 0.2, 0.5, 1, 2 and 5 Hz. The peak PO (PP), mean PO (MP), the time to PP (TP) and the fatigue index (FI) for each sampling rate were extracted sequentially to study the effect of sub-sampling on the measurements commonly used in a WAnT.

The PP was the maximal PO attained at any moment during the 30 s test, which was expressed as absolute (W) and relative values (W·kg⁻¹). The MP was the mean PO during the 30 s, the TP was expressed as the time elapsing from a standpoint to the moment when PP was observed and the FI was the percent difference between the PP and the PO at the end of test. Furthermore, in order to compare the time response of the power during WAnT, the relative PO was averaged for 5 s intervals for each sampling rate, then the mean PO values for each sampling rate were paired as a function of the sampling rate and the time interval.

**Statistics**

The reference values for all the calculations and further comparisons used the PO calculated at a sampling rate of 30 Hz. Basic descriptive statistics were performed on each variable, and the assumptions of normality and homoscedasticity were confirmed. These measurements showed that the distribution was normal and homoscedastic for each variable. The reliability of the WAnT was assessed, and no differences were found between the 2 assessment times: the test-retest correlation was $r=0.92$. Then, data from the second WAnT test were used for analysis. The effect of the sampling rate in the WAnT measurements was determined for each variable (PP, MP, TP, FI) using 1-way analysis of variance (ANOVA), and the mean PO over 5 s periods was compared among sampling rates and among periods through 2-way ANOVA. Post-hoc Tukey’s tests were performed as required. The significance level was set at $P\leq 0.05$, and data were expressed as mean±SD.

**Results**

Typical power outputs achieved during the WAnT with different sampling rates are illustrated in Fig. 1. We observed that, during the first seconds of each test, the PO increased to a peak,
which was maintained for few seconds, and, then, decreased progressively throughout the remainder of the test. As we expected, the PO was progressively smoothed at the low sampling rates. Therefore, the peak PO was underestimated and the time to PP was delayed at the low sampling rates.

**Fig. 2** presents the time course of the relative mean PO during the 30 s WAnT at all sampling rates. Despite the large differences among sampling rates during the first 5 s, the relative mean PO presented similar values from 1 to 30 Hz. The values were closest between 5 and 30 Hz. According to the results obtained from ANOVA, the PO at 0.2 Hz presented differences from all of the other sampling rates ($P<0.001$) during the first 15 s, and differences were observed only between 0.2 and 5, or 0.2 and 30 Hz ($P<0.001$) during the last 15 s.

As depicted in **Fig. 3**, the relative peak PO values (**Fig. 3a**) and the relative mean PO values (**Fig. 3c**) decreased with the sampling rate. We calculated the relative PP to be $16.03 \pm 2.22 \text{ W kg}^{-1}$ at 30 Hz. The lowest sampling rate of 0.2 Hz resulted in relative PP values of 22.21 ± 8.13 % (range, 8.87 – 42.07 %) lower than the expected values ($F=2.53$, $P<0.001$). Similarly, the relative PP values at other low sampling rates were also lower than the expected values: 14.51 % (range, 5.68–28.56 %; $P<0.001$) lower at 0.5 Hz, 11.53 % (range, 3.67–26.73 %; $P<0.001$) lower at 1 Hz, 5.89 % (range, 1.05–16.75 %; $P=0.057$) lower at 2 Hz and 1.36 % (range, 0.29–5.63 %; $P=0.63$) lower at 5 Hz. We also found that the MP was 0.75–16.65 % lower at 0.2–5 Hz than at 30 Hz $(10.34 \pm 1.01 \text{ W kg}^{-1})$. Additionally, we found that, at 0.2 Hz, the time to peak (**Fig. 3b**) was delayed by $53.81 \pm 21.12 \%$ ($F=9.76$, $P=0.001$) and the fatigue index (**Fig. 3d**), which averaged $56.97 \pm 0.07 \%$ (at 0.2 Hz), was attenuated by $22.12 \%$ ($P<0.001$), reaching $44.69 \pm 8.77 \%$ at 30 Hz, with significant differences from all sampling rates.

**Discussion**

The kinetics of anaerobic metabolism during high-intensity exercise have been extensively investigated [8,13] using different approaches to describe the metabolic contribution for either sports performance or disabilities. In this context, the WAnT has been widely applied to evaluate anaerobic performance [3,7], because it is a non-invasive test, easily applicable, validated and highly reproducible [3]. In the present study, we hypothesized that different sampling rates could imply either under- or over-estimation of the parameters extracted from the temporal response of the PO. Therefore, we developed a simple method for acquiring the PO at a high sampling rate (30 Hz) during the WAnT, and we compared both the time response of the PO and the accuracy of the parameters extracted directly from the WAnT at various sampling rates simulating the results obtained from some ergometers. We found that there were important differences in the extracted parameters at the various sampling rates. Several studies have focused on high-intensity cycling exercises of different durations, including 60 s maximal tests [27,34], 30 s tests [12,18,22–28–30] and 6 s tests [6,16]. As we have already acknowledged, the literature expresses the PO for a wide range of sampling rates from 0.2 to 500 Hz [6,10,25,28,29]. Even at high sampling rates, it is common to report the PO as a mean value over intervals of 3–5 s [3,9,10,14,26], which results in smoothed parameters.
As we expected, the PO presented a temporal pattern similar to the literature [10, 27, 29, 34]. As depicted in Fig. 1, we observed that the peak PO decreased at the low sampling rates. Furthermore, the time to PP was progressively delayed at the low sampling rates and was delayed the most when the PO was acquired using the classical method (i.e., every 5 s).

Direct inter-study comparison is confounded by the many methodological variants of the WAnT and the analytical limitations inherent in several studies [1]. These factors, as well as the effects of inertia [17, 33] and of body positioning [29, 30] might affect the interpretation of cycle ergometer power tests and cause misinterpretation of WAnT results. For instance, the discrete PO values found in this study were achieved by non-athletes, and were comparable to the presented in the literature achieved by athletes [4, 12, 21]. We obtained a mean PP value of 1 174 ± 216 W (30Hz) for non-athletes, whereas some authors, as summarized in Table 1, have obtained PP values in a range of 1 122–1 547 W for athletes [4, 12, 14, 30] and PP values in a range of 781–1 099 W for a healthy, non-athletic population [10, 20, 28]. In spite of the different methodologies, most of the results presented in Table 1 were achieved at a low S_p (0.2 Hz) or, equivalently, at a high S_p that was sub-sampled to 0.2 Hz.

Reiser and co-workers [30] have sampled the PO at 1 Hz and have found a PP during a standing WAnT protocol that was 8.2% greater than that observed in the seated WAnT protocol. The same comparison using the mean PO over 5 s periods resulted in a PP value that was 7.8% greater than that observed in the seated WAnT protocol. The same comparison using the mean PO over 5 s periods resulted in a PP value that was 7.8% greater than that of the seated protocol. Even though it was not the focus of discussion of the article, the PP at 0.2 Hz (16.8 ± 0.9 W·kg⁻¹) was underestimated in comparison to the PP at 1 Hz (19.4 ± 1.4 W·kg⁻¹) by around 13%, which is very close to the present results. In our study, the lowest sampling rate (0.2 Hz) resulted in values that were 8.87–42.07% lower than the reference values (P<0.001). The PO was underestimated over the entire duration of testing, but it was underestimated the most around the peak, when the higher pedaling rates were recorded. This finding confirms our hypothesis that the classical method for sampling the PO underestimates the peak PO, which may cause misunderstandings of the parameters that are extracted from the WAnT.

Consequently, the low sampling rates, such as from 0.2 to 1 Hz, attenuated the peak PO values by approximately 3.67–42.07% compared to the highest sampling rate (30Hz). During the last few seconds, the slow time course of the PO resulted in similar values of PO at all of the sampling rates except for 0.2 Hz. Hence, an important issue refers to the interpretation of the results obtained from the Wingate Anaerobic test when the PO is sub-sampled. Most of the indices obtained from the WAnT found in the literature for athletes [4, 9, 12, 14, 21, 30] are comparable to the results presented here and, correspondingly, those for non-athletes [10, 15, 20, 25, 32] are lower than our results. In fact, considering the large range of sampling rates used in the literature, the comparison among different works tends to be meaningless. Similarly, normative tables, such as those classically proposed by Bar-Or [3] to estimate the anaerobic capacity, should be used cautiously considering the dependence on the sampling rate. Based on this assertion, while there is no uniformity of the methodology for applying the WAnT, particularly concerning the sampling rate of PO, which is the focus of the present work, each individual result can only be compared within dependent samples.

As shown in Fig. 3, no significant differences were found among the sampling rates from 2 to 30Hz, and the higher frequencies presented very close results, mostly between 5 and 30Hz. Fig. 4, in which the time course of pedaling rate obtained for all subjects, also illustrates this finding. The cadences developed by the subjects varied from 0 (at rest) to 2.78 Hz (at the peak) and averaged 2.40±0.27 Hz. It means that independent of the fast variations of the cadence or even the PO, on average, subjects studied here developed 2.4 cycles over the flywheel around the peak. The Nyquist sampling theorem states that if H is the highest frequency of any continuous function, then the sampling rate must be at least twice H to allow for perfect signal reconstruction and to avoid a distortion known as aliasing. Consequently, any sampling rate lower than 2H should neglect and distort information about the cadence as well as its derivatives. Our results are consistent with this theorem, i.e., the PO sampled at 5 Hz was very close to the PO at 30 Hz. The PO extracted from lower sampling rates was mainly affected around the peak, which is associated with the highest pedaling rates. Thus, most of the results obtained in a WAnT using low sampling rates tend to be inconsistent. Furthermore, supposing a peak pedaling rate of 2.5–3.0 Hz (150–180 rotations·min⁻¹), the parameters extracted from time response of the PO are biased unless the sampling rate is at least 5–6 Hz. In order to confirm this finding, the fast Fourier transform (FFT) was applied to the cadence signals of all subjects. Not surprisingly, 99% of the spectral energy was concentrated up to 2.92 Hz, which is comparable to the peak pedaling rate.

The present study provides an objective evaluation of the power output sampling rate effect on the results of the Wingate anaerobic test. The present results indicate a strong influence of the sampling rate on the parameters extracted from this test, mainly for lower sampling rates and particularly for 0.2 Hz (5 s interval) which is the most commonly used in the literature. In order to standardize the Wingate anaerobic test, or even to allow further comparisons among different groups, we propose a sampling rate which preserves the frequency content integrity. Accordingly, supposing a peak pedaling rate of 2–2.5 Hz, a sampling rate of 5 Hz is more appropriated for visualizing and analyzing the PO signal free of frequency aliasing and resulting biased estimates.
In conclusion, the time course of the PO from a single WAnT was compared at different sampling rates, and significant differences were found in all of the parameters extracted from the test, including the PP, MP, FI and time to PP. The power output was mainly affected during the first seconds of the test and around the time of peak exercise. In order to avoid biased errors and misunderstandings of the WAnT results, we strongly recommend that the PO should be sampled at a sampling rate of at least 5 Hz.

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