A 3-min All-Out Test to Determine Peak Oxygen Uptake and the Maximal Steady State

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ABSTRACT

BURNLEY, M., J. H. DOUST, and A. VANHATALO. A 3-min All-Out Test to Determine Peak Oxygen Uptake and the Maximal Steady State. Med. Sci. Sports Exerc., Vol. 38, No. 11, pp. 1995–2003, 2006. Purpose: We tested the hypothesis that a 3-min all-out cycling test would provide a measure of peak oxygen uptake (VO₂peak) and estimate the maximal steady-state power output. Methods: Eleven habitually active subjects performed a ramp test, three 3-min all-out tests against a fixed resistance, and two further submaximal tests lasting up to 30 min, 15 W below or above the power output attained in the last 30 s of the 3-min test (the end-test power). Results: The VO₂peak measured during the 3-min all-out test (mean ± SD: 3.78 ± 0.68 L min⁻¹) was not different from that of the ramp test (3.84 ± 0.79 L min⁻¹; P = 0.75). The end-test power (257 ± 49 W) was significantly lower than that at the end of the ramp test (368 ± 73 W) and significantly higher than the power at the gas exchange threshold (169 ± 55 W; P < 0.001). Nine subjects were able to complete 30 min of exercise at 15 W below the end-test power, and seven of these did so with a steady-state blood [lactate] and VO₂ response profile. In contrast, when subjects exercised at 15 W above the end-test power, blood [lactate] and VO₂ rose inexorably until exhaustion, which occurred in approximately 13 ± 7 min. Conclusions: These data suggest that a 3-min all-out exercise test can be used to establish VO₂peak and to estimate the maximal steady state. Key Words: EXERCISE INTENSITY DOMAINS, CRITICAL POWER, FIXED RESISTANCE, CYCLING

Based on the pulmonary oxygen uptake (VO₂) and blood lactate responses to constant–work rate cycling exercise, three intensity domains have been identified (11,26,28): moderate, heavy, and severe. The moderate-intensity domain encompasses those work rates for which VO₂ rises with finite kinetics to reach a steady state within 2–3 min. The heavy-intensity domain is defined as those work rates that engender an increase in blood [lactate] that is stabilized after the initial 5–10 min. It may also require 5–15 min to attain a steady-state VO₂ at these work rates as a consequence of a slow component of the VO₂ response emerging after the initial transient phase (20,23), which results in a higher O₂ cost than predicted from moderate work rates (26). Finally, in the severe-intensity domain, both blood lactate and VO₂ rise with time until VO₂ reaches its peak value (VO₂peak), and fatigue ensues soon (but predictably) thereafter (14). The three domains of exercise intensity each have their specific demarcations (16). The boundary between the moderate and heavy domains is given by the lactate threshold, the boundary between the heavy and severe domains is given by the maximal steady state or the asymptote of the power–duration curve (the critical power), and the upper limit of the severe domain has been suggested to be the highest work rate at which VO₂peak can be attained before fatigue ensues (14).

Aerobic function is often assessed using an incremental ramp protocol lasting 10–15 min (27) or a longer, staged protocol for the assessment of the blood lactate response (20). The utility of these tests is that the lactate threshold (commonly identified using gas exchange criteria, the gas exchange threshold (GET)) (3), the VO₂–work rate relationship, and VO₂peak can be assessed in one 10- to 15-min test (27). In so doing, the boundary between the moderate- and heavy-intensity domains and the upper limit of aerobic function are established. The boundary between the heavy- and severe-intensity domains escapes detection during incremental exercise because the definition of the boundary is based either on the behavior of VO₂ and/or blood lactate during prolonged exercise (the maximal steady state) (4) or the tolerance to exercise exclusively in the severe domain (the critical power) (20,21). Both approaches require repeated and, in the case of the critical power, exhaustive exercise testing. The work rate representing the boundary between the heavy- and severe-intensity domains is important both practically and experimentally: it separates work rates for which a steady state is possible from those for which it is not (20), and the maximal steady-state running speed has been shown to be closely associated with distance-running performance (15). It would therefore be
useful if a valid and reliable means of establishing this domain boundary were available in a single test.

There are several reports in the literature of the physiological response to all-out exercise of approximately 90-s duration (6,8,13,29,30). Although these studies showed power output to fall below that associated with VO2peak, Dekkerle et al. (8) showed that power output was still considerably higher than the previously established critical power at the end of a 90-s all-out effort. Williams et al. (29) further established that a 90-s all-out effort yielded a peak VO2 similar to that measured using a more conventional ramp protocol in adolescents. It is possible that in a longer all-out test, power output would continue to fall to an end-test power that would equal that associated with the transition from the heavy to the severe domain (the maximal steady state). This possibility is based on the hyperbolic character of the power-duration curve, which is given by:

\[ t = \frac{W'}{(P - CP)} \]  

where \( t \) is time to exhaustion, \( P \) is the power output of the task, and \( W' \) is the curvature constant defining a fixed amount of work that can be performed above the critical power, \( CP \) (19). Critical power has been shown to be similar to the maximal steady-state power output (20). The linear formulation of this relationship is given by:

\[ P = (W'(t) + CP) \]

where \( W' \) is the slope and \( CP \) is the intercept (10,20). In theory, if all-out exercise were performed for an extended period of time, the value of \( W' \) would reduce to zero, at which point the highest possible power output that could be attained would equal critical power, because equation 2 would reduce to \( P = CP \). Consequently, exercise below this end-test power output should result in steady-state profiles of blood [lactate] and VO2, whereas exercise above it should not. We chose to investigate a 3-min all-out test because recent data (8) suggest that tests of 90-s duration are not long enough to yield reductions in power output to that associated with critical power, and our own pilot work demonstrated that a reproducible leveling out of power output occurred after approximately 2.5 min had elapsed. We therefore tested the following experimental hypotheses: 1) that 3 min of all-out exercise would provide a reproducible power output profile; 2) that the test would elicit a peak VO2 that would not differ from that measured in a ramp test; and 3) that the physiological response to prolonged exercise 15 W below the power attained in the last 30 s of the all-out test would result in a steady state in VO2 and blood [lactate] indicative of heavy exercise, whereas exercise 15 W above the end-test power output would result in a continued rise in VO2 and blood [lactate] over time, indicative of exercise in the severe-intensity domain.

**METHODS**

Eleven recreationally active subjects (nine male, mean ± SD: age 27 ± 7 yr; height 1.76 ± 0.10 m; body mass 68.4 ± 12.0 kg) provided written informed consent to participate in this study, which was approved by the ethics committee of the University of Wales, Aberystwyth. Subjects were instructed to arrive at the laboratory rested (no strenuous exercise in the preceding 24 h) and adequately hydrated without having consumed food or caffeine for 3 h before each test. The subjects were accustomed to high-intensity exercise and included competitive cyclists, runners, and others involved in general fitness training.

**Experimental design.** Subjects visited the laboratory on six occasions, with a minimum of 24 h of recovery between each test, and all tests were completed within 14 d. Subjects first performed a ramp protocol for the determination of VO2peak and GET. During the second visit, subjects performed a 3-min bout of all-out cycling, which served as a familiarization trial to reduce the practice effect associated with multiple tests involving maximal effort (24) and was not included in subsequent data analysis. On each of the following two visits, subjects performed a 3-min all-out trial. On the last two visits, subjects cycled for 30 min or until exhaustion at constant work rates 15 W above or below the end-test power of the 3-min trial in a random order.

**Determination of VO2peak and GET.** All exercise testing was conducted using an electromagnetically braked cycle ergometer (Lode Excalibur Sport, Groningen, the Netherlands) in a well-ventilated laboratory at a temperature of 21–25°C. Each subject adjusted the ergometer for comfort, including fitting their own pedals if required, and the adjustments were recorded and replicated during subsequent tests. VO2peak and GET were determined using a ramp protocol that consisted of 3 min of unloaded baseline pedaling and then a 30-W·min⁻¹ increase in work rate until volitional exhaustion. Subjects were instructed to maintain their preferred cadence (80 rpm, N = 3; 90 rpm, N = 8) throughout the test. The test was terminated when the cadence fell by more than 5 rpm below the chosen cadence for more than 10 s, despite strong verbal encouragement. Throughout the test, pulmonary gas exchange was measured breath-by-breath as described below. VO2peak was determined as the highest average VO2 over a 30-s period. Data were reduced to 10-s averages for the estimation of GET using the V-slope method (2).

**Three-minute tests.** Before each trial, subjects were given a 5-min warm-up at 100 W and then 5 min of rest. The subjects performed three tests in total. Each trial started with 3 min of unloaded cycling at 90 rpm, followed by an all-out 3-min effort. The subjects were asked to increase their cadence to approximately 120 rpm during the last 5 s of unloaded cycling. The resistance to pedaling during the all-out effort was set so that the subjects would attain a power output of 50% of the difference between GET and VO2peak on reaching their preferred cadence (80–90 rpm), using the linear factor of the Lode ergometer (linear factor = power/cadence²). Verbal encouragement was given throughout the tests, but subjects were not informed of the elapsed time so that pacing might be prevented. For an all-out effort,
Subjects were instructed and strongly encouraged to maintain the cadence as high as possible at all times throughout the test. Pulmonary gas exchange was monitored breath-by-breath throughout the test, and blood [lactate] was measured immediately at the end of the test and at 3 and 5 min afterwards. The peak VO\textsubscript{2} was taken as the highest VO\textsubscript{2} measured for 30 s during the test, and the highest [lactate] was recorded as peak [lactate]. The end-test power was determined as the average power output during the final 30 s of the test. The power output–time integral above the end-test power was also calculated, which provided an estimate of W\textsuperscript{2} (8).

**Constant-work rate tests.** These tests were performed after a 5-min warm-up at 100 W and 5 min of rest. Subjects performed up to 30 min of constant–work rate exercise at 15 W above or below the end-test power measured in the 3-min test. Pulmonary gas exchange was measured breath-by-breath throughout the tests and was recorded in 30-s intervals. A fingertip capillary blood sample was collected every 5 min during the test and analyzed for whole-blood lactate concentration. Subjects pedaled at their preferred cadence and were told that the target time was 30 min. They were not informed whether the test was above or below the end-test power. Subjects thus exercised to exhaustion (the test was terminated when the cadence fell by more than 5 rpm below the chosen cadence for more than 10 s, despite strong verbal encouragement) or to 30 min, whichever came first. The steady state was defined as an increase of < 1.0 mM in blood [lactate] from 10 to 30 min of exercise (3,15).

**Equipment.** Throughout all tests, subjects wore a nose clip and breathed through a low-deadspace (90 mL), low-resistance (0.75 mm Hg L\textsuperscript{−1}s\textsuperscript{−1} at 15 L s\textsuperscript{−1}) mouthpiece and impeller turbine assembly (Jaeger Triple V). The inspired and expired gas volume and gas concentration signals were continuously sampled at 100 Hz, the latter using paramagnetic (O\textsubscript{2}) and infrared (CO\textsubscript{2}) analyzers (Jaeger Oxycon Pro, Hoechberg, Germany) via a capillary line connected to the mouthpiece. These analyzers were calibrated before each test with gases of known concentration, and the turbine volume transducer was calibrated using a 3-L syringe (Hans Rudolph, MO). The volume and concentration signals were time aligned by accounting for the delay in capillary gas transit and analyzer rise time relative to the volume signal. Oxygen uptake, carbon dioxide output, and minute ventilation were calculated using standard formulae (1) and displayed breath-by-breath. Heart rate was measured every 5 s using short-range radio telemetry (Polar S610, Polar Electro Oy, Kempele, Finland). Fingertip blood (~25 μL) was collected into capillary tubes and analyzed for blood [lactate] using an automated lactate analyzer (YSI Stat 2300, Yellow Springs, OH), which was calibrated hourly using the manufacturer’s standard (YSI 2747).

**Data analysis.** Reliability of the power output at the end of the test was determined using the intraclass correlation coefficient and the typical error of measurement. Bland–Altman analyses were performed to establish limits of agreement between the end-test power output in the 3-min test and between the VO\textsubscript{2peak} measurements made during ramp and all-out exercise. A one-way repeated-measures ANOVA was used to determine main effects between the ramp test VO\textsubscript{2peak} and the highest VO\textsubscript{2} values achieved in the two 3-min all-out tests and to establish changes over time in VO\textsubscript{2} and blood [lactate] in 30-min trials. Statistical significance was accepted at the P < 0.05 level. Specific differences were then established using 95% paired-samples confidence intervals. Data are presented as mean ± SD unless otherwise stated.

**RESULTS**

The subjects’ VO\textsubscript{2peak} was 3.84 ± 0.79 L min\textsuperscript{−1} and was associated with a peak power output of 368 ± 73 W during the ramp test. The GET occurred at 2.45 ± 0.66 L min\textsuperscript{−1} (169 ± 55 W). Table 1 shows the averaged individual responses to the 3-min all-out tests. Figure 1 shows the results of a Bland–Altman analysis for the comparison of VO\textsubscript{2peak} in the ramp and all-out tests. The peak VO\textsubscript{2} attained in these 3-min tests was similar (3.77 ± 0.73 and 3.78 ± 0.73 L min\textsuperscript{−1} for tests 1 and 2), and these were not significantly different from that measured during the ramp test (mean difference 0.06 L min\textsuperscript{−1}, 95% confidence interval).

**Table 1. Individual responses to 3 min of all-out cycling exercise.**

<table>
<thead>
<tr>
<th>Subject</th>
<th>VO\textsubscript{2peak} (L min\textsuperscript{−1})</th>
<th>Percent Ramp VO\textsubscript{2peak}</th>
<th>End Power Output (W)</th>
<th>Percent Ramp End Power</th>
<th>%GET</th>
<th>%Δ</th>
<th>Peak Blood (Lactate) (mM)</th>
<th>Peak Power Output (W)</th>
<th>Percent Ramp End Power</th>
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<td>154</td>
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GET, gas exchange threshold; VO\textsubscript{2peak}, peak oxygen uptake; %Δ, percent difference between VO\textsubscript{2peak} and the GET.

**ALL-OUT EXERCISE AND THE MAXIMAL STEADY STATE**

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confidence limits 0.22, −0.11 L·min⁻¹; \( F_{2,10} = 0.11, P = 0.75 \). It should be noted that with such a small effect and a small sample size, the power associated with these comparisons was low (1−\( \beta \) = 10.9%). The VO₂ in the last 30 s of the all-out test was 3.74 ± 0.69 L·min⁻¹, which was only slightly, but statistically significantly, lower than the peak value (mean difference 0.04 L·min⁻¹, 95% confidence limits 0.07, 0.01 L·min⁻¹). The finding of a statistically significant difference in this case is merely a reflection of the fact that VO₂peak was chosen as the highest VO₂ recorded. Consequently, the end-test VO₂ was either equal to (three cases) or below VO₂peak. The peak power output for the 3-min test, in most cases attained within 5 s of commencing the test, was 764 ± 207 W, or 207 ± 47% of the peak power output achieved in the ramp test (Table 1). The end-test power outputs were not significantly different from each other (256 ± 48 W for test 1 vs 257 ± 55 W for test 2, 95% confidence limits 8, −5 W). The intraclass correlation coefficient for the end-test power between the two tests was \( r = 0.99 (P < 0.001) \), and the typical error between the two tests was ± 7 W, or 3% of the mean value presented in Table 1 (Fig. 1D). The end-test power was significantly lower than the peak power measured during the ramp test (\( F_{2,10} = 156.2, P < 0.001 \)) and significantly higher than the power at the GET (Table 1), equivalent to approximately 70% of peak power at the end of the ramp test, approximately 154% of the power output at the GET, or approximately 43% of the difference (Δ) between VO₂peak and GET (i.e., 43% Δ, Table 1). The group mean responses to the 3-min all-out test are shown in Figure 2. Power output declined rapidly over the first 60 s in all tests but was relatively stable in the last 60 s (panel A). When the time data were expressed as 30-s averages and compared (panel B), all time points differed significantly from each subsequent 30-s time bin (\( F_{5,10} = 97.2, P < 0.001 \)), with the exception of 120–150 s and 150–180 s, which differed by just 5 W (95% confidence limits 11, −1 W). Figure 3 shows the power output (panel A) and VO₂ response (panel B) profiles during the 3-min all-out test in a representative subject. As also shown in Table 1, the end-test power was situated below VO₂peak but above the GET. The cadence attained during the test peaked at 150 ± 14 rpm and fell to 88 ± 5 rpm at the end of the test. The total work done during

FIGURE 1—Correlation and Bland–Altman analyses for the difference between ramp-determined VO₂ and VO₂peak measured during all-out exercise (panels A and B) and the end-test power output during the all-out test (panels C and D). In panels A and C, the solid line is the best-fit linear regression, and the dashed line is the line of identity. In panels B and D (Bland–Altman plots), the solid horizontal line represents the mean difference between the two measures, and the dashed lines represent the 95% limits of agreement between the measures.
the 3-min test was 60.2 ± 12.8 kJ. The total work done above the end-test power, the component notionally representing W, was 14.3 ± 4.7 kJ.

During the constant-work rate trials at 15 W below the end-test power, 9 of the 11 subjects were able to complete 30 min of exercise (Fig. 4). Of these, seven subjects completed the exercise having met the criterion for a steady-state blood lactate profile (< 1.0 mM increase between 10 and 30 min (3), with an end-exercise blood [lactate] of 5.6 ± 1.6 mM. These subjects also evidenced a delayed steady-state VO₂ response, which reached approximately 85% VO₂peak: the mean change in blood [lactate] and VO₂ between 10 and 30 min in all those completing the full 30-min was 0.9 ± 1.1 mM (95% confidence limits 1.2, 0.6) and 0.01 ± 0.20 L·min⁻¹ (95% confidence limits 0.05, −0.05). The two subjects who failed to complete 30 min of exercise below the end-test power tolerated 15 and 24 min of exercise before volitional exhaustion. None of the subjects were able to complete a full 30 min at 15 W above the end-test power. The mean time to exhaustion was 12 min 46 s (range 1 min 50 s to 23 min 57 s), and the response profiles for VO₂ and blood [lactate] were indicative of severe-intensity exercise (Fig. 4): VO₂ reached 3.78 ± 0.51 L·min⁻¹ at exhaustion, which was not significantly different from VO₂peak (95% confidence limits 0.29, −0.02). Blood [lactate] rose continuously as a function of time, reaching a peak of 8.3 ± 2.2 mM at exhaustion (Fig. 4).

**DISCUSSION**

The present study has shown that a 3-min all-out cycle ergometer test against a fixed resistance results in a reproducible power output profile and in the attainment of VO₂peak, which is consistent with our first and second hypotheses (Figs. 1 and 3B). The end-test power output was above that associated with the GET but below the power output achieved at the end of the ramp test (Figs. 2 and 3). Our third hypothesis was that this end-test power output would represent the boundary between the heavy– and severe–exercise intensity domains. Therefore, we predicted that constant-work rate exercise performed below this power output would result in steady-state blood [lactate] and VO₂ responses, whereas exercise above the end-test power output would result in a continued rise in these variables until fatigue ensued. The present study provides some support for this hypothesis: 9 of the 11 subjects were able to complete 30 min of exercise at 15 W.
below the end-test power, and seven of these met the criteria for a steady-state blood [lactate] profile (Fig. 4). In contrast, none of the subjects completed 30 min of exercise 15 W above the end-test power output, and in all cases blood [lactate] and V\textsubscript{\text{I}}\text{O}\textsubscript{2} continued to rise until exhaustion, at which point V\textsubscript{\text{I}}\text{O}\textsubscript{2} did not differ significantly from V\textsubscript{\text{I}}\text{O}\textsubscript{2peak}. These data suggest that it is possible to establish V\textsubscript{\text{I}}\text{O}\textsubscript{2peak} during all-out exercise even when the power output falls considerably below levels associated with the achievement of V\textsubscript{\text{I}}\text{O}\textsubscript{2peak} during ramp exercise (Table 1, Figs. 1 and 3). It is well established that the work rate need not be maximal for subjects to achieve V\textsubscript{\text{I}}\text{O}\textsubscript{2peak}; submaximal constant–work rate exercise performed in the severe-intensity domain results in a V\textsubscript{\text{I}}\text{O}\textsubscript{2} slow component that drives V\textsubscript{\text{I}}\text{O}\textsubscript{2} to V\textsubscript{\text{I}}\text{O}\textsubscript{2peak} before fatigue ensues (7,14,23). It is now also clear that all-out exercise lasting 1.5–3 min also yields V\textsubscript{\text{I}}\text{O}\textsubscript{2peak}, with little evidence of V\textsubscript{\text{I}}\text{O}\textsubscript{2} declining towards the end of the test in adolescents or adults (29, present study). These data add to the growing body of evidence that V\textsubscript{\text{I}}\text{O}\textsubscript{2peak} can be established using a variety of work rate–forcing functions. Ramp/incremental tests, all-out tests lasting 1.5–3 min, and submaximal constant–work rate tests in the severe-intensity domain performed to volitional exhaustion all result in the same end-point V\textsubscript{\text{I}}\text{O}\textsubscript{2} (i.e., V\textsubscript{\text{I}}\text{O}\textsubscript{2peak}) (7,29).

A common feature of previous work investigating prolonged all-out exercise is that the power output falls below that associated with the attainment of V\textsubscript{\text{I}}\text{O}\textsubscript{2peak} in a ramp or incremental exercise test (6,8,12,29,30). It was our original contention that if the fall in power was continued until a leveling out could be identified, the end-test power would equal the power output demarcating the heavy- and severe-intensity domains. This contention stems from the fact that the power–duration relationship is hyperbolic (19–21), with the critical power representing the maximal steady-state power output (20) and W\textsuperscript{'} representing a fixed amount of work that can be performed above critical power (9).
We reasoned that if the performance of all-out exercise were continued for long enough to reduce $W'$ to zero, then the end-test power output would necessarily equal the maximal steady state. We did not, however, establish the parameters of the power–duration relationship in the present study. The definition of critical power requires mathematical extrapolation of the results of a series of exhaustive exercise tests to the asymptote on the power axis (10), which may (20,21) or may not (4,22) yield a maximum steady-state power output. In establishing the critical power, therefore, the physiological response profile above and below the hypothesized heavy–severe boundary (the end-test power) would have remained uncertain. Instead, we chose to directly address the physiological responses to exercise above and below the end-test power output, using a previously established criterion for the achievement of a blood [lactate] steady state (an increase in blood [lactate] of $< 1 \text{mM}$ between 10 and 30 min of exercise) (4,15,17). Thus, if the end-test power successfully defined the boundary between heavy- and severe-intensity exercise, a steady-state blood [lactate] response below, but not above, this power would be expected.

At the end of the 3-min all-out test, power output had declined to approximately 70% of the power output measured at the end of the ramp test, and power output showed only a small (and statistically insignificant) decline in the last 60 s of the test (of approximately 5 W). Thus, we were successful in conducting an all-out exercise test in which power output reached a relatively stable level (the end-test power, Figs. 2 and 3). The mean results for the end-test power output in relation to the other parameters of aerobic function shown in Table 1 are remarkably similar to the critical power data presented by Poole et al. (20) (see their Table 2). For example, the end-test power occurred at approximately 43% $\Delta$, whereas Poole et al. (20) reported that critical power occurred at approximately 46% $\Delta$. Other investigators have reported similar findings for the exercise intensity at the maximal steady state (22,25). The present results further demonstrate that exercise above the end-test power is situated in the severe-intensity exercise domain, where $\text{VO}_2$ and blood [lactate] increased until exhaustion ensued. Exercise below the end-test power was, in most subjects, situated in the heavy-intensity domain, where blood [lactate] and $\text{VO}_2$ eventually stabilized. In this intensity domain, exercise can be maintained for a considerable, but finite, period of time, with fatigue likely being mediated by limitations in the rate of or capacity for substrate use and/or hyperthermia (11). These results demonstrate that a 3-min all-out exercise test can be used to estimate a power output at the physiologically important boundary between the heavy– and severe–exercise intensity domains in more than 60% of the subjects sampled. Although by no means perfect, we believe this is a promising result in light of the observation that the end-test power output occurred in the correct region of the exercise intensity spectrum to yield the maximal steady state (or critical power) in all subjects (i.e., approximately halfway between the GET and end-ramp power outputs).

The findings of the present investigation have potentially important implications for the power–duration relationship. Assuming that critical power and the maximal steady state can be used interchangeably ((16,20,25), but see (4,22)), the present results suggest that the current formulation of the power–duration relationship (equations 1 and 2) is fundamentally correct and may be generalized to maximal all-out exercise. The power output during 3 min of all-out exercise declined to, or at least towards, a power output below which a steady-state blood [lactate] and $\text{VO}_2$ response profile could be observed (Figs. 3 and 4). This would be expected if $W'$ were reduced to zero during the exercise, at which point the highest power that could theoretically be maintained would be the maximal steady state (5,10). There is currently no standard method of establishing $W'$ during all-out exercise (8). However, the total work done above the end-test power was $14.3 \pm 4.7 \text{kJ}$, which is of the same order of magnitude as $W'$ estimates presented in the literature (5,8,10,20,21), suggesting that $W'$ could also be estimated from a 3-min all-out test. Thus, the expenditure of $W'$ provides the simplest explanation for the attainment of the end-test power, in terms of its proximity to other physiological landmarks (end-ramp and GET power outputs) and the physiological response profiles above and below the end-test power. However, further work is necessary to address this notion quantitatively.

Although the majority of subjects in this study were able to attain a steady state below the end-test power, four subjects did not. We did not undertake further testing to establish the magnitude of the discrepancy between the end-test power and the true heavy–severe domain boundary in these subjects, although it would appear that in two of the four cases the discrepancy would have been small because these subjects completed 30 min of exercise. Therefore, we can only speculate as to why the 3-min test did not establish the domain boundary in these subjects. Firstly, it is important to note that in no instance was the maximal steady state underestimated: the 3-min test either succeeded in identifying the boundary or it overestimated it. Consequently, test failure was not caused by muscle fatigue inducing a continual fall in power output to an end-test power output below the maximal steady state. It is possible that 3 min of all-out exercise is, in some subjects, not long enough to expend the entire $W'$. However, this is unlikely because Medbo et al. (18) reported that a maximal $O_2$ deficit (theoretically analogous to $W'$) (11) could be accumulated in approximately 2 min of constant-power exercise, and Gastin and Lawson (13) reported that the accumulated $O_2$ deficit during all-out exercise did not differ with exercise durations of 60 or 90 s. Perhaps more likely, averaging the power output in the last 30 s of exercise, though apparently justified because power output in the last 60 s was not falling significantly, may have resulted in an overestimation of the heavy–severe domain boundary in those subjects in whom power output was still falling during the last 60 s. In these subjects, a longer test duration (e.g., 4 min) or a shorter period of data averaging.
(15 vs 30 s) may have resulted in successful identification of the domain boundary. It is possible, however, that prolonging the test duration beyond 3 min would result in a continued fall in power output with time, exposing the apparent success of a 3-min test in estimating the maximal steady state as fortuitous, though no less useful. Thus, a 3-min test duration was chosen as a compromise between a test that would be too short for power output to level out and one that might be needlessly long, such as a 5-min test in which subjects might exercise all out with little or no change in power output for the final 3 min. We do not claim, nor do we have any means of showing, that 3 min is the optimal test duration.

The Lode Excalibur Sport ergometer we used in the present study does not operate isokinetically, unlike the ergometers used in recent reports (8,29). Therefore, we set the ergometer’s linear factor so that when (if) the subjects reached their preferred cadence, they would be producing a power output halfway between GET and VO₂peak. We adopted this approach in preference to normalizing the resistance to pedaling based on body mass (12,13) because we were attempting to establish the maximal steady state, rather than anaerobic performance. It is not known whether the approach adopted in the present study is an optimal strategy for the achievement of a valid end-test power in all subjects. However, the cadence at the end of the 3-min test was similar to the subjects’ preferred cadence of 80–90 rpm, despite the variance in power output across the sample (187–338 W). Had the resistance been equivalent to 7.5% of body mass, which is commonly used to set the resistance on a Monark cycle ergometer for all-out tests (12,13), the subjects would have achieved their end-test power output at approximately 50 rpm, approximately 30–40 rpm lower than their preferred cadence. Whether other resistances (based on physiological status or body mass) or the adoption of isokinetic ergometry (8,29) would influence the outcome of the test requires further work.

In summary, we have presented evidence that the power profile in a 3-min all-out test against a fixed resistance is reproducible and that the test can be used to establish VO₂peak in adults, extending the recent findings of Williams et al. (29) in adolescents. For the first time, the present study has demonstrated that during all-out exercise, power output falls towards, and in more than 60% of cases attains, a power output below which steady-state responses in blood [lactate] and pulmonary VO₂ generally occur, but above which these variables rise inexorably until fatigue ensues. The present work therefore suggests that a 3-min bout of all-out exercise represents a promising method of estimating the maximal steady state, which has previously required repeated bouts of prolonged and/or exhaustive exercise to identify.

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