The Total Work Measured During a High Intensity Isokinetic Fatigue Test Is Associated With Anaerobic Work Capacity

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Abstract
The purpose of the study was to determine whether total work measured during a high intensity isokinetic fatigue test (TW FAT) could be considered as a valid measure of anaerobic work capacity (AWC), such as determined by total work measured during a Wingate Anaerobic Test (TWWAnT). Twenty well-trained cyclists performed 2 randomly ordered sessions involving a high intensity isokinetic fatigue test consisting in 30 reciprocal maximal concentric contractions of knee flexors and extensors at 180°·s⁻¹, and a Wingate Anaerobic Test. We found that TW FAT of knee extensors was largely lower than TWWAnT (4151 ± 691 vs 22313 ± 2901 J, respectively, p < 0.05, Hedge’s g = 4.27). Both measures were highly associated (r = 0.83), and the 95% limits of agreement (LoA) represented 24.5% of TWWAnT. Combining TW FAT of knee flexors and knee extensors into a single measure (6302 ± 818 J) did not change neither improved these observations. We still found a large difference with TWWAnT (r < 0.05, g = 9.52). By contrast, both measures were not associated (r = 0.09), and the 95% LoA represented 31.1% of TWWAnT. Combining TW FAT of knee flexors and knee extensors into a single measure (6302 ± 818 J) did not change neither improved these observations. We still found a large difference with TWWAnT (r < 0.05, g = 9.52). By contrast, both measures were not associated (r = 0.09), and the 95% LoA represented 31.1% of TWWAnT. Combining TW FAT of knee flexors and knee extensors into a single measure (6302 ± 818 J) did not change neither improved these observations. However, the mean difference between both measures and their 95% LoA were too large to warrant interchangeability.

Key words: Isokinetic dynamometry, muscle fatigue, Wingate anaerobic test, cyclists, physiological assessment

Introduction
Isokinetic dynamometry is classically used to assess neuromuscular function through different parameters such as peak torque, total work or the peak torque ratio between agonist and antagonist muscles (Croisier, 2004; Gleeson and Mercer, 1996). The assessment of muscle bioenergetics with this kind of dynamometry is less common. Such an approach requires experimental data to warrant both the reliability and the validity of measures obtained during a specific protocol. We previously examined the effect of the lengthening of a high intensity isokinetic fatigue protocol (20 to 50 reciprocal maximal concentric contractions at an angular velocity of 180°·s⁻¹) on the relative and absolute reliability of fatigue measures (Bosquet et al., 2010). We concluded that total work measured during a protocol involving 30 reciprocal maximal concentric contractions represented a good compromise between reliability (intraclass coefficient of correlation = 0.91 and standard error of measurement = 4%) and bioenergetical interpretability of the data. In fact, the mean duration of the test (approximately 40 seconds) fulfills current recommendations for the assessment of anaerobic work capacity (AWC) (Green, 1995). Anaerobic work capacity is defined as the total amount of work performed during an exhaustive work bout underpinned by a relatively high ATP yield (Green, 1995). Since it represents a major contributor to success in events during which anaerobic capacity is nearly completely depleted, such as the 800 m in running (Spencer and Gastin, 2001), it is important for sport scientists to provide athletes and coaches with accurate estimates of this parameter. Although there exists no gold standard per se, the total work performed during a 30 – second Wingate anaerobic test (WAnT) is often considered as one of the best indicators of this ability (Green, 1995; Vandewalle et al., 1987). Several studies have already reported a close association (0.52 < r < 0.96) between peak or mean power during a WAnT and peak or mean torque during an isokinetic fatigue test in moderately trained participants (Brown et al., 1994; Patton and Duggan, 1987; Smith, 1987). However, none of them examined the agreement between total work performed in both tests by cyclists of national performance capacity. Therefore, the purpose of this study was to determine the validity of total work measured during our optimized high intensity isokinetic protocol to assess AWC, and whether it could be used interchangeably with total work measured during WAnT. Given the nature of the tasks (i.e. mono vs multi-joint exercises) and the type of muscular work (i.e. isoinertial vs isokinetic), we hypothesized that both measures would be associated, but could not be used interchangeably.

Methods
Experimental approach to the problem

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Following a thorough briefing and medical screening all participants signed a written statement of informed consent. Subsequently, they participated in 2 randomly ordered exercise test sessions involving a high-intensity isokinetic fatigue test of the knee (FAT), and a force-velocity test (FVT) immediately followed by a Wingate anaerobic test (WAnT). All tests were administered to all the participants by the same investigator, and were separated by at least 72 h of recovery, within a 4-week period. To avoid any residual fatigue induced by a recent workout, participants were asked to refrain from strenuous exercise 48 h before the tests. The protocol was reviewed and approved by the Research Ethics Board in Health Sciences of the University of Montreal (Canada).

Participants
Twenty highly-trained male cyclists without prior history of knee injury volunteered to participate in this study. Their mean (SD) age, height, body mass and sum of skinfolds (triceps, biceps, subscapular and suprailiac) were 30.1 (6.2) years, 1.79 (.06) cm, 72 (8) kg and 28 (7) mm, respectively.

Exercise testing
High-intensity isokinetic fatigue test (FAT): The test was performed on a Biodex System III dynamometer (Biodex Medical Systems, Shirley, New York). A 5-minute warm-up period consisting in pedalling at 100 W with a cadence around 100 rpm was performed before the test. Thereafter, the participant was seated on the dynamometer seat, corresponding to a full active extension. Before testing, the participant was asked to perform 3 submaximal reciprocal concentric contractions at an angular velocity of 180°·s⁻¹. After a 2-min pause, participants were asked to perform 3 submaximal reciprocal concentric contractions at an angular velocity of 180°·s⁻¹. Afterwards, they performed 30 consecutive maximal reciprocal concentric contractions at an angular velocity of 180°·s⁻¹. Participants were encouraged to push/pull as hard and as fast as possible and to complete the full range of motion. Strong verbal encouragements were given throughout the test to motivate participants to develop maximal contraction during each repetition (McNair et al., 1996). Total work (J) performed during the entire range of motion of each repetition was computed using the device’s software, and summed to obtain FAT total work (TW FAT, in J). We previously showed that this measure was very highly reliable for knee extensors (ICC = 0.91) and highly reliable for knee flexors (ICC = 0.75) (Bosquet et al., 2010).

Force-velocity (FVT) and Wingate anaerobic (WAnT) tests: These tests were performed on an electromagnetically-braked cycle ergometer (Excalibur, Lode B.V., Groningen, The Netherlands) with automatic pedals (i.e. toe strap pedals that allow development of power during the whole revolution). Saddle and handlebar height as well as forward placement were adjusted at the beginning of the session to determine optimal position. Participants completed a 7-min warm-up period at 100 W with a cadence around 100 rpm. Thereafter they performed a set of 3 sprints of 6 seconds at 0.7, 0.8 and 0.9 Nm·kg⁻¹ of body mass, interspersed by 54 seconds of passive recovery. A 5-minute rest period was allowed before FVT. This test consisted in several 6-second sprints against increasing load, interspersed with 5-minute periods of recovery. Initial resistance was set at 0.9 Nm·kg⁻¹ and increased by 0.1 Nm·kg⁻¹ until power output decreased during two consecutive sprints. The highest power output observed during the test was considered as FVT peak power output (PPO FVT, in W). A 10-minute rest period was allowed between FVT and WAnT. Thereafter workload was set at the resistance that allowed reaching PPO FVT and the test was executed according to standard instructions (Inbar et al., 1996). Verbal encouragement was given up to the end of the test. The highest power output observed during the test was considered as WAnT peak power output (PPO W AnT). Mean power output over the test was also computed (MPO W AnT), and converted in cumulated total work by multiplying it by 30 (TW W AnT). This latest measure was considered as the reference measure for AWC (Green, 1995).

Statistical analysis
Standard statistical methods were used for the calculation of means and standard deviations. Normal Gaussian distribution of the data was verified by the Shapiro-Wilk test, and homoscedasticity by a modified Levene Test. All variables met these underlying hypotheses. A paired t-test was used to test the null hypothesis that there was no difference between parameters measured during FAT and WAnT. The magnitude of the difference was assessed by the Hedges g (g), as presented elsewhere (Dupuy et al., 2014). The scale proposed by Cohen (Cohen, 1988) was used for interpretation. The magnitude of the difference was considered either small (0.2 < g ≤ 0.5), moderate (0.5 < g ≤ 0.8), or large (g > 0.8). Pearson product moment correlation and the level of agreement (Ludbrook, 2010) were used to assess the association between relevant parameters. The scale by Munro (Munro, 1997) was used for interpretation. A correlation over 0.90 is as very high, between 0.70 and 0.89 as high and between 0.50 and 0.69 as moderate. Statistical significance was set at p < 0.05.

Results
Peak and mean power output measured during WAnT were 1415 ± 55 and 744 ± 97 W, respectively. Total work, which was considered as the reference measure for AWC, was 22313 ± 2901 J. The work accumulated during FAT by each muscle group (TW FAT) and its comparison with TW W AnT are presented in Table 1. TW FAT of knee extensors was largely lower than TW W AnT (p < 0.05, g = 4.27). Both measures were highly associated (Figure 1; r = 0.83, p < 0.05), and the 95% limits of agreement represented 24.5% of TW W AnT. Similarly, TW FAT of knee
Isokinetic dynamometry and anaerobic work capacity

Table 1. Comparison of total work (TW) measured during the high intensity isokinetic fatigue test (FAT) with TW measured during the Wingate anaerobic test (WAnT; 22313 ± 2901 J). Data are means (±SD).

<table>
<thead>
<tr>
<th></th>
<th>TW FAT (J)</th>
<th>Difference with TW WAnT (J)</th>
<th>Magnitude of the difference (Hedge’s g)</th>
<th>Level of association (r)</th>
<th>95% limits of agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee extensors</td>
<td>4151 (691)</td>
<td>18162 (2355)</td>
<td>4.27</td>
<td>.83</td>
<td>5459 ± 24.5</td>
</tr>
<tr>
<td>Knee flexors</td>
<td>2151 (540)</td>
<td>20162 (2995)</td>
<td>9.52</td>
<td>.09</td>
<td>6942 ± 31.1</td>
</tr>
<tr>
<td>Combination</td>
<td>6302 (818)</td>
<td>16011 (5451)</td>
<td>5.26</td>
<td>.65</td>
<td>5680 ± 25.5</td>
</tr>
</tbody>
</table>

* different from other measures (p<0.05); † different from total work measured during WAnT (p < 0.05); a the magnitude of the difference was considered either small (0.2 < g ≤ 0.5), moderate (0.5 < g ≤ 0.8), or large (g > 0.8). b expressed in percentage of TW measured during WAnT.

flexors was largely lower than TW_WAnT (p < 0.05, g = 9.52). By contrast, both measures were not associated (Figure 2; r = 0.09), and the 95% limits of agreement represented 31.1% of TW_WAnT. Combining TW FAT of knee flexors and knee extensors into a single measure (TW_{combined}; 6302 ± 818 J) did not change neither improved these observations, since we still found a large difference with TW_WAnT (p < 0.05, g = 5.26), a moderate association (r = 0.65, p < 0.05) and 95% limits of agreement representing 25.5% of TW_WAnT.

Discussion

A first purpose of this study was to determine whether TW FAT could be considered as a measure of AWC in well to highly trained cyclists. In the absence of a gold standard, we considered the work accumulated during a 30-sec WAnT as the reference criterion for AWC (Green, 1995; Vandewalle et al., 1987). A second purpose was to determine whether TW FAT and TW_WAnT could be used interchangeably. The statistical approach we opted for consisted in measuring the difference between TW FAT and TW_WAnT, as well as their association and their 95% limits of agreement. Given the nature of the tasks (i.e. mono vs multi-joint exercises), we hypothesized that both measures would be associated, but could not be used interchangeably.

When considering performance level and training background of our participants, TW_WAnT measured in this study was in the range of expected values (Calbet et al., 2003; Withers et al., 1991). Given differences in the modes of exercise (isoinertial closed chain cycling vs isokinetic open chain knee flexion/extension) and in the muscle mass involved, it was not surprising to find a large difference between TW_WAnT and the TW FAT of knee flexors and knee extensors. Since both muscle groups are contributing to performance during WAnT (a consequence of automatic pedals), we decided to combine their respective TW FAT into a single measure (TW_{combined}). Although it largely increased TW FAT (p < 0.05, 2.47 < g < 5.67), we still found a large difference with TW_WAnT. The main reason for this residual difference was that performance in FAT involved knee extensors and flexors muscles of the dominant leg, when performance in WAnT involved ankle, knee and hip extensors and flexors of both legs. An alternative solution would have been to measure TW FAT of both legs, as done by Brown et al. (1994). Nevertheless, they still found a large difference between both measures (g > 2).

In spite of the quantitative difference between both measures, we found a high correlation between TW FAT of knee extensors and TW_WAnT, with a common variance of 69%. This close association allows establishing the validity of knee extensors TW FAT as a measure of AWC, and is in agreement with previously published studies comparing peak or mean power during a WAnT and peak or mean torque during an isokinetic fatigue test in moderately trained participants (0.52 < r < 0.96) (Brown et al., 1994; Patton and Duggan, 1987; Smith, 1987). However, the magnitude of the 95% limits of agreement (24.5% of TW_WAnT) was too large to warrant interchangeability between both measures, particularly if we consider the large difference in means we previously discussed. Mean-
ing of knee flexors data appeared questionable, since we found no association with TW_WAnT and large 95% limits of agreement (31.1% of TW_WAnT). This is an important result of the study, but it is difficult to provide a clear explanation of this observation. Several hypotheses have been proposed, including a lower reliability of knee flexors performance, or some neuromuscular phenomena that could be more detrimental to performance of this muscle group, including a specific interaction between motoneuron recruitment, rate of coding and co-contractions (Bosquet et al., 2010; Gleeson and Mercer, 1992; Maffiuletti et al., 2007). Although these explanations are receivable, we must recognize that there is no robust rational to justify why knee extensors should be less affected by these phenomena, by the exception of the intensity of reciprocal contractions. In fact, it is possible that knee flexors are probably not solicited to their maximum during isoinertial cycling, while they are during isokinetic testing. Whatever the exact origin of this noise, the absence of association is probably explained by the fact that knee flexors are not solicited to the same extent during FAT and WAnT. As expected, TW_combined was negatively affected by the absence of association of knee flexor’s TW_FAT with TW_WAnT, and did not add value to knee extensor’s TW_FAT regarding the validity and interchangeability of the data.

The originality of this study was also to provide experimental data that could support a bioenergetical interpretation of the total work derived from a high intensity isokinetic fatigue test. Although it is highly associated to AWC, we previously showed that TW_FAT was also moderately associated to peak oxygen uptake (VO2peak) (Bosquet et al., 2015). The common variance (34%) was very close from the ~35% predicted by Gastin (2001) for a maximal intensity exercise of 40 seconds. TW_FAT should therefore be considered as a composite measure that depends on both aerobic and anaerobic energy systems according to proportions that are determined by the duration of the test (~40 seconds). It should be kept in mind that this observation is not specific to FAT and also applies to WAnT. Granier et al. (1995) investigated aerobic and anaerobic contribution during a WAnT in sprint and middle-distance runners. Each population of participants used preferentially a metabolic system that depended on its speciality. In fact, mean aerobic contribution was 28±5% for sprint runners, and 45 ± 11% for middle-distance runners, which was very close from the 30% predicted by the model of Gastin (Gastin, 2001). Independently of the metabolic reasons that subdend this difference, energy expenditure during a short-duration high-intensity test such as WAnT or FAT is therefore a mixture between aerobic and anaerobic pathways. An interesting perspective would be to assess the sentivity of TW_FAT to training induced changes, and to compare the predictive value of TW_FAT and TW_WAnT for athletic events with bioenergetical characteristics that are close to those of these tests, such as the 400m in running.

**Practical applications**

Regarding the purpose of this study, we can conclude that TW_FAT of knee extensors can be considered as a valid measure of AWC, such as determined by TW_WAnT, but also that both measures cannot be used interchangeably. Practically speaking, it means that those who perform higher quantities of work during FAT are likely to perform higher quantities of work during WAnT, but also that it is not possible to make a quantitative estimation of this improvement. Considering the difficulty to compare the performance of knee flexors during FAT and WAnT, it is not possible to provide a definitive answer to the question of the validity of TW_FAT of knee flexors to measure AWC. It is clear that both measures are not associated. However, there is no reason to exclude the possibility that TW_FAT of knee flexors provides a valid measure of AWC from this specific muscle group, and that TW_combined provides a valid measure of AWC from the muscles of this specific joint. All together, our results suggest that sport scientists or practitioners may use a high intensity isokinetic fatigue test to assess AWC when it is not possible to implement a WAnT. Indeed, FAT is less time consuming than WAnT, and easier to perform and to repeat throughout a season. However, we also showed that results should be interpreted with nuance.

**Conclusion**

The purpose of this study was to determine whether the work accumulated during FAT could be considered as a measure of AWC during a multi-joint task such as the WAnT, and whether both measures could be used interchangeably. We concluded that TW_FAT of knee extensors could be considered as a valid measure of AWC, since both measure were highly associated. However, the 95% limits of agreement were too large to warrant interchangeability. The difficulty to compare the performance of knee flexors during FAT and WAnT did not allow to provide a definitive answer to the question of the validity of TW_FAT of knee flexors to measure AWC. This study has several practical implications for clinicians, particularly in the bioenergetical follow-up of athletes that should now be tested in training studies.

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**Key points**

- Total work performed during a high intensity isokinetic fatigue test can be considered as a valid measure of anaerobic work capacity (as determined by total work performance during a 30-s Wingate anaerobic test).
- The 95% limits of agreement are two large to allow a direct comparison between both measures. In other words, it is not possible to estimate the magnitude of performance improvement during a 30-s Wingate anaerobic test from that observed during a high intensity isokinetic fatigue test.
- In addition to provide sport scientists and coaches with measures of peak torque and ratios between agonists and antagonists muscles in a perspective of injury prevention, isokinetic dynamometry can also be used in the physiological assessment of athletes. However, some precautions should be taken in the interpretation of data.

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