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Title: Repeated Anaerobic Tests Predicts Performance Among a Group of Advanced CrossFit® Trained Athletes

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Abstract

High-intensity functional training (HIFT) (i.e. CrossFit training) uses a combination of movements, and self-selected time periods of work and rest. However, little is known regarding the physiological responses to an acute bout of HIFT exercise or the physical parameters that distinguish performance. The purpose of this study was to examine the physiological response to consecutive Wingate trials with short, active recovery periods in advanced CrossFit athletes. Twenty-nine advance level CrossFit trained athletes volunteered for this study. Participants were required to complete four-consecutive Wingate anaerobic tests (WAT), and a 15-minute CrossFit style workout. Across the four WAnT trials, significant ($p < 0.001$) changes were observed in VO_2, RER, and HR. Significant ($p \leq 0.001$) differences between WAnT trials were observed in all anaerobic performance measures. Compared to all other trials, greater PP ($p < 0.04$), RPP ($p < 0.02$), AP ($p < 0.001$), RAP ($p < 0.001$), and TW ($p < 0.001$), along with a lower FI ($p < 0.01$), were observed during WAnT 1. Overall, the four consecutive WAnT trials resulted in a significant ($F = 177.0$, $p < 0.001$) increase of blood lactate response. Stepwise regression revealed that the ability to predict total repetitions completed during the 15-min AMRAP improved as the participants progressed from the first to the third WAnT trial. Our data suggests that combined with the ability to better maintain performance across high-intensity exercise bouts, the ability to quickly recover between bouts is most important for CF performance.

Keywords: Wingate, HIFT, Fitness, Competition, Athlete, Performance

Introduction

As the popularity of high-intensity training programs continue in the fitness industry, a new form of high-intensity training has emerged – high-intensity functional training (HIFT). Unlike interval training, where specific predetermined breaks are used, HIFT uses a combination of movements, and self-selected time periods of work and rest. Moreover, HIFT emphasizes functional movements that can be modified to any fitness level and elicit greater muscle recruitment, thereby improving cardiovascular endurance, strength, and flexibility (Heinrich et al. 2012; Heinrich et al. 2015). An example of HIFT is CrossFit® training (CFT), which defines itself as "constantly varied, functional movements executed at high intensity" (Glassman 2004). The goal of CFT is to increase work capacity across several physical domains and thus enhance general physical preparedness or fitness. However, little is known regarding the physiological responses to an acute bout of CFT exercise or the physical parameters that distinguish performance. Previously, CFT has been demonstrated to improve performance during traditional aerobic capacity (i.e., graded exercise test [GXT] on cycle ergometer and treadmill) and anaerobic power (i.e., Wingate Anaerobic Test [WAnT]) assessments (Outlaw et al. 2014; Murawska-Cialowicz et al. 2015), but the influence of these traditional performance measures on performance during CF workouts has been equivocal (Bellar et al. 2015; Butcher et al. 2015b). Bellar and colleagues (2015) found aerobic capacity and anaerobic power (peak and mean) to be influential of performance during a 12-minute exercise bout but not a protocol that lasted approximate 3.5 – 5 minutes. In contrast, Butcher and colleagues (2015b) reported no relationships between aerobic or anaerobic power and performance during short (~2.3 – 3.4 minutes) or long

(20 minutes) benchmark workouts (i.e., Fran, Grace, or Cindy). Nonetheless, it is possible that the traditional methodology for assessing these physiological parameters may have lacked specificity for assessing their role in CFT performance.

A common CFT paradigm is to develop a list of two or more exercises performed at a standardized load and for a specified number of repetitions. The trainee is then asked to complete as many repetitions as possible (AMRAP) of the exercises (usually performed in circuits) within a specified time span (e.g., 10 – 20 minutes). Thus, it might be assumed that performance within shorter (e.g., 3 – 5 minutes) and longer (e.g., 10 – 20 minutes) duration workouts may be dominated by anaerobic and aerobic energy production pathways, respectively. However, as we have previously mentioned, current evidence does not indicate consistent relationships (Bellar et al. 2015; Butcher et al. 2015b). Traditionally, aerobic capacity is assessed by gradually increasing intensity during continuous movement (i.e., GXT), while anaerobic power is assessed via maximal continuous effort for 30 seconds (i.e., WAnT). However, CFT workouts often require the trainee to transition between several distinct movements (or exercises) that, due to different repetition and loading schemes, require varying levels of effort; in spite of the overall workout's goal of maximal effort (Heinrich et al. 2012; Butcher et al. 2015b; Heinrich et al. 2015). Consequently, the trainee may adopt a strategy of emphasizing a greater amount of effort during movements in which they excel (or can perform repetitions more quickly) and less effort during the other movements (i.e., active recovery). In short, the trainee may not exercise continuously or with constant (or increasing) intensity throughout the entire workout. Therefore, the consistent and continuous nature of the GXT and WAnT protocols may not adequately represent how energy is utilized during a typical CFT workout.

Performance during the WAnT protocol (i.e., 30-s maximal sprint on a cycle ergometer against a standard resistance) is known to be indicative of an individual's ability to derive energy via the phosphagen system and anaerobic glycolysis (Parolin et al. 1999). However, training protocols that have utilized multiple, consecutive maximal exercise bouts (e.g., repeated WAnT) separated by short active recovery periods have been shown to elicit greater anaerobic and comparable aerobic adaptations than traditional, continuous endurance training (Burgomaster et al. 2005; Dupont et al. 2007). While repeated maximal sprints clearly require a competent anaerobic energy system, it has been hypothesized that the ability to recover between successive sprints is dependent upon oxidative capacity (Inbar et al. 1996). Given the similarities between repeated, maximal sprint protocol with short, activity recovery periods and CFT, it is possible that the accompanying physiological responses may be indicative of CFT performance. Therefore, the purpose of this study was to examine the physiological response to consecutive WAnT trials with short, active recovery periods in advanced CF trained participants. In addition, a secondary purpose was to determine if the observed physiological responses were influential of performance during a typical bout of high-intensity function training.

Materials and Methods

Study Design

Repeated Wingate anaerobic tests (WAnT) performance and its ability to predict performance in a 15-minute bout of HIFT was determined in advanced CF participants.

Participants reported to the Exercise Physiology Laboratory (EPL) on two separate occasions. On the first visit (T1), eligible participants were advised of the purpose, risks, and benefits associated with the study, followed by anthropometric and anaerobic performance measurements. Seven days after, participants returned to the EPL for their second visit (T2) to complete an acute bout of a CF training-based session. On both occasions, participants were instructed to report to the EPL without having consumed alcohol for 24 hours, exercised for 12 hours, and consumed food or any beverage other than water for four hours prior to testing. All testing was performed wearing light and comfortable clothing (e.g. shorts and t-shirt) as desired by the athlete, and in a standardized environment (e.g., temperature and humidity changes, etc.).

Participants

A total of 15 males and 14 females (N = 29) physically-active adults (28.6 ± 5.7 years [range: 19 – 43 years], 79.2 ± 14.0 kg [range: 58.6 – 103.0 kg], 172.9 ± 9.4 cm [range: 151.8 – 188.6 cm) volunteered to participate in this study. All participants possessed over two years of CF training experience and were considered advanced based upon their self-reported and confirmed "Fran" time (Fran times were confirmed by the affiliate coach). Briefly, "Fran" is considered a benchmark workout within CFT and consists of two exercises performed in alternating fashion in a descending 21-15-9 repetition scheme and scored based on time to completion. That is, individuals complete 21 repetitions of the first exercise (i.e., Thrusters: front squat to overhead press with a loaded barbell [men: 95 lbs. / 43 kg; women: 65 lbs. / 29.5 kg]), then 21 repetitions for the second exercise (i.e., pull-ups), and then repeat for 15 repetitions and so forth. To be included within this investigation, participants must had completed "Fran" within 3 minutes (for men) or 4 minutes (for women). These times are typical of advanced and elite level athletes (Serafini et al. 2017), and provide evidence of the participants' capability of completing the anaerobic testing protocol. None of the participants were known to be pregnant, and all were considered low risk according to the American College of Sports Medicine risk stratification criteria (American College of Sports Medicine 2017), as determined by a health history questionnaire. In addition, all participants were active members of a training affiliate. The Institutional Review Board approved this study and written consent was obtained prior to participation.

Anaerobic performance assessments

Initially, height (± 0.1 cm) and body mass (± 0.1 kg) were measured using a Tanita WB-3000 (Arlington Heights, IL) digital beam scale. Anaerobic performance was then assessed via four, successive WAnT on a Lode Excalibur Sport electromagnetic braked cycle ergometer (Lode BV, Groningen, The Netherlands). Prior to the WAnT, participants completed a self-selected stretching routine without time limit. Participants were then fitted with the Cosmed K4b^2 portable metabolic system (K4; Concord, CA) and a Polar heart rate (HR) monitor (Lake Success, NY). The K4 consists of a facemask and two small units mounted on a harness that is secured to the body (Figure 1). The K4 has previously been demonstrated to be an accurate and reliable device for estimating oxygen consumption (VO_2) and carbon dioxide production (VCO_2) (Duffield et al. 2004) to calculate respiratory exchange ratio (RER; VCO_2/VO_2). The Polar monitor strap was attached around the chest, at the level of the xiphoid process. Subsequently, participants completed a 4-minute warm-up on the bike at a self-selected pace (approximately 60 to 90 rpm) at a load of 50 watts. At the end of the warm-up period, and five seconds before the start of each WAnT, the participants were encouraged to pedal as fast as possible in an “all out” effort before a weight-adjusted workload was implemented for 30 seconds. Based on previous work in highly-trained individuals (Dotan et al. 1983), the weight-adjusted workload was set at 8.5% and 8.2% of body mass for males and females, respectively. During each WAnT, strong verbal encouragement was provided by the research team for all participants. Between WAnT trials, participants were allotted 90 seconds for active recovery using a self-selected pace at 30 Watts. This work-to-rest ratio (i.e., 30:90), as opposed to other ratios (e.g. 10:20, 30:60, etc.) was used to more closely resemble CF training (i.e., short bouts of active recovery between successive high intensity bouts) (Zabukovec et al. 1995; Bogdanis et al. 1996; Bogdanis et al. 1998). The “all out” effort and the 90-second active recovery sequence was repeated three consecutive times (for a total of four WAnT trials) without any additional resting period.

Upon the completion of all four WAnTs each participant performed a 3-minute active recovery period pedaling at a self-selected speed at 30 Watts followed by a 7-minute passive cool down while sitting in a chair. From each trial, average power (AP; W), peak power within a 5-second window (PP; W), relative average power (RAP; $W \cdot kg^{-1}$), relative peak power (RPP; $W \cdot kg^{-1}$), total work (TW; kJ) and a fatigue index (FI; percent decrease in power) were all extracted via Lode Ergometry Manager-Pedal Force Manager software (Mortara Instrument, Castle Hill, NSW, Australia). Fatigue rate (FR) was also determined for each of these measurements by calculating their respective slope across trials. Additionally, the difference (DIF) between the average of all trials and the best trial was also used as an estimate of relative fatigue for each measure.

Lactate assessment

Blood lactate concentrations were measured following each WAnT trial. Assessment was done via finger prick using the Lactate Plus Analyzer (Nova Biomedical, Waltham, MA) following manufacturer recommendations. The Lactate Plus Analyzer is a valid (Hart et al. 2013) and easy to use only requiring minimum amounts of blood (0.7 μL).

Acute exercise bout

On T2, the participants completed an acute bout of high-intensity exercise that closely resembled a CF training session in the EPL. Prior to exercise, the participants were encouraged to perform a light, self-selected warm up that included major muscle groups (e.g. quadriceps, hip flexors, shoulders, etc.), as if they were preparing for a typical workout. Subsequently, the participants were asked to complete a 15-minute bout of high-intensity exercise. The workout was a circuit that consisted of 250-m of rowing on an ergometer (Concept 2, Morrisville, VT), 20 Kettle bell swings (16 kg for men and 12 kg for women), and 15 dumbbell thrusters (16 kg for men and 9 kg for women). Each participant was encouraged to move as fast as possible between the three movements but were free to stop as needed throughout the exercise period. Completing all exercises within the circuit was defined as completing one round. Upon completing each round, the participants were instructed to repeat the circuit while time remained for the purpose of completing as many repetitions as possible (AMRAP). Thus, performance during the exercise bout was quantified by the total number repetitions completed within 15 minutes. For the 250-m row, every 10 meters completed was worth one repetition. Upon completion of the 15-minute AMRAP, participants were instructed to walk for 3-minutes as an active recovery period, and a seven-minute passive recovery while sitting in a chair.

Statistical analysis

Statistical software (SPSS, v.24.0, Chicago, IL) was used to perform all analyses. To describe the effect of four consecutive WAnT trials, separate one-way repeated measures analyses of variance (RMANOVA) were performed on all anaerobic performance variables. Four levels (WAnT 1, WAnT 2, WAnT 3, and WAnT 4) were used to analyze PP, RPP, AP, RAP, TW, Fatigue Index, and blood lactate. Likewise, separate RMANOVA's were performed on each aerobic measure (i.e., VO_2, RER, and HR) using twelve levels (i.e., each WAnT trial, as well as 30P and 60P following each trial). Following a significant F-ratio, pair-wise comparisons with Bonferroni adjustments to confidence intervals were used to examine specific differences between time points.

To assess the influence of performance during four consecutive WAnT trials on 15-min AMRAP performance, Pearson product-moment correlation coefficients were calculated between total repetitions completed and each anaerobic variable collected surrounding the four trials. Subsequently, stepwise regression analysis was performed to determine the ability of one, two, three, and four consecutive WAnT trials to predict total repetitions completed, as well as to determine the single best predictor. All variables are reported as means ± standard deviations and the significance level was set at $p \leq 0.05$ for all statistical comparisons.

Results

Across the four WAnT trials, significant ($p < 0.001$) changes were observed in VO_2, RER, and HR. During each trial, VO2 was significantly elevated from IP at 30P ($p < 0.03$) and reduced from IP at 60P ($p < 0.03$), as well as from 30P to 60P ($p < 0.001$). Compared to WAnT 1, a greater VO2 response was noted at IP following WAnT 2 ($p = 0.008$) and at 30P following WAnT 2 – 4 ($p < 0.03$), while VO2 at 60P following WAnT 4 was lower ($p < 0.001$) than all other trials.

For RER, the ratio increased ($p < 0.001$) from IP at 30P and 60P during WAnT 1, but decreased ($p < 0.001$) from IP at 30P for WAnT 2 – 4. At 60P, RER values were similar to IP values for WAnT 2 – 3 and elevated ($p < 0.001$) beyond IP and 30P values following WAnT 4. Compared to all other trials, WAnT 1 elicited lower RER values at IP ($p < 0.001$) and higher ($p < 0.001$) RER values at 30P and 60P. Higher ($p < 0.001$) RER values were observed at each time point during WAnT 2 compared to WAnT 3 – 4. Likewise, higher ($p < 0.001$) RER values were observed at IP and 30P during WAnT 3 compared to WAnT 4, but not at 60P.

During all trials, HR was elevated ($p < 0.001$) from IP at 30P and 60P but decreased ($p < 0.001$) from 30P at 60P. A lesser ($p \leq 0.001$) response was observed at each time point during WAnT 1 compared to all other trials except for WAnT 4 where the responses were similar at 60P ($p = 0.630$). During WAnT 2, HR was lower at IP ($p < 0.02$) compared to WAnT 3 – 4 and at 60P compared to WAnT 3, but higher at 60P compared to WAnT 4 ($p < 0.001$); HR at 60P during WAnT 4 was also lower ($p < 0.001$) than HR at 60P during WAnT 3. No other differences were observed. The changes in VO_2, RER, and HR across each WAnT trial are illustrated in Figure 2.

Anaerobic performance assessments

Significant ($p \leq 0.001$) differences between WAnT trials were observed in all anaerobic performance measures. Compared to all other trials, greater PP ($p < 0.04$), RPP ($p < 0.02$), AP ($p < 0.001$), RAP ($p < 0.001$), and TW ($p < 0.001$), along with a lower FI ($p < 0.01$), were observed during WAnT 1. During WAnT 2, greater ($p < 0.001$) AP, RAP, and TW values, as well as a lower FI ($p < 0.01$) were observed compared to WAnT 3 and WAnT 4. Further, greater ($p < 0.001$) AP, RAP, and TW values were observed during WAnT 3 compared to WAnT 4. All anaerobic performance measures across the four WAnT trials are presented in Table 1. In addition to the scores of all participants, male and female scores are also presented for descriptive purposes.

Lactate values are presented in table 2. Overall, the four consecutive WAnT trials resulted in a significant ($F = 177.0$, $p < 0.001$) increase of blood lactate response with consecutive WAnTs, where blood lactate increased significantly from WAnT 1 (9.15 ± 2.58 $mmol \cdot L^{-1}$) to WAnT 2 (13.46 ± 2.79 $mmol \cdot L^{-1}$, $p < 0.001$) and from WAnT 2 to WAnT 3 (15.2 ± 2.37 $mmol \cdot L^{-1}$, $p < 0.001$). Additionally, blood lactate following WAnT 4 (15.72 ± 2.27 $mmol \cdot L^{-1}$ tended ($p = 0.075$) to be greater than WAnT 3.

Acute exercise bout

Participants completed an average of 311 ± 33 repetitions (Men: 321 ± 36 repetitions; Women: 300 ± 27 repetitions) during the 15-min AMRAP. Due to the novelty of the specific workout, we were unable to make statistical comparisons between the acute exercise bout and the four WAnT trials. Nevertheless, we have provided the peak and average physiological responses (i.e., VO2, RER, HR, and blood lactate) to the workout and during the 3-minute recovery period for all participants, including male and female data, for comparisons with other past and future protocols (see Table 2).

Prediction of 15-AMRAP score

Significant ($p < 0.05$) relationships were observed between the total number of repetitions completed during the 15-min AMRAP and anaerobic performance measures. Briefly, AP, RAP, TW, VO_2 at 30P, and VO_2 at 60P from each WAnT trial were all positively related to total repetitions. Additionally, positive relationships were observed for PP during WAnT 3 and blood lactate during WAnT 4. VO_2 and the fatigue index of the last three trials were positively and negatively related to total repetitions completed, respectively. Negative relationships were also seen between total repetitions and RER at 30P (WAnT 2 and WAnT 3), HR (WAnT 3), HR at 30P (WAnT 1), and HR at 60P (WAnT 1 and WAnT 2). The relationships between WAnT performance and total repetitions completed are presented in Table 3.

Stepwise regression revealed that the ability to predict total repetitions completed during the 15-min AMRAP improved as the participants progressed from the first to the third WAnT trial. Following one trial, VO_2 at 30P was the best ($R^2 = 0.32$) and only significant ($p = 0.002$) predictor of total repetitions. Following WAnT 2, the best predictor remained VO_2 at 30P (i.e., 30 seconds after WAnT 2) and the addition of the second trial improved predictive ability by 16%. However, the stepwise procedure later removed VO_2 at 30P in favor of RAP (WAnT 2) and DIF VO_2 at 30P, which improved variance explained by another 16% (32% overall). Following three trials, TW on WAnT 3 was the best predictor and compared to VO_2 at 30P for two trials, improved variance explained by 5%. Overall, the model for three trials best explained total repetitions completed ($R^2 = 0.74$) and included TW (WAnT 3), VO_2 at 30P (WAnT 3), DIF VO_2 at 30P, and DIF RAP. The final model (i.e., all four sprints) included the best predictor (TW on WAnT 4) and VO_2 at 60P following WAnT 4. However, this model only explained 64% of variance in total repetitions completed. The prediction equations for total repetitions completed during the 15-min AMRAP following one, two, three, and four consecutive WAnT trials are presented in Table 4.

Discussion

There is little evidence available related to CF trained athletes. To our knowledge, this is the first study to measure anaerobic ability via repeated WAnT trials in advanced CF athletes. Consistent with previous studies (Bogdanis et al. 1996; Dupont et al. 2007), power and total work declined across trials, while blood lactate and the rate of fatigue increased. Additionally, oxygen cost increased from the first to second trials and then remained consistent throughout the remaining trials. In contrast, heart rate steadily increased across trials and respiratory exchange ratio initially increased and then steadily declined. These physiological responses were found to be influential of performance during a CF-style workout. Of these, the nature of oxygen uptake during the recovery period between trials appeared to be the most predictive variable, followed by total work completed during later trials. Further, our data suggest that completing three WAnT trials best explained variance in repetitions completed during the 15-min AMRAP, whereas performing only a single trial was least predictive of performance – as previously shown by Butcher et al (2015b). Although the WAnT protocol predominantly relies on anaerobic energy production pathways (Beneke et al. 2002), recovery between trials is heavily influenced by aerobic pathways (McLester et al. 2008). Likewise, individual components of CF workouts (e.g., 250-m row, 20 Kettle bell swings, 15 dumbbell thrusters) performed quickly appear to predominantly rely on anaerobic energy pathways. However, the ability to sustain effort across the entire workout and sufficiently recover between strategized breaks would appear to be influenced by aerobic capacity.

An important assumption of this study was that the participants gave maximal effort on each WAnT trial. That is, they did not strategically withhold effort during the early trials so that they might be less fatigued during later trials. Though it is impossible to ensure maximal effort, our data suggests this was the case. Across all four trials, HR averaged between 68 – 87% of age-predicted maximum heart rate and RER remained above 1.0 (~1.01 – 1.56) with spikes typically occurring within 30 seconds of each trial. These delayed responses are characteristic of the oxygen deficit typically observed at the onset of high-intensity exercise (Tabata et al. 1997). Further, we observed higher absolute and relative peak power values compared to those previously reported in recreational and competitive athletes (Seiler et al. 1990; Hill et al. 1993; Baker et al. 2011). For instance, women in the present study produced greater absolute (902 ± 158 W) and relative (13.5 ± 1.5 $W \cdot kg^{-1}$) peak power values on their final trial (WAnT 4) compared to the 95th percentile rank (absolute: 878.4 W; relative: 12.5 $W \cdot kg^{-1}$) in highly-trained women (Baker et al. 2011). Likewise, male participants produced greater absolute (1337 ± 228 W) and relative (14.7 ± 2.0 $W \cdot kg^{-1}$) peak power outputs on WAnT 4 compared to what has been reported in Division 1 Football players (absolute: 1298 ± 83 W; relative (13.2 ± 1.1 W·kg-1) (Seiler et al. 1990) and comparable to elite kickboxers (absolute: ~1360 W [range = 975 – 1690 W]; relative: ~18.8 $W \cdot kg^{-1}$ [range = 13.5 – 22.8 $W \cdot kg^{-1}$]) (Zabukovec and Tiidus 1995). Interestingly, mean power and total work completed were less in our athletes than what has been reported across several athletic and non-athletic (i.e., healthy, college-aged adults) (Seiler et al. 1990; Hill and Smith 1993; Baker et al. 2011) but still greater than the 90th percentile for physically-active young adults (Inbar et al. 1996). These later differences might, in part, be explained by a much greater fatigue index in our participants (66.5 ± 8.3%) compared to what has been reported (45.0 – 53.2%), as well as slight differences in WAnT protocol intensity loads (Men: 8.3 – 9.5%; Women: 8.5 – 8.6%) (Seiler et al. 1990; Hill and Smith 1993; Baker et al. 2011). Regardless, based on the power produced across all sets, and the higher rate of fatigue, it appears likely that maximal effort was given across all four trials.

The secondary aim of this investigation was to determine whether anaerobic performance during four consecutive WAnT trials was indicative of performance during the 15-min AMRAP. Previously, consistent relationships between performance during a single WAnT trial and various CF workouts have not been observed (Bellar et al. 2015; Butcher et al. 2015b). Bellar and colleagues (2015) found peak anaerobic power to be influential of performance during a 12-min AMRAP, but only after experience and aerobic capacity were considered. Further, WAnT performance was not influential of the second workout (i.e., a triplet of sumo deadlift high pulls, box jumps, and a farmers walk performed for 21-15-9-repetitions) examined in that study. Likewise, Butcher et al. (2015b) reported no relationships between performance during a single WAnT trial and three benchmark CF workouts (i.e., “Fran”, “Cindy”, and “Grace”). However, we hypothesized that the short duration (i.e., 30 seconds) and consistent intensity of a single WAnT trial was not representative of the dynamics (of these variables) within a typical CF workout. That is, a typical CF workout is longer in duration and often includes multiple modalities performed at varying degrees of intensity with unpredictable (usually self-determined) rest interval times and durations (CrossFit Inc. 2018, pg. 51-55) . Similarly, the repeated WAnT protocol used in this study altered intensity between trials and active rest and its total duration (8 minutes) was typical of moderate-duration CF workouts (Butcher et al. 2015a). Consequently, relationships were observed between total repetitions completed and performance (power, total work, fatigue rate, and oxygen uptake) across each WAnT trial. Of these, our results suggest that oxygen uptake during the recovery period and total work completed during the later trials were the best indicators. During each WAnT trial, oxygen uptake would elevate beyond post-exercise levels at 30-seconds post-exercise but would then significantly drop by 60-seconds post-exercise. This would suggest that combined with the ability to better maintain performance across high-intensity exercise bouts, the ability to quickly recover between bouts is most important for CF performance.

During high-intensity exercise, energy requirements are primarily met by the Phosphagen system because it rapidly converts phosphocreatine (PCr) into adenosine triphosphate (ATP) (Harris et al. 1974; Harris et al. 1976). As exercise continues, the PCr supply is depleted and ATP production shifts towards the slower glycolytic system as the primary provider (Tesch et al. 1986; Essen-Gustavsson et al. 1990). In addition to ATP, the glycolytic system produces lactate. Prior to its release into the blood, hydrogen ions dissociate from lactate and lower intracellular pH, which impairs glycolytic enzyme activity, ATP production (Kraemer et al. 1987; Cairns 2006), and performance. Following a short bout of high-intensity exercise, PCr is nearly replenished within 3 – 5 minutes of rest (Harris et al. 1976; de Salles et al. 2009). However, during shorter, active recovery periods, the rate of PCr replenishment is diminished and may not be restored at the onset of the subsequent bout. The ability to sufficiently recover between repeated bouts of high-intensity exercise and maintain performance appears to be dependent on aerobic capacity (McLester et al. 2008). Possessing a greater aerobic capacity has been suggested to assist in anaerobic energy replenishment by providing aerobically derived energy at a faster rate, improving blood flow to active muscle, and enhancing the removal of lactate and hydrogen ions (Tomlin et al. 2001). Although evidence suggesting a relationship between aerobic fitness and CF performance is limited (Bellar et al. 2015), our data appears to support its potential role. More importantly, the importance of this role appears to increase (in a limited capacity) as the number of high-intensity bouts also increases. Here, we observed that a greater difference between recovery oxygen uptake during earlier and later trials was indicative of more repetitions during the 15-min AMRAP. Potentially, a 30-second maximal sprint on a cycle ergometer does not exceed the anaerobic capacity of advanced CF-athletes. Thus, more trials (or possibly, a longer maximal sprint) were necessary to adequately reflect this ability as it relates to CF performance.

The 15-min AMRAP completed in this study, though novel, could be classified as a high-intensity workout based on the participants' physiological responses. Briefly, the workout qualifies as "vigorous" based on previously established American College of Sports Medicine standards for the average HR response (85.9 ± 3.8% of HRmax) (American College of Sports Medicine 2017). The participants also completed 70.0 ± 25.8% of their rounds (within the 15-min AMRAP) at a respiratory exchange ratio that exceeded 1.0, which would suggest that energy production was primarily drawn from anaerobic energy pathways (Goedecke et al. 2000). Compared to previously reported outcomes following CF workouts, these results highlight the variability among CF-style workouts. For instance, Fernandez-Fernandez and colleagues (2015) reported greater HR responses to "Fran" (95.4 ± 3.0% HRmax) and "Cindy" (97.4 ± 2.4), though participants spent less time relying on anaerobic energy pathways during "Cindy" (47.7 ± 21.4%) and a similar amount of time during "Fran" (76.0 ± 29.7%). Likewise, Babiash (2013) reported responses to "Fran" in HR (~86 – 91% of HRmax) that were more similar to ours, as well as changes in blood lactate (8.5 – 11.0 $mmol \cdot L^{-1}$) (Babiash 2013). Comparable, but statistically different from each other, post-exercise levels of blood lactate have been reported following "Cindy" (11.8 ± 2.3 $mmol \cdot L^{-1}$), a 5-minute AMRAP of power cleans at 40% of one-repetition maximum (11.2 ± 2.6 $mmol \cdot L^{-1}$), or 8 sets of a "Tabata" circuit (i.e., 20-second AMRAP of double rope jumping separated by 10-seconds of rest) (10.2 ± 3.0 $mmol \cdot L^{-1}$). Given the differences in observed responses to similar workouts, and the variety of possible CF workout designs, it would be premature to make definitive conclusions based on our findings. Future investigations should assess the influence of repeated WAnT performance, in addition to aerobic capacity, to a greater variety of CF-style protocols in participants of varying levels of CF experience.

Advanced CF athletes can produce and maintain a large amount of power across four consecutive Wingate trials that are separated by 90 seconds of active rest. Between trials, their post-exercise oxygen consumption rises quickly (within 30 seconds), potentially to replenishing diminished ATP, but then quickly returns (within 60 seconds) to post-exercise rates. This would suggest that advanced CF athletes are able to sufficiently replenish energy within 60 seconds of a high-intensity bout of exercise. Further, this ability appears to be related to CF performance, which typically involves intermittent bouts of multi-modal exercise that vary between moderate and high intensity. Specifically, greater differences between oxygen uptake during earlier and later recovery periods, followed by a greater amount of total work completed during later trials, appear to be indicative of CF performance. Future studies are encouraged to test this specific hypothesis across a variety of CF-style workouts.

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Competing Interests:

Mr. Michael Giardina is currently employed by CrossFit, Inc. and serves as Course Supervisor for CrossFit seminars. This work was completed while he was a student at Kennesaw State University.

No other conflict of interest is reported by any of the authors.

Author Contributions:

The current study was conducted in the Exercise Physiology laboratory at Kennesaw State University, Kennesaw, GA. YF & MG contributed to conception and design of the work; YF, MG, SB, and GM contributed to the acquisition, analysis, or interpretation of data for the work; YF, MG, SB, and GM drafted the work and revised it critically for important intellectual content

All authors confirmed they have approved the final version of the manuscript; agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved, and that all persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

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Table 1: Anaerobic performance across four consecutive Wingate trials (Mean ± SD)

	WAnT 1	WAnT 2	WAnT 3	WAnT 4
Peak Power (W)	$1289 \pm 326_{bcd}$	$1169 \pm 329_{a}$	$1155 \pm 276_{a}$	$1127 \pm 294_{a}$
Men	1545 ± 230	1404 ± 285	1356 ± 217	1337 ± 228
Women	1016 ± 126	917 ± 118	940 ± 129	902 ± 158
Relative Peak Power ($W \cdot kg^{-1}$)	$16.3 \pm 2.5_{bcd}$	14.7 ± 2.3	14.6 ± 1.9	14.2 ± 1.9
Men	17.1 ± 2.6	15.5 ± 2.8	15.0 ± 2.2	14.7 ± 2.0
Women	15.4 ± 2.2	13.8 ± 1.3	14.2 ± 1.5	13.5 ± 1.5
Average Power (W)	$625 \pm 159_{bcd}$	$477 \pm 116_{acd}$	$422 \pm 101_{abd}$	$407 \pm 101_{abc}$
Men	759 ± 90	564 ± 92	490 ± 93	472 ± 95
Women	480 ± 47	384 ± 44	349 ± 38	336 ± 44
Relative Average Power ($W \cdot kg^{-1}$)	7.9 ± 1.0b$_{cd}$	$6.0 \pm 0.9_{acd}$	$5.4 \pm 0.9_{abd}$	$5.2 \pm 0.9_{abc}$
Men	8.4 ± 0.8	6.2 ± 1.0	5.4 ± 1.0	5.2 ± 1.0
Women	7.3 ± 0.7	5.8 ± 0.7	5.3 ± 0.7	5.1 ± 0.8
Fatigue Index (%)	$66.5 \pm 8.3_{bcd}$	$71.7 \pm 8.1_{acd}$	$76.7 \pm 8.9_{ab}$	$76.0 \pm 9.9_{ab}$
Men	66.2 ± 9.4	72.1 ± 10.2	78.7 ± 10.8	78.0 ± 11.6
Women	66.8 ± 7.2	71.3 ± 5.2	74.6 ± 6.0	73.8 ± 7.5
Total Work (kJ)	$18.6 \pm 4.7_{bcd}$	$14.2 \pm 3.5_{acd}$	$12.6 \pm 3.0_{abd}$	$12.1 \pm 3.0_{abc}$
Men	22.6 ± 2.7	16.8 ± 2.8	14.6 ± 2.8	14.1 ± 2.8
Women	14.3 ± 1.4	11.5 ± 1.3	10.4 ± 1.1	10.0 ± 1.3

[a] Significantly ($p < 0.05$) different from WAnT 1
[b] Significantly ($p < 0.05$) different from WAnT 2
[c] Significantly ($p < 0.05$) different from WAnT 3
[d] Significantly ($p < 0.05$) different from WAnT 4

Table 2. Physiological responses to 15-minute AMRAP in CF-trained athletes.

	Round 1 M=15; W=14	Round 2 M=15; W=14	Round 3 M=15; W=14	Round 4 M=15; W=14	Round 5 M=15; W=13	Round 6 M=10; W=6	Peak n = 29	Average n = 29	Recovery n = 29
HR (bpm)	148 ± 12	160 ± 10	167 ± 9	170 ± 10	172 ± 9	174 ± 7	175 ± 8	165 ± 8	148 ± 12
Men	146 ± 11	159 ± 10	168 ± 6	170 ± 9	172 ± 8	175 ± 5	176 ± 5	165 ± 5	150 ± 10
Women	150 ± 13	161 ± 10	166 ± 11	170 ± 11	172 ± 10	172 ± 11	174 ± 10	164 ± 10	146 ± 15
HRmax (%)	77.4 ± 5.9	83.6 ± 4.7	87.1 ± 4.4	88.7 ± 5.2	89.9 ± 4.8	90.6 ± 4.0	91.4 ± 3.9	85.9 ± 3.8	77.2 ± 6.5
Men	76.7 ± 5.8	83.5 ± 4.8	87.8 ± 3.3	88.8 ± 5.4	90.3 ± 5.1	91.4 ± 3.4	92.1 ± 3.1	86.1 ± 3.0	78.3 ± 5.3
Women	78.1 ± 6.2	83.8 ± 4.8	86.3 ± 5.4	88.5 ± 5.2	89.4 ± 4.5	89.3 ± 4.8	90.7 ± 4.5	85.7 ± 4.5	76.0 ± 7.5
VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	31.6 ± 3.4	38.5 ± 4.5	38.7 ± 4.9	38.1 ± 4.8	38.0 ± 4.7	39.4 ± 4.5	39.4 ± 4.5	36.9 ± 4.2	21.8 ± 2.9
Men	31.76 ± 3.6	39.7 ± 5.1	40.0 ± 5.2	39.3 ± 5.0	38.7 ± 5.2	39.6 ± 5.1	40.5 ± 4.9	37.8 ± 4.5	22.7 ± 3.3
Women	31.41 ± 3.2	37.2 ± 3.6	37.3 ± 4.2	36.7 ± 4.4	37.2 ± 4.0	39.1 ± 4.0	38.2 ± 3.9	36.0 ± 3.8	20.7 ± 1.9
RER	0.88 ± 0.09	1.06 ± 0.08	1.09 ± 0.08	1.09 ± 0.07	1.08 ± 0.08	1.09 ± 0.08	1.12 ± 0.07	1.05 ± 0.07	1.19 ± 0.08
Men	0.88 ± 0.08	1.07 ± 0.09	1.11 ± 0.08	1.10 ± 0.08	1.10 ± 0.09	1.10 ± 0.09	1.14 ± 0.08	1.06 ± 0.07	1.23 ± 0.07
Women	0.87 ± 0.11	1.06 ± 0.08	1.07 ± 0.07	1.07 ± 0.06	1.07 ± 0.06	1.08 ± 0.06	1.11 ± 0.06	1.03 ± 0.06	1.14 ± 0.07
Lactate ($mmol \cdot L^{-1}$)	5.40 ± 1.80	7.60 ± 2.20	9.40 ± 2.80	10.70 ± 2.90	11.90 ± 2.70	13.00 ± 2.30	11.57 ± 2.71	9.42 ± 2.27	11.52 ± 2.49
Men	5.50 ± 2.01	7.57 ± 1.97	9.32 ± 3.18	11.11 ± 2.86	12.47 ± 2.74	13.89 ± 2.23	12.29 ± 2.60	9.80 ± 2.36	12.57 ± 2.17
Women	5.34 ± 1.53	7.61 ± 2.60	9.54 ± 2.50	10.20 ± 2.87	11.16 ± 2.63	11.53 ± 1.69	10.79 ± 2.70	9.02 ± 2.18	10.39 ± 2.37

Note: HR = Heart Rate; HRmax = Maximum Heart Rate; RER = Respiratory Exchange Ratio; VO_2 = Volume of Oxygen

Table 3. Relationships between anaerobic performance measures across four consecutive Wingate trials and repetitions completed during a 15-min AMRAP (*r*, p-value).

	WAnT 1	WAnT 2	FR 1 - 2	DIF 1 - 2	WAnT 3	FR 1 - 3	DIF 1 - 3	WAnT 4	FR 1 - 4	DIF 1 - 4
PP (W)	0.29	0.26	-0.04	0.09	0.37*	0.03	0.01	0.32	0.01	0.01
RPP ($W \cdot kg^{-1}$)	0.10	0.10	-0.01	0.02	0.22	0.07	-0.06	0.18	0.06	-0.07
AP (W)	0.47*	0.63*	-0.02	0.02	0.72*	-0.01	0.02	0.72*	-0.01	0.01
RAP ($W \cdot kg^{-1}$)	0.47*	0.6*	0.15	-0.15	0.66*	0.14	-0.15	0.64*	0.15	-0.15
Fatigue Index (%)	-0.27	-0.42*	-0.14	0.09	-0.4*	-0.18	-0.11	-0.38*	-0.17	-0.06
Total Work (kJ)	0.47*	0.63*	-0.02	0.02	0.72*	-0.02	0.02	0.72*	-0.01	0.02
VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	0.22	0.44*	0.31	0.34	0.46*	0.22	0.14	0.55*	0.38*	-0.02
VO_2 at 30P ($ml \cdot kg^{-1} \cdot min^{-1}$)	0.56*	0.68*	0.59*	0.59*	0.64*	0.29	0.24	0.68*	0.35	0.24
VO_2 at 60P ($ml \cdot kg^{-1} \cdot min^{-1}$)	0.52*	0.52*	0.02	0.17	0.59*	0.07	0.14	0.64*	-0.10	0.26
RER	-0.13	-0.02	0.10	0.04	0.02	0.13	-0.04	0.02	0.13	-0.08
RER at 30P	-0.30	-0.4*	0.16	-0.25	-0.37*	0.22	-0.25	-0.30	0.25	-0.26
RER at 60P	-0.20	-0.15	0.18	-0.18	0.00	0.24	-0.22	0.23	0.32	-0.26
Heart Rate (bpm)	-0.35	-0.34	0.08	0.08	-0.41*	0.06	0.06	-0.35	0.09	0.16
Heart Rate at 30P (bpm)	-0.40*	-0.36	0.17	0.25	-0.33	0.23	0.21	-0.34	0.20	0.13
Heart Rate at 60P (bpm)	-0.41*	-0.38*	0.18	0.15	-0.30	0.31	0.28	-0.20	0.31	0.11
Blood Lactate ($mmol \cdot L^{-1}$)	0.15	0.13	-0.02	-0.02	0.18	0.01	0.03	0.38*	0.22	0.30

Note: AP = Average power; DIF = Difference between average and best trial; FR = Fatigue Rate; PP = Peak power; RAP = Relative average power; RER = Respiratory exchange ratio; RAP = Relative average power, WAnT = Wingate Anaerobic Test

* = Significant ($p < 0.05$) relationship with total repetitions completed during 15-minute acute exercise bout

Table 4. Predictive anaerobic performance measures of total repetitions completed during the 15-min AMRAP.

	R^2	R^2_{ADJ}	F	p-value	Total Repetitions =
One Trial					
Best Model	0.32	0.30	12.30	0.002	166.6 + (4.3 x VO_2 at 30P) ± 28.2
Two Trials					
Best Predictor	0.48	0.46	24.33	< 0.001	142.863 + (4.7 x VO_2 at 30P [WAnT 2]) ± 24.6
Best Model	0.64	0.61	22.36	< 0.001	155.2 + (25.5 x DIF VO_2 at 30P) + (21.4 x RAP [WAnT 2]) ± 20.9
Three Trials					
Best Predictor	0.53	0.51	29.16	< 0.001	209.0 + (0.008 x TW [WAnT 3]) ± 23.5
Best Model	0.74	0.69	15.97	< 0.001	143.0 + (0.005 x TW [WAnT 3]) + (3.1 x VO_2 at 30P [WAnT 3]) + (13.8 x DIF VO_2 at 60P) - (17.2 x DIF RAP) ± 18.7
Four Trials					
Best Predictor	0.54	0.52	29.94	< 0.001	211.3 + (0.008 x TW [WAnT 4]) ± 23.3
Best Model	0.64	0.614	22.49	< 0.001	118.3 + (0.006 x TW [WAnT 4]) + (5.8 x VO2 at 60P [WAnT 4]) ± 20.8

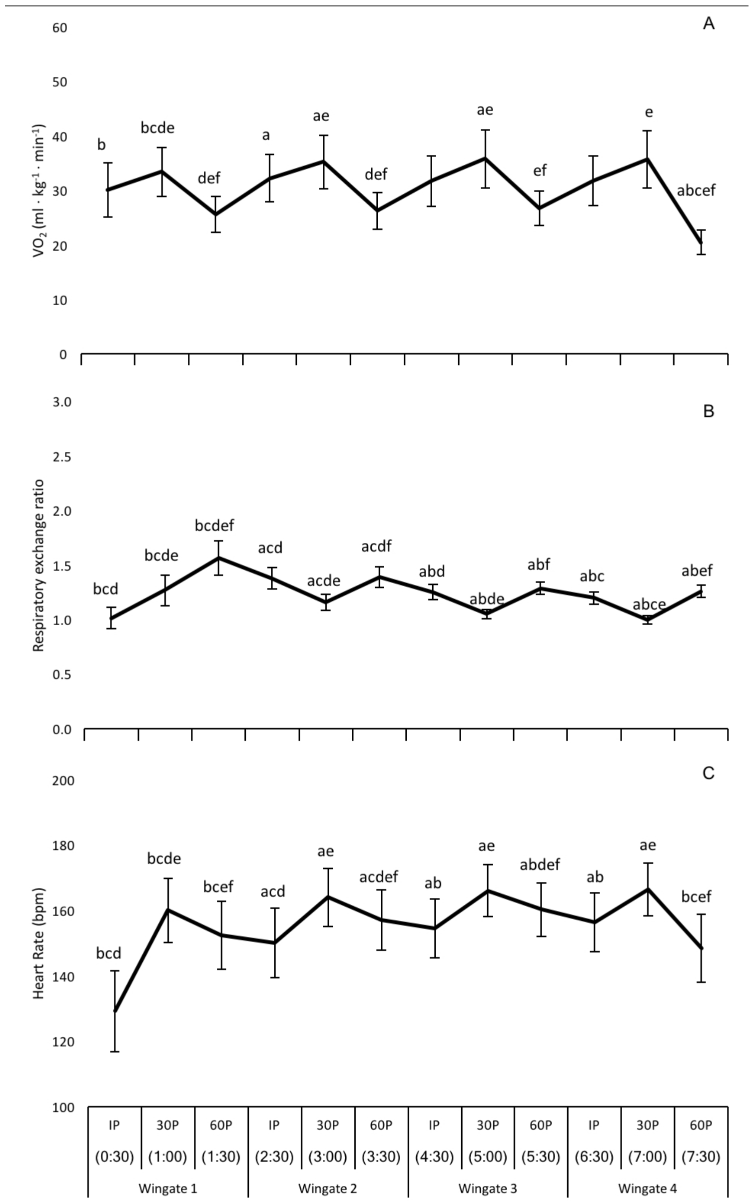
Figures

Figure 1. Configuration of Cosmed ($K4b^2$) device for each participant

Figure 2. Changes in (A) VO_2, (B) respiratory exchange ratio, and (C) heart rate across four consecutive Wingate trials.

$_a$ Significant difference from associated time point during WAnT 1
$_b$ Significant difference from associated time point during WAnT 2
$_c$ Significant difference from associated time point during WAnT 3
$_d$ Significant difference from associated time point during WAnT 4
$_e$ Significant difference from IP within respective WAnT trial
$_f$ Significant difference between 30P and 60P within respective WAnT trial

Configuration of Cosmed (K4b2) device for each participant



Changes in (A) VO2, (B) respiratory exchange ratio, and (C) heart rate across four consecutive Wingate trials.