6-2011

Why is there still so much confusion about VO2 plateau? A re-examination of the work of A.V. Hill

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To the Graduate Council:

I am submitting herewith a thesis written by Richard Vincent Castle entitled "Why is there still so much confusion about VO2 plateau? A re-examination of the work of A.V. Hill." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Kinesiology.

David R. Bassett, Jr., Major Professor

We have read this thesis and recommend its acceptance:

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Why is There Still So Much Confusion About VO_2 Plateau? A Re-examination of the Work of A.V. Hill

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Richie Vincent Castle

August 2011

DEDICATION

This work is dedicated to my mother who was on this earth 26 years of my life. You made me the person that I am today, and I have you to thank for so much of it. I will always love you and I know that you are watching me, proud of everything I am doing.

ACKNOWLEDGEMENTS

I would like to acknowledge my primary professor, Dr. David Bassett Jr., who both conceived this idea and in no small way made it happen. From his near infinite patience and willingness to let an inexperienced student pursue questions, to his genuine concern about the quality and well-being of his students, he has far exceeded my expectations as both a mentor and professor.

I would also like to acknowledge those who assisted in testing, especially Scott Conger. Through his flexibility and desire to help others made my thesis doable instead of impossible. He is also has the talent of criticizing others without ever making them feel inferior.

I have had the support of both this department and my committee through every portion of it. My experiences have been essential in framing a view of a learning environment where we are all pushed to help each other succeed, and in return expect excellence. I want to acknowledge our department for instilling that value in me.

ABSTRACT

Maximal oxygen uptake (VO_{2max}) is regarded as the gold standard for assessing aerobic fitness. In 1923, A.V. Hill et al. proposed that VO_{2max} represents the maximal ability of the body to take in and consume O_2 during strenuous exercise. Recently, however, controversy has arisen over the issue of whether a leveling off, or "plateau" in VO_2 is necessary to verify attainment of VO_{2max}. **Purpose:** To compare two different VO_{2max} protocols and determine if both protocols show direct evidence of an upper limit on O_2 transport capacity. **Methods:** Nine runners (18-35 years old) completed a continuous graded exercise test (CGXT), followed by a discontinuous graded exercise test (DGXT). The CGXT consisted of gradually increasing treadmill running speed to the point of volitional exhaustion; the highest speed attained was labeled the peak treadmill speed. Over the next several days, participants ran at 80%, 90%, 100%, 105%, and 110% of peak treadmill speed for 10 minutes, or until volitional exhaustion was reached. **Results:** All participants (n=9) achieved a "VO_2 ceiling" (or upper limit) on the DGXT, while only 44% (n=4) achieved a "VO_2 plateau" on the CGXT. There was no significant difference between the VO_{2max} obtained from a CGXT (57.4 ± 2.6 $mL*kg^{-1}min^{-1}$) and DGXT (60.0 ± 3.1 $mL*kg^{-1}min^{-1}$). There was no difference between maximal oxygen uptake (VO_{2max}) measured at 90%, 100%, 105%, and 110% of PTV ($p>0.05$). However, the highest VO_2 recorded at 80% PTV was significantly lower than that recorded at all other velocities ($p<0.05$). **Conclusion:** The VO_2 ceiling effect on a DGXT is inherently different than the VO_2 plateau effect on a CGXT. In this study, a ceiling was always seen on the DGXT, but a plateau was not always seen on the CGXT.

PREFACE

"*Bernard of Chartres used to say that we are like dwarfs on the shoulders of giants, so that we can see more than they, and things at a greater distance, not by virtue of any sharpness of sight on our part, or any physical distinction, but because we are carried high and raised up by their giant size.*"

--John of Salisbury, 1159

TABLE OF CONTENTS

List of Figures

Chapter 1

Thesis Introduction

VO_{2max} is defined as the highest rate at which the body can take in and consume oxygen, measured during strenuous exercise [1]. VO_{2max} is widely accepted as a measure of aerobic fitness, and is linked to reduction in all-cause mortality and cardiovascular disease [2-4]. In addition, it is considered and important factor in athletic performance of middle- and long-distance events. The concept of maximal oxygen intake (VO_{2max}) can be traced back to the work of Hill and Lupton in 1923 [5]. In performing a discontinuous graded exercise test (DGXT), Hill and Lupton made several key observations that formed the Hill and Lupton VO_{2max} paradigm, which is still considered to be valid by most researchers.

The central tenets of the Hill and Lupton paradigm are as follows [6]:

1. There is an upper limit to oxygen intake
2. There are inter-individual differences in VO_{2max}
3. A high VO_{2max} is a pre-requisite for successful distance running
4. VO_{2max} is primarily limited by the circulatory and/or respiratory system

Attainment of VO_{2max} must be confirmed by criteria established through rigorous research. Among those criteria is the VO_2 plateau. A VO_2 plateau signifies that, beyond a certain point, further increases in work rate fail to elicit further increases in VO_2. The VO_2 plateau has been cited as a criterion for attaining VO_{2max} during a continuous graded exercise test (CGXT), by

several authors [7-17]. However, Day et al. [10] have shown that the lack of a VO_2 plateau on a CGXT does not necessarily invalidate a VO_{2max} test. In their study, Day et al. found that participants lacking a VO_2 plateau had an equal VO_{2max} when validated with a supramaximal test.

According to Noakes [18] , the presence of a VO_2 plateau during a CGXT is essential to demonstrate an upper limit to oxygen intake. A plateau represents evidence that the upper limit to the oxygen intake has been reached. Because of the low prevalence of plateau during a CGXT, Noakes has questioned the entire VO_{2max} paradigm [18-32] set forth by Hill and Lupton [5]. He has maintained that, "…it is now established beyond doubt that the 'plateau phenomenon' is not a prerequisite for the identification of the 'true VO_{2max}' in a majority of (but not all) subjects…we must now conclude that, according to the Hill model, the achievement of a 'limiting' cardiac output causing skeletal muscle anaerobiosis cannot be the exclusive reason why all subjects terminate maximal exercise. The prediction of the Hill model allow no other conclusion" [23], In more recent years, Noakes has acknowledged that VO_{2max} exists, but he claims that it is limited by a "central governor" in the central nervous system, which limits the recruitment of skeletal muscles at high work rates [19, 22-32].

We believe that part of the confusion over the VO_2 plateau phenomenon results from the fact that the work Hill and Lupton [5]was based upon DGXTs, but most researchers today use CGXTs. The origin of the term "plateau" probably originated from Taylor et al. [33] who also used a DGXT protocol, but their results are not applicable to CGXT protocols. As modern

treadmills and metabolic measurement carts became available, researchers switched to using CGXTs, without rigorously examining whether the VO_2 plateau concept still applied.

By closely mirroring Hill and Lupton's protocol, we sought to determine whether taking runners to higher speeds than those achieved at the end of a CGXT would yield further increases in VO_2. There were 3 hypotheses in this study:

1. There is not a statistically significant difference between VO_{2max} values achieved on a CGXT and DGXT protocol.
2. Having subjects run at supramaximal speeds does not result in further increases in VO_2, beyond those seen at the end of a CGXT.
3. All participants display a VO_2 "ceiling" (or upper limit) on a DGXT, but not all participants display a plateau on a CGXT.

Chapter 2

Review of Literature

VO_{2max}: Determinants and testing criteria

Maximal oxygen uptake is considered the "gold standard" for measuring cardiovascular fitness [34-35]. VO_{2max} is a major determinant of performance in any aerobic endurance activity [36-39]. In addition, prospective observational studies demonstrate that high levels of VO_{2max} are associated with lower rates of cardiovascular disease and all cause mortality [2-3, 40-43]. There is individual variance in cardiovascular fitness with clinical populations of individuals with cardiovascular, metabolic, and pulmonary disease having the lowest values, and elite endurance athletes having the highest values. In the sections that follow, the physiological determinants of VO_{2max} will be discussed, as well as the various methods for measuring VO_{2max}.

VO_{2max} is the product of maximal cardiac output and arteriovenous oxygen difference [1]. Alterations in either of these variables will be associated with alterations in VO_{2max}. The next section will discuss the physiological variables associated with these features.

Pulmonary Features

In healthy individuals, the pulmonary system typically does not limit VO_{2max}. As predicted by Hill et al. [44], desaturation of arterial blood fails to occur during strenuous

exercise based on the observation that the subjects have ”never, even in the severest exercise, shown any signs of cyanosis”, but also states that it would be dangerous to assume that arterial desaturation never occurs during strenuous exercise, as it could occur in those with high maximum cardiac output, due to the rapid movement of blood through pulmonary capillaries.

Though not confirmed by Hill himself, other researchers have found conditions that can cause arterial desaturation and limit VO_{2max} in healthy populations. Powers et al. [45] showed that elite athletes (VO_{2max} mean = 70.1 $ml*kg^{-1}*min^{-1}$) experienced significantly greater arterial desaturation during maximal exercise compared to the recreational athletes (VO_{2max} mean = 56.5 $ml*kg^{-1}*min^{-1}$). This arterial desaturation can be remedied with hyperoxic conditions (26% inspired O_2 gas concentration), resulting in a significant increase of VO_{2max} (6.7%) when compared to normoxic (21% inspired O_2 gas concentration) conditions. Unlike the elite athletes, the recreational athletes showed no difference in VO_{2max} or O_2 saturation between hyperoxic and normoxic conditions.

Dempsey et al. [46] also showed that elite athletes are more likely to undergo arterial desaturation during maximal work, compared to individuals with normal fitness. Given the large difference in cardiac output between these two populations (40 vs. 25 $L*min^{-1}$), Dempsey et al. hypothesized the decreased time for diffusion of atmospheric oxygen to venous blood may be too short to allow an equilibrium to be established between the PO_2 in the alveoli and the pulmonary capillary blood. Thus, arterial desaturation occurs and this limits the VO_{2max} of elite athletes.

In addition, high altitude is known to decrease arterial concentration, and thus VO_{2max}. Due to the decreased atmospheric PO_2 at high elevations, the oxygen gradient that drives diffusion of O_2 from the alveoli into the pulmonary capillaries is reduced. Cymerman et al. [47] showed a decreased arterial saturation and greatly decreased VO_{2max}, as a result of a decrease in arterial oxygen content.

Aside from elite athletes and high altitudes, pulmonary features play little to no part in limitations of VO_{2max} in healthy populations.

Cardiac Output

Cardiac output refers to the rate at which the heart pumps blood through the body (i.e. the systemic circulation). Maximal cardiac output is a central factor affecting VO_{2max}; it is equal to the product of heart rate and stroke volume. Cardiac output has been proven to be a limiting factor of VO_{2max} [1, 35, 48].

During maximal exercise, approximately 80-90% of arterial blood is re-directed to the working muscles [1]. In a study by Andersen and Saltin [48], , the quadriceps muscle group was isolated and exercised at work rates ranging from 10W to 60W . By cuffing the quadriceps just below the knee and measuring changes in the circumference of the quadriceps upon releasing the cuff, the researchers were able to determine blood flow to the quadriceps during exercise. The results showed that mean muscle VO_{2peak} was 0.8 L/min for 2.3 kg of mass in the quadriceps. This calculates to a relative VO_2 of 347 ml*kg of active muscle^{-1}*min^{-1}, which far

exceeds the muscle's rate of oxygen uptake during maximal, whole body exercise. This suggests that blood flow to exercising skeletal muscle is limited by the finite amount of cardiac output, which is not an issue during exercise of isolated muscle groups.

Saltin [35] measured VO_{2max} during various exercises, including cycling, running, arm cranking, and cycling plus arm cranking. Seven subjects completed a DGXT to measure VO_{2max} using VO_2 measurements over 60 seconds. Cycling alone and cycling plus arm ergometry yielded a VO_{2max} of 4.23 and 4.24 L/min of O_2, respectively (p=0. 50). However, there was a significant difference ($p<0.001$) between the VO_{2max} of arm cranking alone (3.27 L/min) and cycling alone (4.66 L/min) in the 3 subjects that completed both these exercises. Combining arm-and-leg cycling failed to increase the VO_2 to amounts equal to the sum of the VO_2 of both activities. Thus, increasing the amount of muscle mass used (beyond a certain point) does not increase VO_{2max} for that exercise, suggesting that a central factor, not the amount of muscle mass recruited, limits VO_{2max}.

Saltin [49] demonstrated the limitations of cardiac output when comparing blood flow of single leg knee extensions versus two-legged cycling in nine healthy men. Saltin used the method previously described [48] to measure blood flow to a limb cuffing the leg just below the knee. During single-leg knee extensions, a work rate of 45 to 75 watts was maintained for 10 minutes, and no leveling off of whole body oxygen uptake could be detected with an increase of work rate. In a representative subject, the cardiac output during single-leg knee extensions was about 12 L/min, and 25 mL*kg of active muscle $^{-1}$*min^{-1}, while the cardiac output during two-legged bicycling was 20 L/min and about 8 mL*kg of active muscle $^{-1}$*min^{-1}. This

corresponds to a 67% increase in cardiac output with a 70% decrease in the cardiac output per kg of working muscle. In addition, doubling the muscle mass used from single-leg knee extensions to two-legged bicycling caused a 67% increase in VO_2 rather than a 100% increase. This strongly suggests that VO_{2max} is limited by the maximal cardiac output.

In 1977, Secher et al. [50] performed testing examining the effects of adding arm to leg exercises. Seven young male subjects were recruited. Subjects performed two, 20-minute bouts of exercise separated by an hour of rest. Each bout began with 10 minutes of either arm exercise (38-62% of VO_{2max} for arm exercise) or leg exercise (58-78% of VO_{2max} for leg exercise) and ended with 10 minutes of arm plus leg exercise (71-83% of VO_{2max} for arm plus leg exercise). The results showed that adding sufficient arm exercise (accounting for 40% of VO_2 for combined exercise) to leg exercise caused a reduction in blood blow without a change in mean arterial blood pressure, while adding leg exercise to arm exercise decreased mean arterial blood pressure. The authors concluded that oxygen supply to a large muscle group is limited by vasoconstriction, when another large muscle group is exercising simultaneously. If the amount of exercising muscle mass increases, vasoconstriction will occur to allow redirection of the limited cardiac output of the body.

Maximal cardiac output is affected by maximal heart rate, left ventricular dimensions, and blood volume. These factors are discussed in detail below.

Maximal Heart Rate

Maximal heart rate is affected by age and genetic factors, more so than training [1]. Two Fitness tests on 31 male and 35 female subjects administered 20 years apart showed a reduction in VO_{2max} by 20% and a reduction in maximal heart rate by 12-15 beats with great individual variability [51], linking age-reduced VO_{2max} with decreased maximal heart rate.

A 1984 study by Ades et al. [52] examined the effect of large and small doses of both pindolol and propranolol (β-adrenergic blocking drugs) on treadmill exercise. Compared to placebo, all drugs decreased exercise duration ($p<0.001$), but the drug or drug dosage did not make a difference in reducing the exercise duration. Though the differences in heart rate and blood pressure varied with dosage for each drug, both showed an increase in the rate-pressure product, indicating a compensation for lower maximal heart rate via increased stroke volume.

Joyner et al. [16] examined the effects of beta-blockade in 11 trained (VO_{2max} of 63.3 $mL*kg^{-1}*min^{-1}$) and 11 untrained (VO_{2max} of 44.5 $mL*kg^{-1}*min^{-1}$) male subjects. The subjects performed two walking treadmill tests to exhaustion prior to any treatment. Subjects were administered a placebo, propanolol, or atenolol for 1 week then tested using the same treadmill protocol. All subjects were tested under all three treatments. Both the trained and untrained individuals experienced a significant decrease in VO_{2max} with beta-blockade compared to placebo. Trained individuals decreased from 63.3 $mL*kg^{-1}*min^{-1}$(placebo) to 59.3 $mL*kg^{-1}*min^{-1}$ (atenolol) or 56.2 $mL*kg^{-1}*min^{-1}$ (propanolol). They also experienced a significant reduction in maximum heart rate from 184 bpm (placebo) to 150 bpm (atenolol) or 143 bpm

(propanolol). These results were mirrored in the untrained group. They experienced a significant decrease in VO_{2max} from 44.5 (placebo) to 42.6 (atenolol) or 41.6 (propanolol), and a significant reduction in maximum heart rate from 197 bpm (placebo) to 149 bpm (atenolol) or 144 bpm (propanolol). The significant drop in maximum heart rate was accompanied by a lower, but still significant, drop in VO_{2max}.

In a review by Tesch [53], administration of beta-blockers in patients, healthy and trained subjects causes a 30-35% reduction in maximal heart rate, 5 to 15% reduction in VO_{2max} and an increase in maximal stroke volume. The decrease in maximal heart rate will affect VO_{2max}, but the relative decrease in VO_{2max} will be less than the relative decrease in maximal heart rate. Thus, acute reductions in maximal heart rate in an individual, due to pharmacological treatment, will cause reductions in VO_{2max}.

Administration of beta-blockade is shown to reduce VO_{2max} by reducing maximum heart rate. This shows that central factors—specifically maximal heart rate—have direct effects on VO_{2max}. The reduction of VO_{2max} from these studies is usually less than the magnitude of the reduction in maximum heart rate, suggesting a compensatory increase in stroke volume.

Left Ventricle Dimensions

Blomqvist and Saltin [54] reviewed several articles showing a correlation between high levels of VO_{2max} and increased heart size and volume. Total heart size was not correlated with

VO_{2max}, but left ventricular volume (LVV) was correlated. Endurance athletes demonstrated a higher stroke volume to heart volume ratio than power-trained athletes [55].

During training, the left ventricle increases in thickness. Ehsani et al. [56] used echocardiography to estimate left ventricle wall thickness in 8 competitive swimmers who underwent a 9-week training program. In the same study, they followed 6 runners who discontinued training for 3 weeks. The swimmers increased left ventricle end-diastolic dimension from 48.7 mm to 52.0 mm ($p<0.005$) and VO_{2max} from 52 to 60 $ml*kg^{-1}*min^{-1}$ ($p<0.005$) over the 9 weeks of training. The detrained running group decreased left ventricular end diastolic thickness from 51 mm to 46.3 mm and VO_{2max} from 62 $ml*kg^{-1}*min^{-1}$ to 57 $ml*kg^{-1}*min^{-1}$ over the 3 weeks of detraining.

The increased left ventricular volume after training allows the heart to maintain the same cardiac output at rest, with fewer beats per minute. Typically, endurance trained athletes often demonstrate sinus bradycardia (heart rate <60 beats/min) at rest. This increased efficiency also allows a person to maintain a work rate with a reduced heart rate response compared to the pre-trained state [57-58]. A study of 253 subjects showed a "minimal" decrease in resting heart rate (1.9 to 3.4 beats per minute) accompanying 20 weeks of endurance training [59]. However, a separate study showed that athletes in the peak of their training are more likely than a sedentary control group to exhibit resting sinus bradycardia [57]. This suggests that the increased left ventricular volume allows for a lower heart rate at rest.

Blood Volume and Blood Doping

Blood volume is shown to increase with endurance training. A review study done by Sawka et al. [60] analyzed 18 reports on the effects of endurance training on blood volume and found a 10% increase in blood, plasma, and erythrocyte volume within 30 days of endurance training. The same review showed significant correlation ($p<0.05$) between total blood volume and VO_{2max} ($r=0.65$ to $r=0.92$ depending on the study) [60].

A 1994 study by Davy et al. [17] examined if aging causes a decrease in total blood volume. Blood volume was measured in 7 young non-obese (24.7 years of age) and 7 older (66.1 years of age) men matched for body mass index and physical activity. Trained subjects were excluded due to a possible masking effect on blood volume. Younger adults were shown to have significantly more blood (6.2L vs. 4.7L), plasma (3.7L vs. 3.0L), and erythrocyte (2.5L vs. 1.8L) volume than older men. Younger men also had significantly higher VO_{2max} (48.7 vs. 32.4 $mL*kg^{-1}*min^{-1}$), suggesting a link between age-related changes in VO_{2max} with reduction in total blood volume.

Blood doping (the act of removing, storing, and then reinfusing blood), is shown to increase VO_{2max}. Glenhill's review [61-62] of several blood doping articles show that a reinfusion of 900 to 1350 mL of blood increases VO_{2max} by 4 to 9%, respectively , compared to control groups (injected with saline) that showed no increase. In the 1970s, Ekblom et al. [63] conducted the first study to show that blood doping increases VO_{2max}. They also showed that loss of 800 and 1200 mL of blood corresponded to a 13 and 18% drop in hemoglobin concentration and VO_{2max}, respectively. Upon re-infusing the blood (which had been frozen and

stored for a couple of months while the subjects produced new red blood cells), there was a 13% increase in hemoglobin concentration and 9% increase in VO_{2max}. Correlation between blood loss and VO_{2max} was r=0.97.

Arterio-venous oxygen difference

The arterio-venous oxygen difference refers to the difference in the oxygen content (ml of O_2 per 100 ml blood) between the arteries and veins. It is an indirect measure of oxygen extraction at the cellular level. In most people of normal fitness level, the arterial hemoglobin is almost completely saturated with oxygen, even during maximal exercise [64].

A study done by Ekblom et al. [65] measured arterio-venous oxygen difference in 7 college-age males before and after 16 weeks of endurance training. The training consisted of cross-country running 3 times a week that was: (a) dash (30-60 second sprint repeated 5-10 times with 2-3 minutes rest between each sprint), (b) interval (70-75% of maximum speed for 3-6 minutes with 3-4 minutes of rest between each run), or (c) distance running (45-75 minutes of continuous running). Arterial concentration was measured during maximal cycling (6-minute cycle to exhaustion) using two catheters placed into the antecubital vein. The results demonstrated an increase in their arterio-venous oxygen difference during maximal exercise, from 138 to 143 mL/liter and an increase of VO_{2max} from 3.12 L/min to 3.5 L/min. Though not as significant as other factors such as blood volume and maximal heart rate, an increase in arterio-venous oxygen difference has been linked to increases in training-induced VO_{2max}.

Capillary Density

Capillary density in the peripheral skeletal muscles affects VO_{2max} in several ways: it increases mean transit time for oxygen exchange in working muscles [49], and decreases peripheral resistance.

Tesch et al. [66] conducted a study in 1984 showing that endurance athletes demonstrate increased capillary density. Taking muscle tissue samples from 8 elite weight/power lifters, 8 endurance athletes, and 8 non-athletes, myofrillar ATPase, NADH-tetrazolium reductase, and amylase-periodic acid-Schiff were used to determine fiber type distribution and capillary density. The number of capillaries per mm^2 of muscle fiber in untrained individuals (306 capillaries per mm^2) was significantly greater than power/weight lifters (199 capillaries per mm^2) and significantly lower than endurance athletes (401 capillaries per mm^2). This was the first study linking endurance training to increased capillary density.

Brodal et al. [67] took muscle biopsies from the lateral part of the quadriceps in 12 untrained (VO_{2max} of 72.0 $mL*kg^{-1}*min^{-1}$) and 11 untrained (VO_{2max} of 51.3 $mL*kg^{-1}*min^{-1}$) young men and examined capillary density using ATPase staining. Compared to untrained men, the trained men had significantly more capillaries per mm^2 (821 vs. 585) and capillaries per fiber (2.49 vs. 1.77).

Ingjer and Brodal [68] examined the capillary density of the quadriceps femoris in 11 young women. Five were endurance trained (62.1 $ml*kg^{-1}*min^{-1}$) and 6 were untrained (43.9 $ml*kg^{-1}*min^{-1}$). The endurance trained athletes had significantly higher capillaries per fiber ratio

(1.69 vs. 1.11) and greater capillaries per mm^2 (404 vs. 301) compared to the untrained group. This provides a link between capillary density and VO_{2max} that exists in females, as well as males.

Andersen and Henriksson [69] showed that endurance training increases capillary density. Taking 5 subjects, and training them on a cycle ergometer for 40 minutes a day at 80% of VO_{2max} for 8 weeks, Andersen and Henriksson measured capillary density and muscle fiber composition before and after training using amylase-PAS method and myofribrillary ATPase. A 16% increase in VO_{2max} (49.0 to 56.6 $mL*kg^{-1}*min^{-1}$) was accompanied by a 20% increase in capillaries per mm^2 (329 to 395), which was increased across type I, type IIa, and type IIb fibers. Capillary density is related to the VO_{2max} increase caused by training.

In his J.B. Wolffe lecture in 1986 [70], Dempsey noted that these capillary density adaptations exceed the adaptations of the lung capillary density during training. Training-induced increases capillary density in skeletal muscle increases the total cross-sectional surface area of the capillaries, allowing more blood to interact with the mitochondria, and allowing the muscles to maintain sufficient arterio-venous oxygen difference even at high rates of blood flow.

Skeletal Muscle Respiratory Capacity

Training increases both the mitochondrial density and concentration of mitochondrial enzymes [71]. Endurance training studies show that an increase in VO_{2max} is generally coupled

with increases in succinate dehydrogenase (SDH), phosphofructokinase [72], lactate dehydrogenase, monocarboxylate transporters (MCT) 1 and 4 [73], and mitochondrial density [74]. Although not as important as cardiac output in determining the VO_{2max}, the increased enzyme activity increases the rate of oxygen utilization within the cell and helps to create the oxygen pressure gradient between pulmonary capillary blood and the mitochondria necessary to maintain arterio-venous oxygen difference.

Although mitochondrial density is associated with increased fitness, a 2.2 fold increase of these mitochondrial enzymes is normally associated with a 20 to 40% increase in VO_{2max} [75]. Holloszy and Coyle have reinforced this by showing that individuals with identical VO_{2max} will actually show two-fold differences in mitochondrial density [76-77]. Despite that possibility that skeletal muscle respiratory factors do not affect VO_{2max}, Holloszy and Coyle [76] observed in a study of runners done by Costill [78] that the succinate dehydrogenase levels of elite runners were 2.5 times greater than untrained controls.

Saltin et al. [79] demonstrated the effects of peripheral limitations on VO_{2max}. Thirteen male participants completed 4 to 5 training sessions per week over 4 weeks of training. Each leg was trained differently. One leg was always trained for sprint or endurance, and the other leg was trained oppositely or not at all. Muscle samples of the quadriceps were sampled before and after training and assayed for SDH and myofibrillar ATPase. Compared to baseline, VO_{2peak} tests on the trained leg demonstrated a 27% increase in VO_{2max} while the untrained leg demonstrated a 7% increase in VO_{2max}. In addition, SDH activity increased in trained legs compared to untrained leg, and lactate was “only continuously released from the [untrained]

leg". The authors concluded that training increases local adaptations that affect the metabolic response to exercise.

Klausen et al. [80] examined the effects of 8 weeks of single-leg cycle ergometer training on maximal single-leg and double leg fitness. Six healthy young males showed a 19% VO_{2max} increase in single-leg exercise and an 11% increase in double leg testing. In addition, heart rate during submaximal single-leg exercise dropped 11% while it dropped 2% during submaximal two-leg exercise. This implies that specificity of training can affect both the VO_{2max} and cardiac adaptations to training.

Protocols for measurement of maximal oxygen uptake

Discontinuous vs. Continuous Protocols

Graded exercise tests (GXT) can be classified as either continuous (CGXT) or discontinuous (DGXT). CGXT are more commonly used today [9-10, 12-14], while DGXT were more common in VO_{2max} studies done in the 1950s and 1960s [5, 33, 81-84].

A DGXT consists of working at a constant load (e.g. running at a single speed or cycling at a fixed wattage) until steady-state VO_2 (or an "apparent steady state" - i.e. leveling off of VO_2 at a supra-maximal work rate) is achieved. That steady state value is the VO_2 for that workload. Constant load tests are repeated until the subject fails to show an increase in VO_2 with an increase in workload (referenced as a plateau, which will be discussed later)[5, 33, 75, 79, 85], or failed to complete the workload for a duration [33]. The highest VO_2 achieved is considered

the VO_{2max}. This protocol typically requires the subject to repeat multiple tests separated by rest, usually a day or more in length.

A CGXT consists of a single continuous test. In it, the work rate or exercise intensity is gradually increased (usually at 1-minute intervals) until the participant reaches volitional exhaustion. The highest VO_2 achieved during any 15-, 30-, or 60-s period is termed the VO_{2max}. The test usually lasts between 8 and 20 minutes, from start to finish.

Validity of CGXT compared to DGXT

Studies show that DGXT and CGXT yielded equally valid VO_{2max} measurements [86-91]. Stamford [86] studied VO_{2max} values of 10 males subjects using various DGXT and CGXT treadmill tests. Each participant was administered a DGXT, 2 CGXTs (test-retest), and 2 constant load tests. The DGXT was performed first to establish a maximal work rate. The DGXT consisted of running 7.0 mph for 3 minutes, resting 10 minutes, and then increasing the treadmill incline by 2.5% for each successive 3 minute run. The test was completed when subject could not complete the 3 minute run. Both CGXT were identical to the DGXT, but the stages were 2 minutes instead of 3 and there was no rest between the bouts. The constant load tests were run at the speed and peak incline from the DGXT, and 2.5% increased incline. The results of each test yielded VO_{2max} of 50.14 (DGXT), 49.58 (best of either CGXT), 49.30 (constant load at peak incline), and 49.41 (constant load at peak incline plus 2.5%) $ml*kg^{-1}*min^{-1}$ ($p>0.05$). Even

with the variance in protocol and supramaximal intensity, all protocols yielded equal VO_{2max} results.

Shephard et al. [87] studied 24 Canadian males varying greatly in fitness (VO_{2max} 30 to 65 ml*kg^{-1}*min^{-1}) across CGXT and DGXT in treadmill, bicycle, and step modes of exercise administered in a randomized order. The treadmill exercise consisted of running uphill at speed of 5 to 6 mph and slopes of 1% to 18%. Bicycle ergometer exercise was performed at 60 to 90 revolutions per minute with varying workloads. Step mode exercise consisted of a single 18-inch step climbed with two paces at a rate of 80 to 140 paces per minute. The CGXT and DGXT were performed by predicting the participants work rate at VO_{2max} based on the physiological response of a respective submaximal work rate. DGXT was a constant load at 110% of predicted maximum work rate, and further bouts were adjusted in light of the participant's performance, while the CGXT was set at 90% to 100% of the predicted maximum work rate and increased slightly every 2 minutes. The VO_{2max} was not significantly different between CGXT (3.84 L/min) and DGXT (3.74 L/min), regardless of whether it was a treadmill, bicycle, or step exercise test.

Washburn and Seals [90] examined CGXT and DGXT in arm cranking in 20 males subjects. The CGXT portion increased power every minute, while the DGXT increased power every two minutes with one minute of rest. Initial power and power increases were identical between the DGXT and CGXT. The initial power for arm cranking was estimated from the assumption that the VO_{2peak} of arm cranking is equivalent to 60% of the participant's treadmill VO_{2max}, and the participant would reach VO_{2max} by the fifth stage. Order of days was randomized, and no significant differences were found between the VO_{2peak} in the CGXT (33.8

ml/kg/min) and DGXT (34.2 ml/kg/min). DGXT and CGXT yield equivalent VO_{2peak} in arm cranking as well.

More recent studies have verified this finding. Duncan et al. [11] compared the VO_{2max} values from a the DGXT protocol used by Taylor et al. [33], and the CGXT protocol used by Stamford [86]. In the 10 males subjects tested, the VO_{2max} of the DGXT (56.8 $mL*kg^{-1}*min^{-1}$) was not significantly different from the CGXT (55.8 $mL*kg^{-1}*min^{-1}$). These results concur with Stamford [86].

Day et al. [10] performed a cycling CGXT on 71 participants. The protocol consisted of pedaling at 20W with an increase of 5W every 20, 15, or 12 seconds until the participant could not maintain a cadence of 60 revolutions per minute. Day et al. then followed up with 6 of the participants to perform a DGXT at varying supramaximal and maximal loads. Results showed that the VO_{2max} of the CGXT (4.50 L/min) did not vary significantly from the DGXT (4.51 L/min).

Rossiter et al. [12] performed a cycling CGXT on 7 subjects followed by a 5-minute recovery at 20W, and then a constant load cycling bout at 95% or 105% of their peak work rate during the CGXT. The following constant load bout was similar to the bout of a DGXT that would be near or at VO_{2max}. The results showed no significant difference between the VO_{2max} of the CGXT (4.3 L/min), the 105% of peak work rate bout (4.3 L/min) and the 95% of peak work rate bout (4.1 L/min).

The validity of VO_{2max} measurements between a DGXT and CGXT equally valid.

Various Exercise Modes

Research has shown that measured VO_{2max} is affected by the amount of muscle mass recruited during exercise. For this reason, various exercise modes will yield different VO_{2max} values, depending on the amount muscle mass being used. Taylor et al. [33] showed that VO_{2max} derived from a treadmill VO_{2max} test increased from 4.0 to 4.2 L/min when arm ergometry was added.

McArdle et al. [92] tested 15 male students across several different exercise tests. They performed a treadmill and cycling CGXT; treadmill and cycling DGXT; Mitchell, Sproule and Chapman treadmill test; and a Balke treadmill test. They found that Balke, CGXT, and DGXT treadmill protocols yielded a VO_{2max} that was 10-11% higher ($p<0.01$) than a cycling protocol, with no significant difference between the DGXT and CGXT cycling VO_{2max} values.

Hermansen and Saltin [93] conducted a study that supported the findings of McArdle et al. [92]. They tested 55 male subjects ranging from 18 to 68 years of age. The participants completed a bicycling DGXT based on Astrand and Saltin's [81] protocol and a treadmill DGXT based on Taylor et al.'s protocol [33]. The resulting VO_{2max} values for bicycling, level treadmill running, and incline treadmill running were 4.34, 4.48, and 4.68 L/min ($p<0.01$ compared to bicycling), respectively. They concluded that inclined running yields a higher VO_{2max} than bicycling due to the usage of more muscle during exercise.

Astrand and Saltin [82] compared VO_{2max} in various exercises (sitting cycling, supine cycling, simultaneous leg and arm work, running on a treadmill, skiing, swimming, and arm

work) in seven subjects. VO_{2max} was 15% lower in seated cycling compared to supine cycling, and 30% lower in arm ergometry than in cycling. Thus, the greater the difference in muscle mass recruitment, the greater the differences in measured VO_{2max}. In addition, even if the working muscle mass is equivalent, the method of work may affect $VO_{2max,}$ as demonstrated by the difference between seated and supine cycling.

Buchfuhrer et al. [94] tested 12 "normal men" by administering a cycling and treadmill CGXT, and found that VO_{2max} values measured on treadmill running were 6% higher compared to cycling. Bergh et al. [95] had 10 males perform VO_{2max} tests with cycling, cycling plus arm cranking, and treadmill running. Running yielded the highest VO_{2max} (4.44 L/min) which was significantly greater than cycling (4.12 L/min), but not significantly greater than cycling plus arm cranking (4.40 L/min). These were all significantly greater than arm cranking alone (VO_{2max} of 3.01 L/min). They concluded that VO_{2max} relies on the exercising muscle mass to a certain extent.

However, there are certain exceptions to the fact that running yields higher VO_{2max} than cycling. If an athlete is particularly well trained in one exercise mode, he or she can achieve relatively high VO_{2max} (compared to other modes) despite differences in muscle mass usage. For example, Stromme et al. [96] took 37 athletes (24 cross country skiers, 8 rowers, and 5 cyclists) and administered VO_{2max} tests using both their respective sport and treadmill incline protocol. The 5 cyclists achieved a VO_{2max} on the cycle test that was about 5-10% higher than uphill running. All other athletes achieved VO_{2max} in their respective sport that was higher than during

uphill running, ranging from 2.5 to 6.0% higher. The cycling result contrasts with previous studies showing that running elicits a VO_{2max} value that is 10% higher than cycling.

Magel et al. [97] trained 15 college-age male recreational swimmers in swimming for 10 weeks. Training consisted of 1 hour of practice 3 days per week. The first week was one set of ten 50-yard swims and five 100-yard swims. After the second week, 200- and 300-yard swims at maximum speed were added. After the fourth week, 300, 400, and 500 yard swims were added increasing the volume from750 yards to 2000 yards over the course of the training. Prior to the training, the participants completed treadmill (VO_{2max} of 4.05 L/min) and swimming (VO_{2max} of 3.44 L/min) VO_{2max} tests. After training, their VO_{2max} from the swimming test (3.82 L/min) increased significantly, but their VO_{2max} on the treadmill test (4.11 L/min) did not. By training specifically for swimming, the participants' VO_{2max} during swimming became relatively higher, and therefore VO_{2max} measurements would vary depending on the training of the exercise mode being tested.

Pechar et al. [98] enrolled 60 college age men, and randomly assigned them to 8 weeks of bicycle ergometer training, 8 weeks of treadmill training, or a no-training control group. Before and after training, they administered cycling and treadmill VO_{2max} tests. The largest gains in cycle VO_{2max} were seen in the bicycle-trained group, and the largest gains in treadmill VO_{2max} were seen in the run-trained group. However, the bicycle-trained group showed significantly lower improvements in their treadmill VO_{2max} compared to their cycling VO_{2max}. This indicates that training for a specific activity will yield greater improvements in VO_{2max}, with that specific exercise mode. Again, training causes relative increases in the trained exercise mode with little

change to other exercise modes. Aside from the exercise mode itself, the amount of training in the mode will affect the measured VO_{2max}.

A 1974 study by Secher et al.[99] compared VO_{2max} of 16 subjects performing running, cycling, arm, leg, and combined arm plus leg work. The VO_{2max} for arm ergometry was on average 85% of the VO_{2max} achieved during leg exercise, while the VO_{2max} of arm-plus-leg exercise was 99% to 117% of the VO_{2max} achieved during leg exercise. The authors suggest that when two muscle groups are combined for exercise, the increase in oxygen uptake is proportional, but not equal to, the respiratory capacity of each muscle group individually. By increasing the amount of muscle used, the VO_{2max} of the test will increase.

In 1984, Nagle et al. [100] tested the relative contributions of the arms and legs in eliciting VO_{2max}. 10 healthy non-arm-trained males performed CGXTs for arm only, leg only, 10% arms/90% legs, 20% arms/80% legs, and 30% arms/70% legs. The results showed that 10% arms/90% legs elicited significantly greater VO_{2max} than 100% legs, 100% arms and 30% arms/70% legs. The authors concluded that the significantly lower VO_{2max} during exercise with the legs alone was caused by a reduction in the active muscle mass, while during 30% arms/70% legs, the cause of the lower VO_{2max} was excessive arm loading and insufficient leg loading. Depending on the distribution of work, VO_{2max} can be affected by the relative division of work between muscle groups.

Altering the amount of muscles used during an exercise will affect the VO_{2max}, with greater muscle usage yielding higher VO_{2max} (to a point). In addition, the specificity of training to certain exercise modes will affect the measured VO_{2max}.

Criteria for achieving maximal oxygen uptake

Because maximal exercise tests rely on the participant to voluntarily work to maximal effort, there is a need for objective criteria to validate VO_{2max} measurements. If a participant failed to give a maximal effort, the VO_{2max} measurements would be underestimated, and the results of that test would be invalid. Without proper criteria for validation, the results of a VO_{2max} test could actually be submaximal, and therefore, invalid.

VO_2 Plateau

The operational definition of a VO_2 plateau can be ambiguous, as Howley et al. [101] observed. The assumption is that at the final intensity of a CGXT, VO_2 will be identical to the stage before it, yielding a perfectly flat slope. However, this type of a "true plateau" does not usually occur. The final stage may demonstrate an increase in VO_2 ranging from no increase to the same increase as seen on the previous stage. As a result, one must choose a cut-point for the increase in VO_2 that will constitute a VO_2 plateau. The criterion for VO_2 plateau was established in 1955 by Taylor et al. [33], and determined to be an increase less than 150 ml/min with an increase of 2.5% incline at 7 mph on a treadmill. Their reasoning was that the standard increase between stages was 300 ml/min, and they recognized that there is variability in VO_2 from minute-to-minute, and setting the plateau threshold at no VO_2 increase in the last stage

would not properly capture the phenomenon. Thus, a VO_2 plateau was operationally defined as being less than one-half of the expected increase.

Despite the VO_2 plateau criterion established by Taylor et al. [33], only 20-50% of VO_{2max} tests result in a plateau by this definition [7-15]. Thus, although it has been considered by some to be a primary criterion for achieving VO_{2max} [16-17, 102-103], the ACSM Guidelines for Exercise Testing and Prescription [104] does not recognize it as such.

This has led some investigators to use the term VO_{2peak} instead of VO_{2max} to describe the key outcome variable resulting from a maximal GXT. VO_{2peak} refers to the highest VO_2 attained during a graded exercise test, without regard to whether an individual achieves a plateau, or any of the secondary criteria for attainment of VO_{2max}. For example, most of the research on maximal exercise testing in children uses VO_{2peak} instead of VO_{2max}, due to the difficulty in showing evidence of a VO_2 plateau in children [105]. VO_{2peak} is also commonly used to describe the results of maximal GXTs using smaller muscle groups (e.g. arm cranking or one-legged cycling).

Blood lactate

Blood lactate is an indicator of relative exercise intensity. High levels of blood lactic acid are associated with recruitment of fast-twitch muscle fiber, elevation in plasma epinephrine concentrations, and reduction in liver blood flow [101].

Astrand [106] established a criterion value for blood lactic acid levels 3 minutes following a maximal GXT. Out of all of the participants in the study, roughly 50% of them demonstrated a VO_2 plateau. Of those who did, the onset of the plateau was correlated to 3 minutes post-exercise lactate concentrations of 7.4-8.4 mM, while the blood lactate values 3 minutes post-exercise for the whole test ranged from 6.7 to 10.1 mM. However, the participants in Astrand's study were children ranging from 14-18 years of age, and so the results can only be applied to that group.

Other investigators have used a blood lactate of 7.3 mM [107-108] or 5.5 mM [109]. Also, other researchers have demonstrated lower blood lactate values during maximal testing, however they also used a single supramaximal test [110] or a CGXT [111] compared to the DGXT used by Astrand [106]. The criterion for blood lactate concentrations should be set after considering both the test and population being studied.

Respiratory Exchange Ratio

Respiratory exchange ratio (RER) is the ratio of the carbon dioxide production to oxygen consumption, measured at the mouth. It is mathematically computed by dividing VO_2 /VCO_2. Although the body produces CO_2 as a result of metabolism, it is also produced by buffering hydrogen ions (produced by lactic acid) with bicarbonate anions, resulting in CO_2 and H_2O formation. Thus, RER can be used as an indirect measure of lactic acid accumulation, and this was confirmed by Wasserman et al. [112]. Issekutz et al. [107, 113] established RER ≥ 1.15 as a

criterion for achieving VO_{2max}. By following excess CO_2 and lactic acid concentrations pre to post exercise, they determined a linear relationship between the excess CO_2 and lactic acid concentrations [107]. Following up on this, Issekutz et al. [113] determined from a sample of 32 untrained subjects, all achieved a maximum RER of 1.15.

However, other research has shown that RER ≥ 1.15 is not achievable by everyone. Robinson [110] suggested that this criteria was reasonable for those aged 20 to 60 years, however younger participants could not achieve this RER. Cunningham et al. [111] showed that sixty-six, 10-year old hockey players could not achieve an RER >1.10 on a maximal treadmill exercise test. Sidney and Shephard [114] also demonstrated that men and women aged 60 to 83 who gave a "good effort" showed low prevalence of RER ≥ 1.15 (20% in women and 37% in men) during maximal treadmill GXT's. Though RER of 1.15 is an established criterion for attainment of VO_{2max} from previous studies, an RER of 1.10 would be more appropriate for general populations

Maximal Heart Rate

Maximal heart rate is predicted by the ACSM as 220 minus age in years [104]. This criterion is problematic because the standard deviation of this estimate is ±11 beats/min [115]. ACSM [104] suggests using it as a secondary criterion rather than a primary criterion for this reason.

Robergs and Landwehr [116] present the origins and subsequent basis of information for this age-predicted equation. One of the original works by Astrand et al. [106] measured heart rate during maximum exercise testing of 225 subjects (4 to 33 years of age), and found significant correlation (r=0.43), but also considerable variation (standard deviation = ±11 beats/min). The most common citation of age-predicted maximal heart rate is derived from Fox et al. [117], who estimated the equation from 35 data points and no regression. Fox et al. states:

"…no single line will adequately represent the data on the apparent decline of maximal heart rate with age. The formula maximum heart rate=220–age in years defines a line not far from many of the data points…" [117]

Tanaka et al. [118] conducted a meta-analysis of studies that have examined changes in maximal heart rate with age. They found that the ACSM equation (220-age) was accurate in the early decades (20 and 30), but it under-estimated maximal heart rate in older individuals. These variations were not affected by gender or training state. In fact, Robergs and Landwehr [116] examined the origins of the 220-age and determined that it was based more on subjective and anecdotal information rather than on rigorous research. Tanaka et al. [118] suggested 208 – 0.7*age in years as a more accurate estimate of heart rate based on age.

Rating of perceived exertion

Rating of perceived exertion (RPE) is a subjective measure of exercise intensity [1]. It was developed by Gunnar Borg, a Swedish psychophysiologist [119]. The scale takes into account personal fitness level, environmental conditions, and general fatigue levels [120]. Ratings of perceived exertion can be affected by psychological factors, mood states, environmental conditions, exercise modes, and age, which can reduce its practicality [121].

Based on ACSM guidelines [104], RPE must be standardized to minimize misinterpretation. The following paragraph should be read to the participant:

"During the exercise test we want you to pay close attention to how hard you feel the exercise work rate is. This feeling should reflect your total amount of exertion and fatigue, combining all sensations and feelings of physical stress, effort, and fatigue. Don't concern yourself with any one factor such as leg pain, shortness of breath or exercise intensity, but try to concentrate on your total, inner feelings of exertion; be as accurate as you can" [104]

Two RPE scales are commonly used today: the original category scale, which goes from 6 ("very, very light") to 20 ("very very hard"); and the revised or category ratio scale which goes from 0 ("Nothing at all") to 10 ("extremely strong"). A study of 28 healthy young adults showed that the Borg scale correlated closely (r=0.90) with VO_{2max} percentages and max heart rate percentages [122]. This data was repeated again at high workloads with equivalent success [123]. Typically, the criterion for RPE is >18 for original category scale, or >9 for the category ratio scale.

In summary, few of the criteria listed here can absolutely verify, beyond the shadow of a doubt, that a participant has attained VO_{2max}. Thus, over the past 5-10 years, exercise physiologists have begun to move away from using the aforementioned primary and secondary criteria. Presently, the only true method of verifying that VO_{2max} has been attained is to retest the person at a supramaximal work rate. Rossiter et al. [12] did precisely this by having subjects perform a CGXT on the cycle ergometer, allowing a short 5-minute recovery, then taking subjects to 105% of the peak work rate achieved during the CGXT. This verifies the attainment of VO_{2max} using the same principle as a VO_2 "ceiling" during a DGXT. Both of these show that further increases in work rate will not yield further increases in VO_2.

The VO_2 Plateau

Validity of the VO2 plateau concept

Despite the continued use of VO_2 plateau as a criterion for the attainment of VO_{2max}, several recent studies have shown that lack of VO_2 plateau prevalence does not invalidate a CGXT.

The low prevalence of VO_2 plateau in CGXT's is best shown in a study performed by Day et al. [10] . Seventy-one male subjects aged 19 to 61 performed a CGXT bike incremental ramp exercise test. The intensity was increased by 5W every 12, 15, or 20 seconds—depending on the fitness of the subject—to volitional exhaustion (unable to maintain cadence of ≥60 rpm).

After completing the CGXT, 38 of the 71 subjects completed a constant-load exercise at 90% of the peak work rate achieved in the CGXT. Then, 6 of the 38 subjects completed 5 more constant-load tests at varying submaximal, maximal, and supramaximal workloads. To test for the presence of a VO_2 plateau, a linear regression was fit to the "main portion" VO_2 response, which excluded the first 4 minutes and last 3 minutes. The first 4 minutes were excluded because the beginning of a CGXT demonstrates a steep increase of VO_2 from rest (called the fast portion), and including it in the VO_2 response creates an artificially high VO_2 increase. The last 3 minutes were considered the "tail portion" to appraise the VO_2 plateau.

A line of best fit was drawn for the main portion and extended through the tail portion. A VO_2 plateau was present if the tail portion deviated from the line of best fit enough to consider the tail portion significantly different than the main portion. The results showed that of the 71 participants, 12 individuals (17%) achieved a plateau, 40 individuals (56%) showed no linear variance, and 19 individuals (27%) showed an increase in VO_2 uptake. In addition, when 38 of the subjects performed a constant load test-to-exhaustion at 90% of the peak work load they showed a "ceiling" effect, in which their highest VO_2 did not exceed their VO_{2peak} from their cycling test.

Following up on this study Rossiter, et al. [12] again examined the validity of the VO_2 plateau. Seven male adults performed a CGXT cycle ergometry protocol (increase 20W/min) until exhaustion, recovered for 5 minutes at 20W, then performed a constant load test at 105% of the final work rate achieved in the ramp incremental protocol. By doing this, they tested whether the lack of a plateau in the CGXT would yield a difference in peak VO_2 between

constant load and ramp incremental tests. Despite the fact that none of the seven participants achieved a VO_2 plateau by methods previously described [10], VO_{2peak} was not significantly different between the CGXT and 105% constant load tests. The authors concluded that the presence of a plateau is not necessary to attain the VO_{2peak}, showing that a plateau is not necessary for reaching VO_{2max}.

Criticism by Noakes of the VO_2 plateau phenomenon and its implications

Since 1987, Timothy Noakes M.D. has been critical of the entire concept of VO_{2max} as it was understood by Hill and Lupton, citing the low prevalence of VO_2 plateau as a reason for this.

His book *Lore of Running* [20] has criticized both the foundation and concept of VO_{2max}.

"On the basis of certain assumptions that were probably incorrect [21], Hill and Lupton postulated that shortly before the individual reached maximum work capacity, or running speed, the rate of oxygen consumption reached a plateau and did not increase further. Although able to exercise a little harder the athlete took up no more oxygen. At this point the athlete was said to have reached maximum oxygen consumption…However, modern studies suggest that only approximately half of all tested subjects show true plateaus in oxygen consumption during maximal exercise; in the remainder no such plateaus are present, and the factors that determine these subjects' maximal exercise performances are presently unclear. I have suggest that factors related to muscle not the cardiovascular system (and thus not oxygen transport) limit the maximal exercise performance of these persons[21]…This would explain the observations by Lydiard and Gilmour [124] and Pirie [125] that the distance runners who are fastest over the shortest distances will also be the fastest at all longer distances, including the ultramarathon… Obviously, these ideas are quite heretical, and it will be some time before they are either proven to be incorrect or are accepted by the international community of exercise physiologists"

Since then, Noakes has continued to criticize the VO_{2max} paradigm of Hill and Lupton [5] in his scientific publications. His maximal exercise testing of 43 marathon and ultra-marathon runners showed that peak treadmill velocity predicted running performance better than VO2max [19], suggesting that VO_{2max} was irrelevant altogether in predicting performance. In 1996, Noakes delivered the J.B. Wolffe Memorial lecture [18], and again criticized Hill and Lupton's work:

"Hill and Lupton concluded that the constant VO2 they measured at the fastest running speed (16km/h in Fig. 1) represented an apparent, not a true, steady state. The basis for this conclusion was a circular argument based on Hill's subconscious model explaining fatigue during exercise (Fig. 2). For Hill began with the subliminal premise that fatigue during exercise is caused by an oxygen deficiency…Not only did Hill et al. [5] fail to measure concurrently either the oxygen debt or muscle or blood lactate levels during these subsequent studies, they also failed to subject their hypothesis to the accepted process of refutation. For the next logical study would have been to measure Hill's VO2 when he ran at a speed faster than 16km/h. Their hypothesis would have been supported if the VO2 at that higher speed was either the same or lower than that measured at 16 km/h"

Afterwards, Noakes entered into a debate concerning an article published by Bassett and Howley [6] titled, "Maximum oxygen uptake: 'classical' versus 'contemporary' viewpoints". In it, he continues to criticize the work of Hill and Lupton [22]. In 2008, he published two works that call into question both the work of Hill and Lupton, and the concept of VO_{2max} [23-24]. The articles titled "Testing for maximum oxygen consumption has produced a brainless model of human exercise performance" [24] and "How did A V Hill understand the VO_{2max} and the 'plateau phenomenon'? Still no clarity?" [23]

At this point, Noakes introduced a new theory to refute the A. V. Hill paradigm: the central governor theory (CGT) [23]. Previously he had argued that peak treadmill velocity (PTV)

predicted marathon performance better than VO_{2max}, and thus factors that affect PTV (including the percentage of type II muscle fibers) were the real determinants of VO_{2max}. If only an individual could run faster, Noakes argued, his VO_{2max} would go higher. In 2008, Noakes began to propose the CGT, which he claimed incorrectly had first been proposed by A.V. Hill. (In fact, he called it the Noakes-Hill theory.) The CGT states that aerobic performance is limited by the central nervous system's recruitment of skeletal muscle fibers, rather than by cardiac factors previously explained. The purpose of the central governor is to prevent ischemia of the heart during maximal exercise.

Again in 2008, Noakes published a letter to the editor of Medicine and Science in Sports and Exercise [25] proposing his CGT in response to a study showing that supramaximal tests yielded identical VO_{2max} values to a CGXT [126], Noakes stated that even at 130% of VO_{2max} the muscular forces generated and muscle fiber recruitment are less than those generated by a maximal voluntary contraction. Thus, he reasons, our performance is regulated by a "central governor" that limits motor unit recruitment, rather than by the maximal cardiac output. Although Noakes is correct in the assumption that forces generated during maximal volitional contraction are higher than those created at 100% of VO_{2max}, the primary fuel during a single contraction at 100% MVC is ATP/CP. This energy system is intrinsically different than the systems that are used during supra-maximal, high-intensity exercise at 110-150% VO_{2max}.

Later in 2008, Noakes published another letter to the editor of European Journal of Applied Physiology [29]. Noakes claims that the purpose of the central governor is not to protect the heart from ischemia (despite previously stating that was the reason for a central

governor). He then finished by saying, “The point of course is that the brain could always choose to continue the exercise bout by increasing the extent of muscle recruitment until 100% of all available motor units were active. But clearly it chooses not to adopt that strategy”. Noakes finished the year with another letter to the editor of European Journal of Applied Physiology [32] again describing his view of the central governor.

In 2009, the Journal of Applied Physiology published a point-counterpoint debate between Noakes [30] and BT Ekblom [127] with commentary by RJ Shephard [128], WG Hopkins [129], C. Foster and A. Lucia [130], JA Calbet [131], J. Gonzalez-Alonzo, SP Mortensen [132] and numerous letters written by other researchers. Noakes titled his piece “Maximal oxygen uptake is/is not limited by a central nervous system governor”.

Noakes claimed that, contrary to popular teaching, maximal oxygen uptake is limited by a “central governor” rather than the ability of the cardiac system to deliver oxygen to working muscles. In it, Noakes claims that a central governor prevents the body from reaching maximal exertion because doing so would cause myocardial damage, which is in direct contradiction to his letter to the editor in the previous year [29], which stated “The [central governor model] does not predict, as Brink-Elfedoun et al. [133] incorrectly claim: ‘To prevent the heart muscle from becoming ischemic…”. He finished the point/counterpoint still espousing his CGT [31]. Ekblom’s elegant and short final argument in the debate stated,

“If the aim of a Central Governor mechanism was to prevent the heart from myocardial ischemia during maximal exercise, why use a complicated system of “peripheral” regulations—a system we know can fail in different environments? A more secure system for prevention would have been concentrated directly on the initiation of the heart beat. There are direct and indirect possibilities through the autonomic nervous system or even an intramyocardial feed back system. But there are no such signs. Therefore, the overwhelming results from many observations are that the healthy heart

is the bottle neck for VO_{2max} with good reserve capacity of the heart muscle without risk of heart failure and hypoxic damage."[127]

Aside from Noakes and Marino, all other respondents to the point/counterpoint refuted the CGT and its tenets. Noakes has continued to publish reviews and letters endorsing the CGT, with five articles published between 2009 and 2011 [26, 28, 134-135]. In addition to directly supporting the CGT, he has been listed as a secondary author on other papers that endorse this idea.

In 2009, Swart et al. [134] performed exercise tests with methylphenidate, and found that those who were administered methylphenidate (a psychostimulant used in treatment of ADHD) cycled 32% longer before achieving fatigue (defined as cycling at 70% of original power output). They concluded that exercise is "highly regulated" by the central nervous system.

Later in 2009, Noakes co-authored another paper published in the British Journal of Sports Medicine, concluding that mechanisms of peripheral fatigue could not be explained by physiological factors [135], hinting at an inhibition from the central nervous system.

In a reply to an article by Roy Shephard [26], Noakes stated "Furthermore, to advance the case for the [central governor model], I now include evidence from more than 30 studies, which, in my opinion, can only be interpreted according to a model of exercise regulation where the [central nervous system], acting in an anticipatory manner, regulates the exercise behavior by altering skeletal muscle recruitment…". Our body will react "in anticipation" to expected workloads, such as athletes who—despite training daily under high heat conditions—fail to present with heat stroke more often. He cites the several psychological factors that can affect performance of an athlete. Noakes criticizes the science community as a whole of being

unwilling to accept his ideas, and he believes that over time his work will be accepted. He claims, “First they say that what you claim is wrong. Second, they say that what you claim is true but irrelevant. Finally they say that what you say is true but ‘we have always known it’ ”.

His most recent work pushes to abandon the entire A.V. Hill paradigm altogether [27]. His results are summarized in the following paragraph.

“The cardinal weakness of the Hill model is that it allows no role for the brain in the regulation of exercise performance. As a result, it is unable to explain at least 6 common phenomena, including (*i*) differential pacing strategies for different exercise durations; (*ii*) the end spurt; (*iii*) the presence of fatigue even though homeostasis is maintained; (*iv*) fewer than 100% of the muscle fibers have been recruited in the exercising limbs; (*v*) the evidence that a range of interventions that act exclusively on the brain can modify exercise performance; and (*vi*) the finding that the rating of perceived exertion is a function of the relative exercise duration rather than the exercise intensity”

Over the past 15 years, Noakes has been highly critical of the VO_{2max} paradigm of Hill and Lupton [5]. Despite a substantial body of scientific evidence that supports the classical model, Noakes rejects the central tenets of the VO_{2max} model.

VO_2 Plateau: DGXT versus CGXT Protocols

Older studies in the 1920’s to 1960’s [5, 33, 81-82] established the VO_2 plateau criterion based on the results of DGXTs, and these studies showed that the vast majority of subjects displayed a VO_2 plateau. More recent studies, however, have used CGXTs and have found that only about one -quarter to one-half of subjects display a VO2 plateau.

Taylor, Henschel, and Buskirk [33] completed a DGXT on a large sample, and established the criterion measure for VO_2 plateau. Their protocol used a series of discontinuous 3-minute runs, and they only collected expired air between 1:45 and 2:45. Each time, the participant ran at steeper inclines until they could not maintain exercise for the full 3-minute duration or they demonstrated a VO_2 plateau (when the treadmill grade was increased, they failed to demonstrate an increase of > 150 ml/min compared to the previous stage,). Of 115 participants, 108 demonstrated a VO_2 plateau using this DGXT.

Earlier studies [5, 33, 81-82] used a DGXT, consisting of several constant-load tests over a number of days. With a DGXT, the participant runs at a constant speed until steady state is achieved, and once that steady state is achieved, that is considered the VO_2 demand for that workload. However, at supra-maximal speeds the subject will only attain an "apparent steady state"; the VO_2 levels off but the oxygen requirement exceeds the oxygen consumption so metabolic steady-state cannot be achieved. By plotting the workload on the X-axis, and the corresponding VO_2 on the Y-axis, you create a data point. After resting for a period of time, the participant will perform another constant load test at a higher intensity. This continues until the participant performs a test where the workload increases but the VO_2 does not. Taylor et al. [33], which first established the plateau criterion, ran subjects at 7 mph for 3 minutes on the first visit, then the next visit would increase the incline by 2.5%. The incline would be increased for every visit until the subject showed a VO_2 increase that was less than 150 $ml*kg^{-1}*min^{-1}$ or could not complete the full 3 minutes, assuming that to be the stage to yield a VO_2 plateau.

Earlier tests used a DGXT because a CGXT would have been nearly impossible to perform with equipment at that time. Hill and Lupton [5] used a grass track with a timer calling out splits to the subject, relying on the runner's experience to maintain a certain average pace over the bout. Without a treadmill, they could not gradually increase the velocity every minute, as required by a CGXT. In addition, metabolic carts were not available. So in order to examine the VO_2 kinetics during the run, the participant would have to repeat the run several times with one Douglas bag for a 30-second portion of the run. For example, when running at 9.9 miles per hour for 8 minutes, the subject would run at this speed and open up a valve to breath into the Douglas bag for 0:15 to 0:45, before switching the valve to breath into the atmosphere. The participant would have to repeat the run, but open the valve from 1:15 to 1:45. This was repeated several times until enough data could give an accurate picture of the VO_2 kinetics.

Taylor et al. [33] had access to a motorized treadmill, and even with this tool, performing a CGXT still would have been challenging and time-consuming. They measured a single Douglas bag for each constant-speed run (from 1:45 to 2:45). With each of their participants performing 2 to 4 constant load runs, this demanded two to four bags per subject. To perform a CXGT would have required 1 Douglas bag for each stage, which could be as few as 8, or as many as 20 depending on the protocol. A CGXT could require as many as 12 different stages, depending on the fitness of the subject. That would demand 12 different Douglas bags to be used for a single test, and 12 different gas analyses, which would be incredibly time consuming for results from a single test. As a result, the use of the DGXT during this time was

not necessarily because it was the most valid or appropriate method, but rather because it was easier to do with the equipment available during that time.

Once the methods and technology (treadmills, oxygen measuring devices, and other exercise equipment that could have an adjustable workload) became available, tests were done to compare the validity of the DGXT to CGXT [13, 86-91]. Since it was shown that they both yield the same values for VO_{2max}, researchers switched over to using a CGXT because it takes far less time and fewer visits to complete. Reasearchers failed to realize that notion of a VO_2 plateau developed by Taylor et al. [33] on a DGXT cannot be applied to the CGXT protocols.

The origin of the VO_2 plateau from the work of Hill, Lupton, and Taylor et al.

The first recorded instance of VO_{2max} testing came from Hill and Lupton [5] when Hill described the concept of VO_{2max} by saying, "however much the speed be increased beyond this limit, no further increase in oxygen intake can occur". This described the notion of an upper limit (or "ceiling") during a DGXT. Although Hill and Lupton never tested this hypothesis (because they did not push the participant to supra-maximal speeds), it was inferred that running at higher speeds would not increase the VO_2 once you reached VO_{2max}. Hill and Lupton never used the word “plateau” to describe the phenomenon, and "ceiling" is a more appropriate term to use to describe the upper limit on VO_2 on a DGXT.

Based on the work by Taylor et al. [33], VO_2 plateau was established as a criterion measure for attainment of VO_{2max} on DGXT protocols. Given the high prevalence of the plateau

among Taylor et al.'s population, it was reasonable to believe that the presence of a plateau could be used to verify the attainment of a maximal effort. Thus, the VO_2 plateau criterion was established for DGXT.

The difference between a VO_2 plateau and a VO_2 ceiling

The DGXT and CGXT are very different exercise protocols. Normally, the result of a DGXT is illustrated using a graph of time on the x-axis vs. VO_2 on the y-axis.For each constant-speed stage, a line graph is constructed, and several of these are overlaid onto the same graph. Once the subject reaches a work-rate where increases in exercise intensity fail to elicit any further rise in VO_2, they have hit their upper ceiling (VO_2 max). Figure 1 represents an example of this.

In contrast, a CGXT does not rely on constant load tests, but rather a single incremental exercise bout. The data are normally illustrated using a graph of work rate or speed on the x-axis, versus VO2 on the y-axis. The lack of a VO_2 plateau does not necessarily mean that the participant has chosen to terminate the test prematurely (i.e. before attaining VO_{2max}), and thus invalidate the attainment of VO_{2max}.This is why Day et al. [10], after finishing the CGXT, had the participant complete another constant-load test at a work rate 105% of the highest work rate achieved during the CGXT. If the VO_2 on the supra-maximal effort failed to elicit a higher VO_2, then they could correctly conclude that the VO_{2max} had been reached. Rossiter et al. [12] repeated these results in 7 participants who, despite showing no VO_2 plateau on a CGXT, failed to increase VO_2 at a work rate 105% of the highest one achieved during the CGXT.

The key difference in CGXT and DGXT protocols is the capacity to work at supramaximal intensities during the test. During a CGXT, the participant is already fatigued when they approach VO_{2max} and therefore are unable to continue running at supramaximal speeds. Contrarily, during a DGXT, the participant begins each run without fatigue and can run at supramaximal speeds long enough to achieve steady-state VO_2 at VO_{2max}. [insert chart showing an overlay of CGXT and DGXT]. In the example of subject X, the oxygen requirements at certain speeds were identical, but the DGXT continued to higher speeds than the DGXT. As a result the plateau phenomenon and ceiling phenomenon are different.

Whereas a CGXT will terminate at or near VO_{2max}, a DGXT actually attempt to measure the VO_2 response at intensities beyond VO_{2max}. The ceiling of the DGXT accounts for supramaximal intensities that will fail to increase the VO_2 with increased work rate, but the CGXT plateau occurs near VO_{2max} without necessarily reaching supramaximal speeds.

Chapter 3

Abstract

Maximal oxygen uptake (VO_{2max}) is regarded as the gold standard for assessing aerobic fitness. In 1923, Hill et al. proposed that VO_{2max} represents the maximal ability of the body to take in and consume O_2 during strenuous exercise. Recently, however, controversy has arisen over the issue of whether a leveling off, or "plateau" in VO_2 is necessary to verify attainment of VO_{2max}. **Purpose:** To compare two different VO_{2max} protocols and determine if both protocols show direct evidence of an upper limit on VO_2. **Methods:** Nine runners (18-35 years old) completed a continuous graded exercise test (CGXT), followed by a discontinuous graded exercise test (DGXT). The CGXT consisted of gradually increasing treadmill running speed to the point of volitional exhaustion; the highest speed attained was labeled the peak treadmill speed. Over the next several days, participants ran at 80%, 90%, 100%, 105%, and 110% of peak treadmill speed for 10 minutes, or until volitional exhaustion was reached. **Results:** All participants (n=9) achieved a "VO_2 ceiling" (or upper limit) on the DGXT, while only 44% (n=4) achieved a "VO_2 plateau" on the CGXT. There was no significant difference between the VO_{2max} obtained from a CGXT (57.4 ± 2.6 $mL*kg^{-1}min^{-1}$) and DGXT (60.0 ± 3.1 $mL*kg^{-1}min^{-1}$). There was no difference between oxygen uptake measured at 90%, 100%, 105%, and 110% of PTV ($p>0.05$). However, the highest VO_2 recorded at 80% PTV was significantly lower than that recorded at all other velocities ($p<0.05$). **Conclusion:** The VO_2 ceiling effect on a DGXT is inherently different than the VO_2 plateau effect on a CGXT. In this study, a ceiling was always seen on the DGXT, but a plateau was not always seen on the CGXT.

Introduction

Maximal oxygen intake (VO_{2max}) is defined as the highest rate at which oxygen can be taken in and consumed by the body during strenuous, dynamic exercise [1]. VO_{2max} is widely accepted as a measure of aerobic fitness and has been linked to numerous health outcomes [2-4]. In addition, VO_{2max} is an important determinant of athletic performance in middle- and long-distance athletic events. For these reasons, VO_{2max} is widely used in the field of exercise science.

Historically, the concept of VO_{2max} can be traced back to the work of Hill and Lupton [5]. Their VO_{2max} paradigm has four central tenets: (1) there is an upper limit to oxygen intake; (2) there are inter-individual differences in VO_{2max}; (3) a high VO_{2max} is a pre-requisite for successful distance running; and (4) VO_{2max} is primarily limited by the circulatory and/or respiratory systems [136]. In addition, their model states that it is possible to exercise at work rates in excess of VO_{2max}, by increasing one's reliance on anaerobic metabolism. Thus, once the participant reaches a work rate that elicits VO_{2max}, any further increase in work rate will not yield a further increase in VO_2. This is often referred to as the VO_2 plateau phenomenon [5, 9-10, 12-14, 33, 137-144].

For several decades, a VO_2 plateau was used as a criterion for the attainment of VO_{2max}. However, the use of a VO_2 plateau as a criterion during continuous graded exercise tests (CGXT) has become problematic. Although several sources list the VO_2 plateau as a primary criterion for attainment of VO_{2max} [16-17, 23, 33, 83-84, 93, 106], a review of studies in which VO_{2max} was

measured showed that most individuals do not show evidence of a VO_2 plateau at the end of a CGXT [7, 9, 13, 15, 137, 140, 145-146].

In addition, some researchers have concluded that the low prevalence of VO_2 plateau indicates that entire VO_{2max} paradigm proposed by Hill and Lupton [5] is incorrect [18, 20-23, 147-148]. Noakes et al. [18, 20, 22-27] has argued that since some individuals do not show evidence of a plateau during maximal exercise tests, then it cannot be stated that they have truly attained their VO_{2max}. This has led them to speculate that if only these individuals could run faster, their VO_2 would reach higher levels. As a consequence, Noakes [18-20, 22] has stated that VO_{2max} is actually limited by the physiological factors that determine maximal running velocity (such as muscle fiber type) or central nervous system factors, rather than the physiological factors that limit oxygen transport from the lungs to the mitochondria.

The classic studies of Hill and Lupton [5] introduced the concept of VO_{2max} , but they used different maximal exercise testing protocols than those used currently. VO_{2max} studies in the 1920's used a discontinuous graded exercise test (DGXT), which consisted of several constant load tests performed to exhaustion and separated by lengthy rest periods. In contrast, modern day researchers typically use a CGXT, in which the exercise intensity is gradually increased each minute, until volitional exhaustion is reached. The DGXT protocols yield a higher prevalence of VO_2 plateau [5, 33, 83-84, 106] than modern CGXT protocols [7, 9, 13, 15, 137, 140, 145-146].

The purpose of this study was to re-examine the classic work of Hill and Lupton [5], using modern-day techniques. We planned to compare their DGXT protocol to a modern-day CGXT protocol. There were 3 hypotheses in this study:

1. There is not a statistically significant difference between VO_{2max} values achieved on a CGXT and DGXT protocol.
2. Having subjects run at supramaximal speeds does not result in further increases in VO_2, beyond those seen at the end of a CGXT.
3. All participants display a VO_2 "ceiling" (or upper limit) on a DGXT, but not all participants display a plateau on a CGXT.

Methods

Participants

Nine runners (7 men, 2 women) were recruited from Knoxville, TN to participate in this study. Eligibility criteria included: 18-35 years of age, running at least 15 miles per week on average over the past 6 months, and low risk for cardiovascular disease as defined by ACSM/AHA [104]. Prior to participating in the study, participants signed an informed consent form that was approved by the university's Institutional Review Board (Appendix A). All testing

was completed in the Applied Physiology Laboratory in the Health, Physical Education, and Recreation Building on the University of Tennessee campus.

Exercise Protocol

During the initial visit, the participant's weight and body fat were assessed using a Tanita BCA-418 bioelectrical impedance analyzer (Tanita, Chiba, Japan) in the morning prior to exercise. All but 1 participant ate nothing the morning of the initial visit. Weight was measured then recorded to the nearest 0.1 kg and body fat was estimated to the nearest 0.1%. Height was measured to the nearest 0.1 cm using a wall-mounted standiometer. Both weight and height were measured in light running clothing, without shoes.

Participants were instructed not to exercise for 24 hours prior to each test. They were informed that testing would be vigorous and asked to adjust their personal workouts accordingly. All testing was completed on calibrated treadmill (Quinton Q65 series 90, Seattle, WA, USA). For all tests, the subject first straddled the treadmill belt while the speed was brought up to the appropriate setting. Once up to speed, the participant straddled the belt for 3 minutes while standing oxygen consumption was measured. Once testing began, the participant suspended himself or herself above the belt using the handrails. The participant then lowered himself or herself onto the belt and began running, releasing the hand rails once he or she felt comfortable with the speed. The bout started when the participant's foot touched the treadmill.

On the first day, participants completed a CGXT. The CGXT protocol began with treadmill running at 9.7 kilometers per hour (kph), and speed was increased by 0.8 kph each minute until the participant reached volitional exhaustion. Respiratory gas exchange was measured using an Oxycon Mobile [Viasys Healthcare, Hochberg, Germany] device. The Oxycon Mobile is a portable breath-by-breath system which can accurately determine the V_E, VO_2, VCO_2, FEO_2, and $FECO_2$ of individual breaths [149-150]. The device was chosen for its ability to measure VO_2 responses during brief high-intensity exercise. Participants wore a facemask (model 7450 V2 Mask, Hans Rudolph, Shawnee, KS) that was held tight by a head strap. The facemask fits over the nose and mouth and allows for measurement of ventilation and gas fractions. When the mask was placed on the participant, the participant would cover the opening with his or her palm and exhale normally to make sure there were no gas leaks during exhalation. Participants were given verbal encouragement to continue as long as possible, and were able to see their speed and time spent exercising on the treadmill. The highest speed maintained for 40 seconds or more on the CGXT was considered the peak treadmill velocity (PTV). VO_{2max} was determined from the highest measured VO_2 for any 15-second period.

Three more days of testing were performed in a randomized order. On these testing days, the participants ran at either (a) 90% and 100%, (b) 105%, or (c) 110% of PTV on the CGXT. Testing days were separated by 1 to 6 days of rest. Before each of these trials, participants warmed up by running at 80% of PTV for 10 minutes, followed by a 5-minute cool-down at a self-selected speed and 10 minutes of rest.

The 90% and 100% PTV trials began with the previously described warm-up and cool-down and rest. The participant ran at 90% of PTV for 10 minutes, followed by a 15-min cool-down and rest period. On the same day, the participant then completed a second warm-up run at 80% of PTV for 3 minutes to sufficiently warm up the body without exhausting it for the final bout. After 5 minutes of cool-down and rest, the participant ran at 100% of PTV for 10 minutes or until volitional exhaustion was reached.

The 105% PTV trial began with a warm-up, then after a 5-minute cool-down and rest, running at 105% PTV until volitional exhaustion. The 110% PTV trial was identical, except it was run at 110% of PTV.

Participants were allowed to view both speed and duration during the tests, and the researchers provided verbal encouragement to give a maximal effort. At the point of volitional exhaustion, the participant grabbed the handrails and straddled the treadmill belt while the speed was lowered to 2.0 mph. The participant then completed a cool-down at a self-selected pace.

VO_2 Plateau Determination

For the CGXT, we checked for a VO_2 plateau by graphing treadmill speed against VO_2. For plateau determination, the first two velocities (6.0 and 6.5 mph) were excluded. If the participant failed to complete a full minute at the final velocity, the VO_2 measurements were excluded. Because the exercise started from rest, the initial velocities had large increases in VO_2

for the increases in work rate (i.e. the VO_2 increase from rest to 6 mph is much larger than the increase from 7 to 7.5 mph). Including them in the analysis would have yielded an artificially high VO_2 increase, so they were excluded. A plateau was defined by constructing a line of best fit for the graph of running speed versus VO_2, excluding the first two velocities and peak treadmill velocity . We then extrapolated the line of best fit to the peak treadmill velocity. A plateau in VO_2 was defined as an increase in the measured VO_2 corresponding to less than one-half of the "expected" increase in VO_2.

VO_2 Ceiling Determination

For the DGXT, the presence of a VO_2 ceiling was determined by examining the VO_{2max} values for all 5 of the DGXT trials. If the VO_{2max} of 105% and 110% of PTV were essentially the same as the VO_{2max} measured at 100% of PTV, then this demonstrated the presence of a VO_2 ceiling. If the variation between these 3 values for each participant was less than 5% (i.e.- the day-to-day coefficient of variation generally associated with VO_{2max} testing [151-153], then they were considered to be essentially the same. A variation greater than 5% in these 3 values indicates that there is a difference greater than what can be attributed to day-to-day variation.

Statistical Analysis

All data were analyzed using SPSS software (v16, SPSS, Insc, Chicago, IL). The VO_{2peak}, VO_{2max}, and RER values are presented in 15-second epochs. Comparisons between VO_{2peak} and VO_{2max} values for different constant speed runs and CGXT were conducted using a repeated-measures ANOVA to detect for significant difference between the groups. If significance was found ($p<0.05$), pairwise analysis with Bonferonni adjustments were made to identify which protocols or intensities yielded significantly different VO_{2peak}, and VO_{2max} measurements.

Results

Participant Description

Descriptive statistics of participants are described in Table 1.

Table 1 Physiological characteristics of participants (N=9; 7 males and 2 females)

Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Estimated Body Fat (%)
28.7±1.5	175.9±1.9	71.6±2.8	23.0±0.6	14.9±1.7

* Values are mean ± standard error; BMI = body mass index

Continuous Graded Exercise Test

Four of the 9 participants achieved a plateau on the CGXT, as previously described. Figure 1 illustrates an example of a participant who demonstrated a VO_2 plateau, while figure 2 illustrates and example of a participant who failed to demonstrate a VO_2 plateau.

Discontinuous Graded Exercise Test

All 9 participants demonstrated an "upper ceiling" for VO_2 on the DGXT. This ceiling prevalence was significantly different from the plateau prevalence ($p=0.013$). The vast majority also achieved secondary criteria for attainment of VO_{2max} [101]. Eight were within 10 beats of age-predicted maximal heart rate, and 7 achieved an RER ≥ 1.10 during any of the constant-load tests, with 6 of them achieving both criteria.

The VO_{2peak}, V_{Epeak}, HR_{peak}, and of the 10-min run at 80% of PTV were significantly lower ($p<0.05$) than all other constant speed runs, indicating that this was clearly a sub-maximal effort. The VO_{2peak}, V_{Epeak}, and HR_{peak} of all other constant speed runs were not significantly different from each other, but were all higher than the values achieved at 80% of PTV . The 105% and 110% of PTV runs had significantly higher RER_{peak} than 80%, 90%, and 100% of PTV, but no other significant differences in these variables were found. These results are displayed in Figures 3, 4, 5, and 6.

The prevalence of the achievement of criteria for both the DGXT and CGXT are presented in Table 2.

Table 2. Achievement of criteria on CGXT and DGXT

Subject	Achieved plateau on CGXT	Achieved ceiling on DGXT	HR within 10 beats of age-predicted max on CGXT	HR within 10 beats of age-predicted max on DGXT	Achieved RER ≥1.10 on CGXT	Achieved RER ≥1.10 on DGXT
Subject 1	Yes	Yes	No	Yes	No	No
Subject 2	No	Yes	Yes	Yes	Yes	Yes
Subject 3	No	Yes	Yes	Yes	Yes	No
Subject 4	Yes	Yes	Yes	Yes	Yes	Yes
Subject 5	Yes	Yes	Yes	Yes	Yes	Yes
Subject 6	Yes	Yes	Yes	Yes	No	Yes
Subject 7	No	Yes	Yes	Yes	Yes	Yes
Subject 8	No	Yes	No	No	Yes	Yes
Subject 9	No	Yes	Yes	Yes	No	Yes
Total (Percent)	4 (44%)	9 (100%)	7 (78%)	8 (89%)	6 (67%)	7 (78%)

Duration

Among the constant-speed tests, the duration of the runs at 80% of PTV and 90% of PTV did not differ from each other, but they were significantly less ($p<0.05$) from all other run durations. None of the bouts at 80% of PTV, as well as 3of the bouts at 90% PTV, were not to carried out to volitional exhaustion, but were terminated at 10 minutes. The durations of the 100% of PTV run and 105% of PTV run were not significantly different from each other, but they were significantly different from all other runs ($p<0.05$). The duration of 110% of PTV was significantly shorter than all other runs. These results are displayed in Figure 7.

Time course of VO_2 response

The time course of the VO_2 response for each of the constant-speed runs for each subject can be seen in Figures 8 though 16. Comparisons of the mean values for the CGXT and DGXT are shown in Table 3.

Table 3. Comparison of maximal exercise responses with a continuous and a discontinuous graded exercise test protocol (n=9).

	CGXT	DGXT
VO_{2max} STPD ($ml*kg^{-1}*min^{-1}$)	57.7±2.6	60.3±3.2
V_{Emax} BTPS (L/min)	146±11	155±13*
RER_{max}	1.11±0.02	1.15±0.02
HR_{max} (beats/min)	186±3.4	186±2.7
HR_{max} (% of age-predicted HR_{max})	97±1.8	97±1.3
Duration (seconds)	665±47	---
Velocity at VO_{2max} (kph)	17.7±0.6	---

All values expressed as mean ± standard error
*Significantly different from CGXT (p=0.011)

For the DGXT, the VO_{2max}, V_{Emax}, and RER_{max}, we took the highest values reached on any of the 5 DGXT bouts to represent the maximal values for the test.

There was no significant difference in the VO_{2max} between the CGXT or DGXT. The CGXT and DGXT also did not differ on RER_{max} maximum heart rate, or maximum heart rate expressed as a percentage of age-predicted maximum. However, V_{Emax} was significantly higher on the DGXT compared to the CGXT.

Discussion

All of the participants demonstrated a VO_2 ceiling (i.e. an upper limit on VO_2, with increasing running speeds) during the DGXT. However, only 44% of them showed a VO_2 plateau during the CGXT, despite the fact that there was no significant difference between the VO_{2max} values measured on both protocols. Thus, while the VO_2 ceiling on a DGXT appears to be a valid criterion for the attainment of VO_{2max}, the lack of VO_2 plateau on a CGXT does not invalidate the VO_{2max} obtained during such a test. The presence of the VO_2 ceiling in the DGXT shows that, contrary to what has been hypothesized by Noakes [18], VO_2 will not continue to increase indefinitely as velocity increases.

Our results are in close agreement with those of Snell et al. [154]. In their study, 52 participants (36 men, 16 women) performed a treadmill CGXT, starting at 8 or 9 miles per hour with 0% grade. The treadmill grade was then increased by 2% every 2 minutes until volitional exhaustion ensued. The participants returned for a second day of testing where they ran at the same velocity as on the CGXT but with an additional 8% increase in the treadmill incline. The results showed no difference between the VO_2 of the CGXT and the brief, supramaximal test. Thus, they concluded that, on average, CGXT and DGXT protocols yield the same values for VO_{2max}. They also confirmed A.V. Hill's hypothesis that at high exercise intensities eventually the VO_2 reaches a maximal value, beyond which no effort can drive it.

Stamford's 1976 study [86] was similar to that of Snell et al. [154] and yielded similar results. Ten male subjects completed a DGXT, 2 CGXTs, and 2 constant load tests. The DGXT

consisted of running at 7.0 mph for 3 minutes, resting for 10 minutes, and then increasing the treadmill incline by 2.5% for each successive 3-minute bout (with 10-minute rests in between). The test continued until the subject could not complete the full 3 minutes, and the final completed stage was considered the maximal work rate. The CGXT was identical to the DGXT in work rate increments, but each stage lasted 2minutes instead of 3 and there was no rest between stages. The supra-maximal, constant load test was conducted using the peak speed and incline of the DGXT with an extra 2.5% incline added on. The results of the test showed no significant difference between the VO_{2max} of each test whether it was DGXT, CGXT, or supramaximal.

Shephard et al. [87] confirmed these findings with a study of 24 Canadian males. The participants were administered a CGXT and a DGXT in treadmill, bicycle, and step exercise. Each test was preceded by a submaximal warm-up, which was used to estimate the maximal work rate during the exercise. In the case of the DGXT, a constant load of 110% of predicted maximum work rate was administered, and further bouts were adjusted in relation to the participant's performance. The CGXT began at 90% to 100% of maximal work rate with slight increases in work rate every 2 minutes. Regardless of the mode of exercise, there was no significant difference between DGXT and CGXT results. Thus, the concurrent validity of the DGXT and CGXT has been consistently demonstrated, across several modes of exercise and testing protocols.

The fact that a participant can show a VO_2 ceiling on a DGXT, but fail to show a VO_2 plateau on a CGXT indicates that these two events represent different phenomena. We believe

that subjects are more likely to show a "ceiling" or upper limit on VO2 with a DGXT, because at the beginning of each stage they are well rested and can summon anaerobic metabolism to a greater extent. This enables them to reach higher exercise intensities than they would with a CGXT, thus increasing the likelihood that they will attain supra-maximal running speeds where the oxygen requirement far exceeds the subjects VO_{2max}. Furthermore, the lack of significant difference between the VO_{2max} of the CGXT and DGXT is consistent with previous research [13, 86-91].

Day, et al. [10] found that the VO_2 plateau only occurs in only a small percentage of individuals who perform a maximal CGXT on the cycle ergometer. The methods used by Day et al. [10] were meticulous and rigidly controlled. By using a small increment of increase (5W every 12-20 seconds) on a cycle ergometer, they were able to show a low-residual linear response to the exercise during the “linear portion” (they omitted the first four minutes and last three minutes of the CGXT to arrive at the linear portion). Most protocols use larger jumps in work rate at 1- or 2-minute intervals, creating more of a “step” shape rather than a “true” linear response. In addition, the breath-by-breath response, which typically exhibits a fair amount of “noise”, was normalized by removing errant breaths. Without this tight control, it would be much more difficult to determine the presence of a VO_2 plateau. Their results clearly showed that a relatively small percentage of people (17%) demonstrate a VO_2 plateau on a CGXT. Most individuals demonstrate a linear increase in VO_2 throughout exercise (56%), while some actually demonstrate an acceleration in VO_2 response at the end of a CGXT (27%).

Rossiter et al. [12] showed that, in addition to the low prevalence of VO_2 plateau during a cycling CGXT, the lack of VO_2 plateau does not invalidate the attainment of VO_{2max}. Seven subjects completed a modified cycle ergometer CGXT. They began at 20 W with an increase of 1 W every 3 seconds until volitional exhaustion was reached. After achieving exhaustion, they recovered by cycling at 20W for 5 minutes, and then completed a constant load bout at 105% of the peak work rate achieved in the CGXT. After at least 5 days of rest, the protocol was repeated, but using 95% of the peak work rate achieved during the CGXT. Results showed no significant difference between the VO_2 achieved during the CGXT or 105% bout. This was true despite the fact that of the 14 tests, only 2 had a "tendency toward a plateau". This study demonstrated that exercising at supramaximal rates does not increase the VO_2 above values measured on a CGXT. In addition, the lack of a VO_2 plateau on a CGXT did not invalidate VO_{2max} values obtained during the test.

Our study confirms the findings of Day et al. [10] and Rossiter et al. [12] by demonstrating that a VO_2 plateau is not a necessary criterion for attainment of VO_{2max}, and that subjecting participants to supramaximal work rates results in them achieving VO_{2max} values that are no higher than those achieved on a CGXT.

Duncan, et al. [11] sought to determine if there was a difference in VO_2 plateau and ceiling prevalence between CGXT and DGXT. Their DGXT mirrored that of Taylor et al. [33], even including the collection of expired respiratory gases in Douglas bags. The participants ran at 7 miles per hour for three minutes with gas collection between 1:45 and 2:45. Each successive test was repeated at the same speed with an incline increased 2.5% from the previous bout. If

the participant showed an increase of VO_2 less than 150 mL/min, then they were said to have demonstrated a plateau. Duncan et al. used a CGXT that was similar to their DGXT, except that it had 1-minute stages rather than 3-minute stages, and there was no rest between each stage. Though Duncan et al. showed little difference in VO_2 plateau prevalence between protocols (5 of 10 for CGXT and 6 of 10 for DGXT), this is likely due to premature termination of the DGXT. Both Taylor et al. and Duncan et al. failed to show 100% plateau prevalence in the DGXT because only bouts of at least 2.75 minutes were included. Thus, if a participant's final bout was 2 minutes and 44 seconds or less it was excluded. However, in our study, 2 out of 9 (22%) participants were not able to run at 100% of PTV for 2.75 minutes, but they were still able to attain VO_{2max} within about two minutes, which allowed them to show evidence of a VO_2 ceiling on the DGXT. For these individuals, the maximal DGXT protocols of Taylor et al. and Duncan et al. would not have included the data from runs at supramaximal running speeds. As a result, they would have failed to demonstrate a plateau; not because their body was incapable of reaching a plateau during a DGXT, but rather because the supramaximal bouts were excluded. This likely explains why some of the participants in the studies of Taylor et al. and Duncan et al. failed to show a ceiling effect, while all of the individuals in the present study did.

Noakes has been an ardent opponent of the VO_2 paradigm proposed by Hill and Lupton for over a decade. Part of his criticism was based on the fact that there is low prevalence of VO_2 plateau when CGXT are used. In his J.B. Wolffe Memorial lecture [18], Noakes stated,

"Not only did Hill et al. [5] fail to measure concurrently either the oxygen debt or muscle or blood lactate levels during these subsequent studies, they also failed to subject their hypothesis to the accepted process of refutation. For the next logical

study would have been to measure Hill's VO_2 when he ran at a speed faster than 16 km/h." [18]

The major purpose of the present study was to conduct the critical experiment that would answer this question. As our results clearly showed, taking subjects to supra-maximal speeds (where the O_2 requirement exceeded their VO_{2max}) yielded a "ceiling effect" just as Hill and Lupton [5] had predicted, not a continued linear increase in VO_2 as hypothesized by Noakes [18]. Hill and Lupton described in VO_2-vs-running speed graph as follows, "oxygen requirement rises continuously at an increasing rate, as the velocity increases, attaining enormous values…however much the speed be increased beyond this limit, no further increase in oxygen intake can occur: the heart, lungs, circulation, and the diffusion of oxygen to the active muscle-fibres have attain their maximum activity."

The DGXT protocol used for the present study closely resembled that of Hill and Lupton [5]. They used a protocol designed around changes in running speed, rather than the more common practice of increasing percent grade on the treadmill [11, 33]. This procedure was used for both the CGXT and DGXT, which meant that the participants reached volitional exhaustion while running on a level surface. Nevertheless, there were some differences between our methods and those of Hill and Lupton [5]. First, rather than running around a grass track, our participants ran on a motor-driven treadmill so that the speed and environmental conditions could be controlled more easily. Second, we used a portable indirect calorimeter system that employs breath-by-breath gas analysis, rather than the Douglas bag method used by Hill and Lupton. Lastly we pushed our runners to supra-maximal speeds, while Hill and

Lupton did not (at least not in the experiment where they studied the time course in the VO_2 response to running at various speeds). Our purpose in doing this was to test the validity of Hill and Lupton's assertion that "however much the speed be increased beyond this limit, no further increase in oxygen intake can occur."

Because of the similarities between our protocol and that of Hill and Lupton, the results of this study are comparable to Hill and Lupton's work and can properly validate their results. However, it should be noted that several excellent studies have examined the time-course of the VO_2 response to DGXT protocols on cycle ergometers [5, 10, 12, 33, 81]. One caution, however, is that the VO_{2max} values measured during treadmill running are generally 5-10% higher than those measured during cycle ergometry, especially for individuals not trained in bicycling. Thus, we sought to examine the VO_2 response to DGXT protocol during level running, to extend the work of Hill and Lupton.

In conclusion, the results of this study reaffirm the findings of Hill and Lupton [5]. It also confirms previous work by Day et al. [10] and Rossiter et al. [12] showing that a VO_2 plateau is not a necessary criterion for the attainment of VO_{2max}. Furthermore, it shows that at supramaximal running speeds, VO_{2max} values do not exceed those achieved in a maximal CGXT, confirming the work of Snell et al. [154] and other researchers. These results strongly refute Noakes' hypothesis that running at speeds beyond 100% of PTV would yield a further increase in VO_2. Hill and Lupton were absolutely correct in asserting that, "…oxygen requirement rises continuously at an increasing rate, as the velocity increases, attaining enormous values…however much the speed be increased beyond this limit, no further increase in oxygen

intake can occur: the heart, lungs, circulation, and the diffusion of oxygen to the active muscle-fibres have attain their maximum activity."

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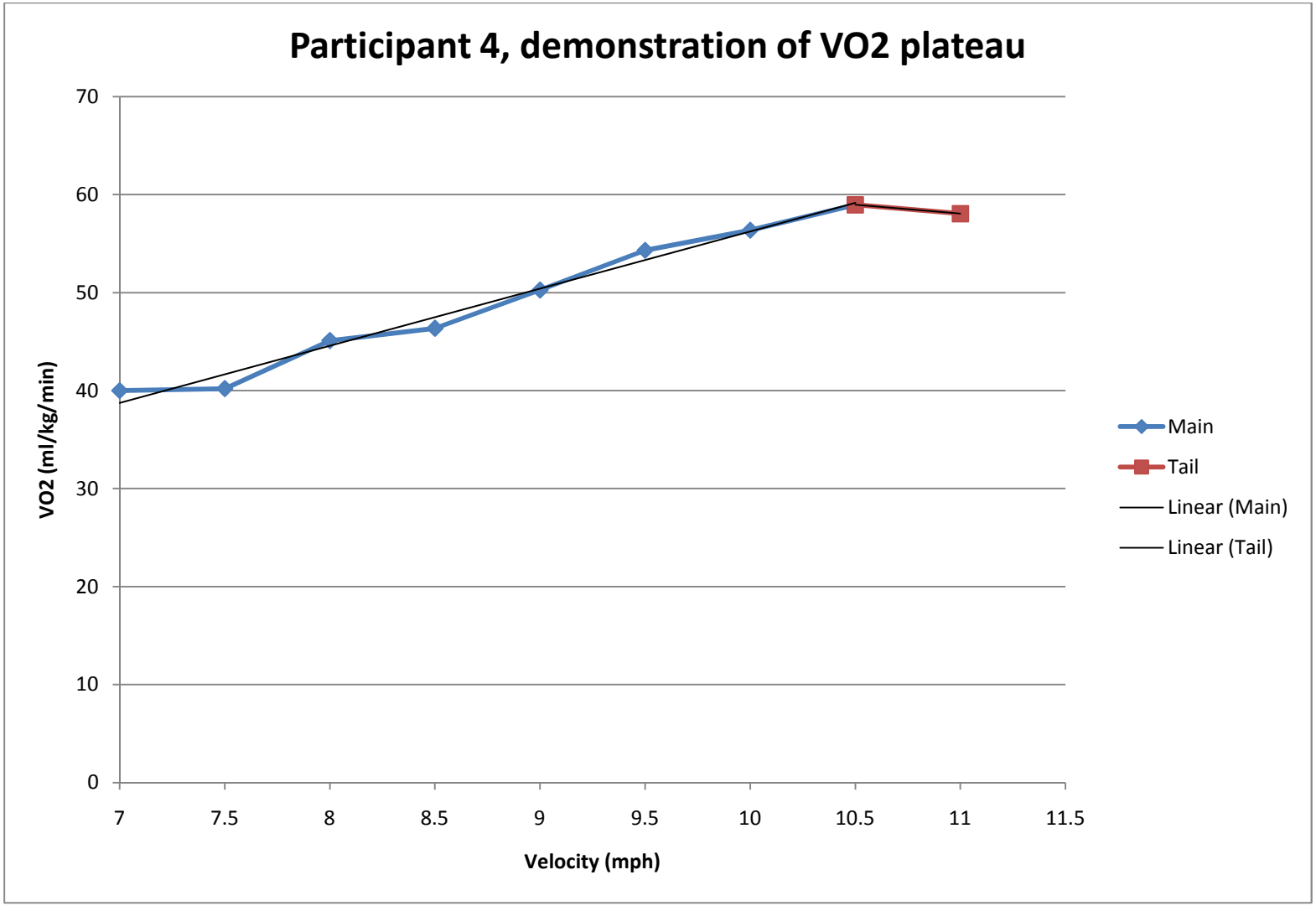


Figure 1, Demonstration of VO_2 Plateau

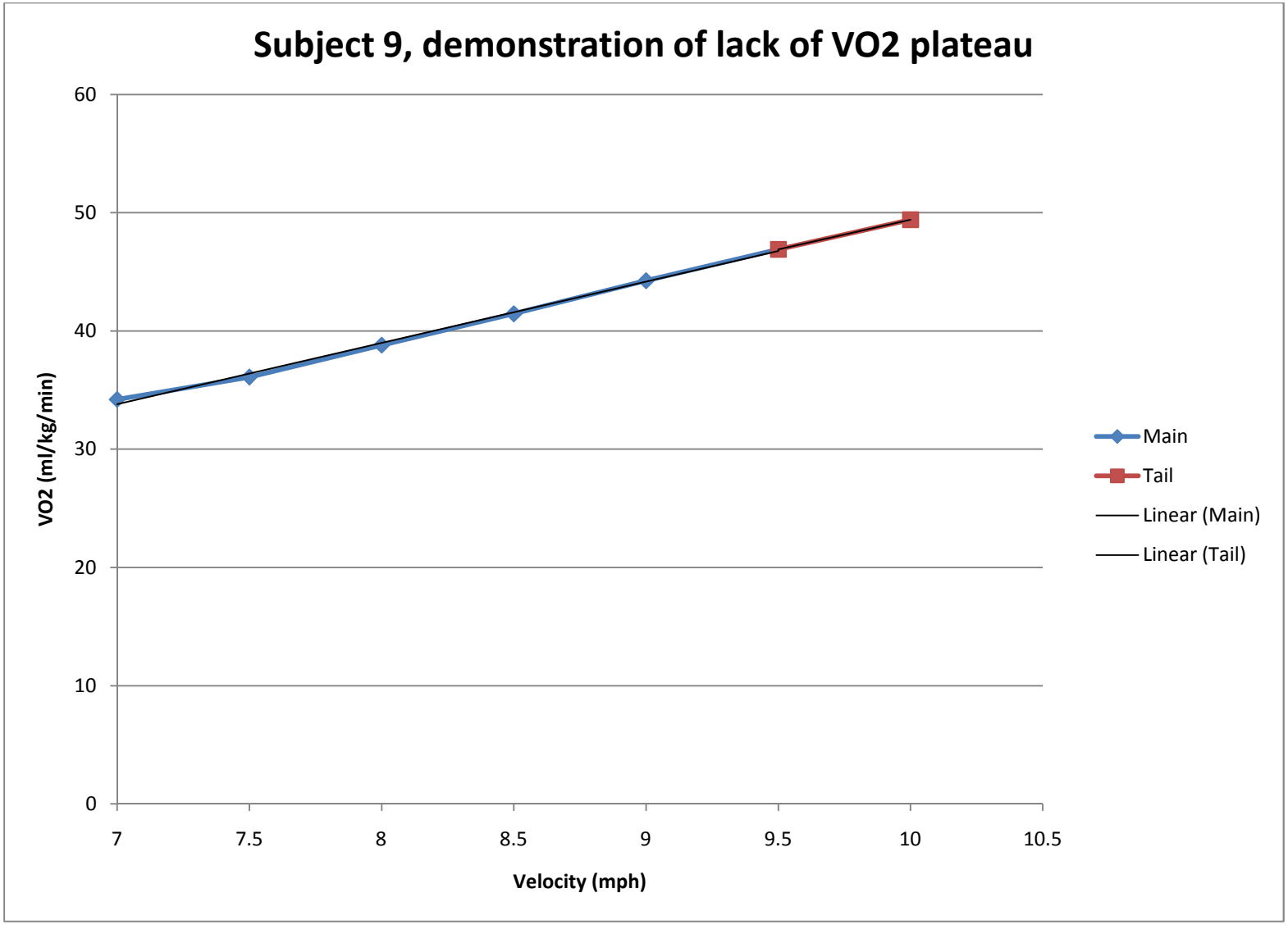


Figure 2, Demonstration of Lack of VO_2 Plateau

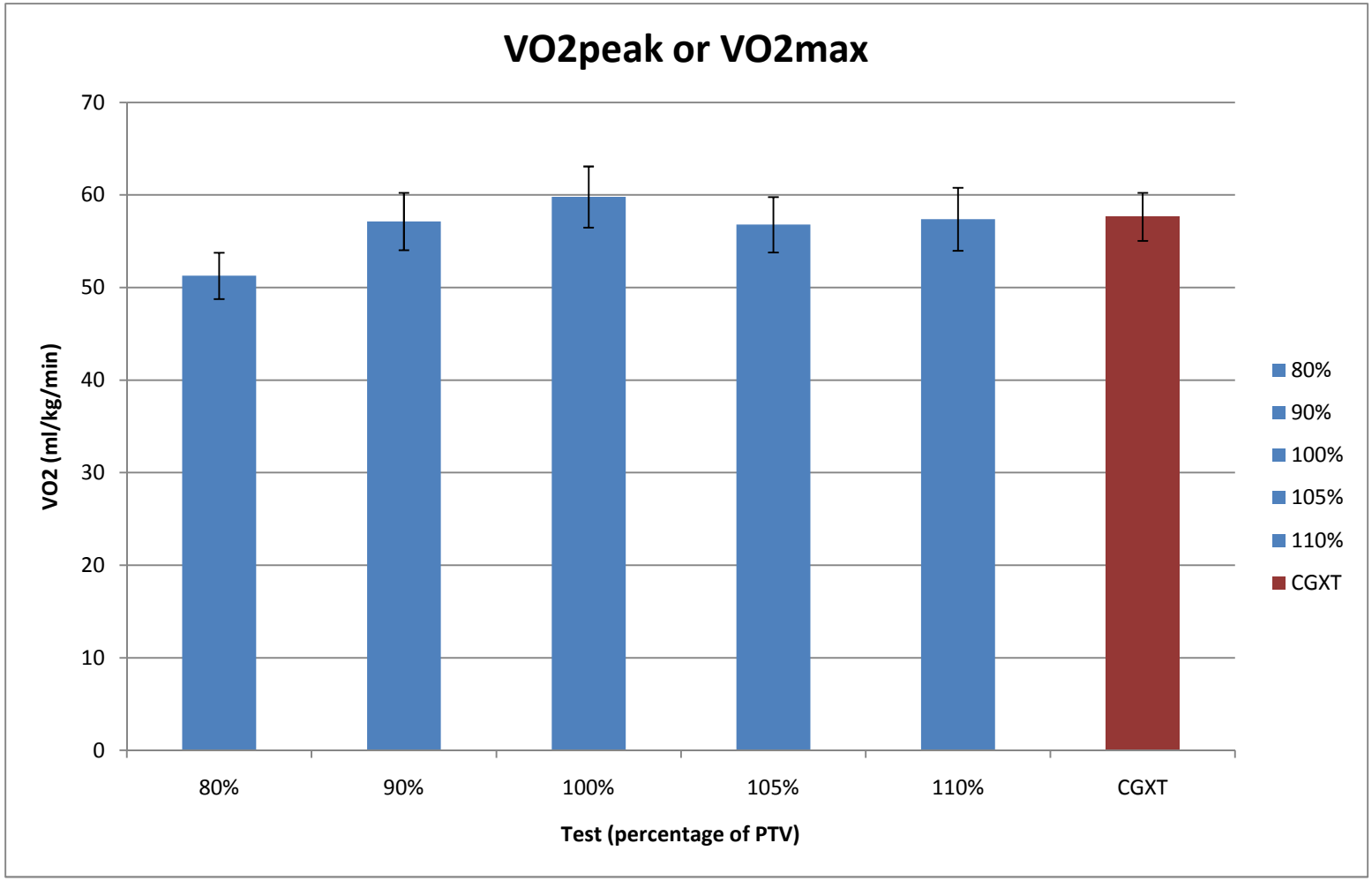


Figure 3, VO_2 Comparison between DGXT and CGXT

Expressed as mean ± standard error

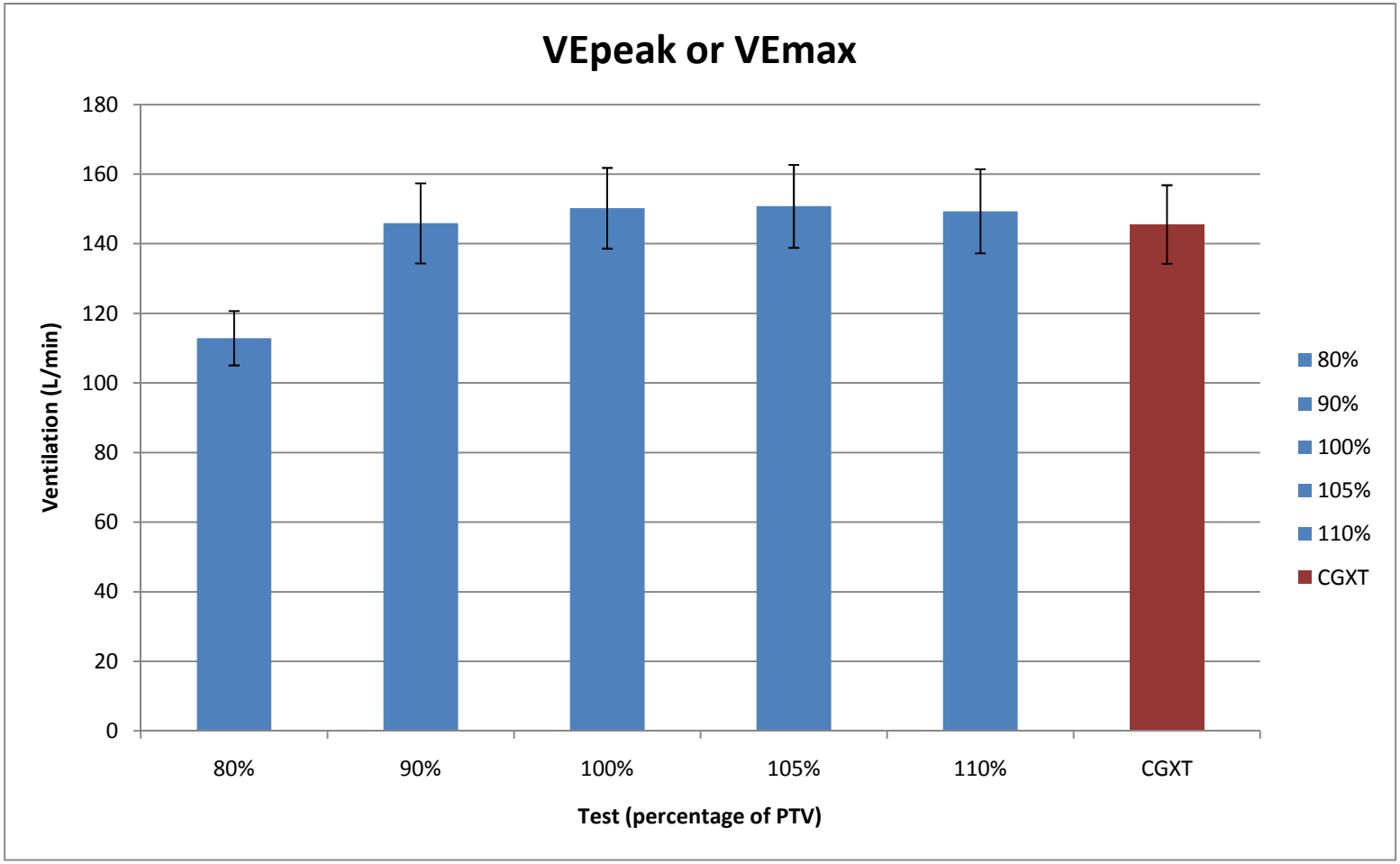


Figure 4, V_E Comparisons between CGXT and DGXT

Expressed as mean ± standard error

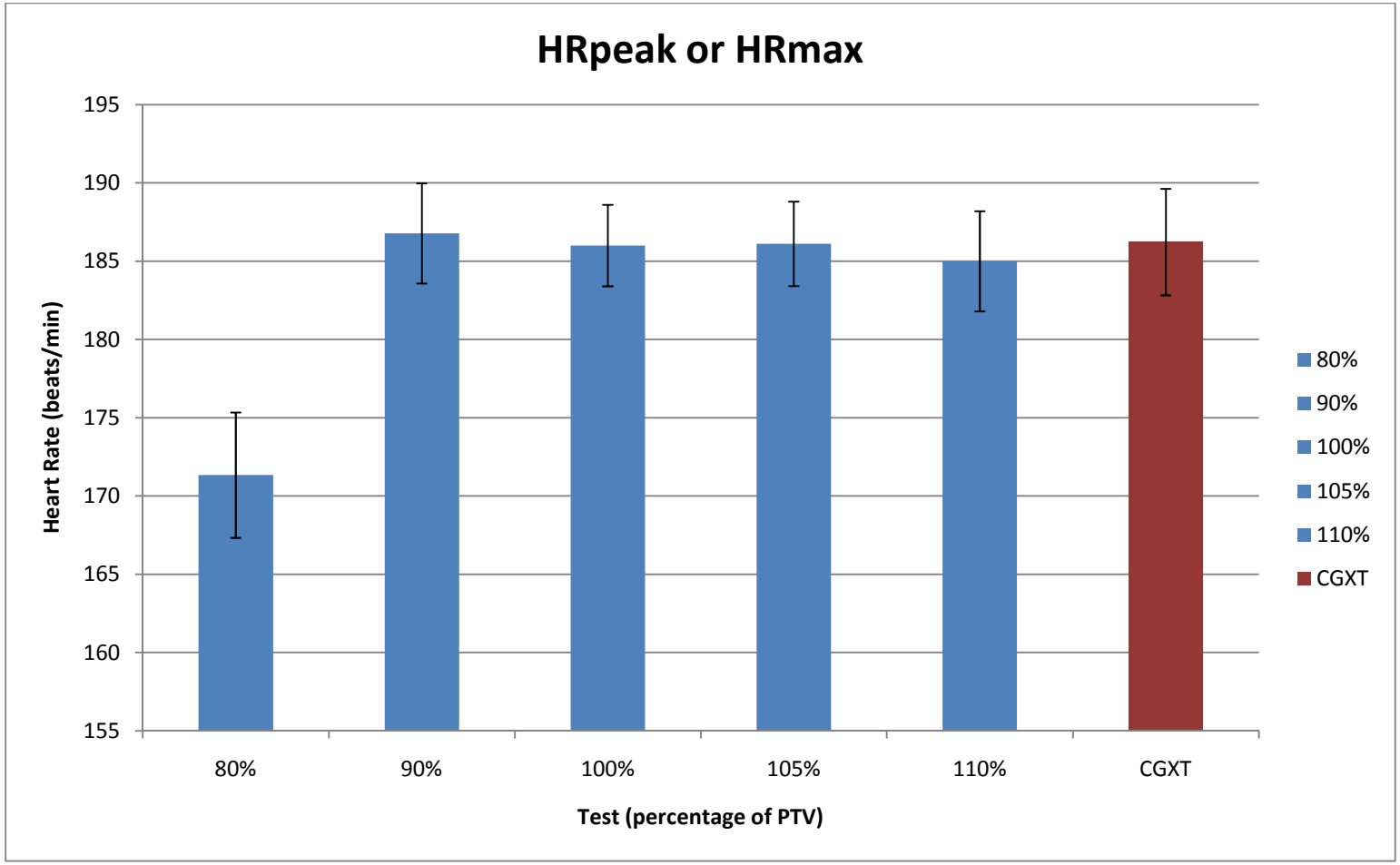


Figure 5, Heart Rate Comparisons between DGXT and CGXT

Expressed as mean ± standard error

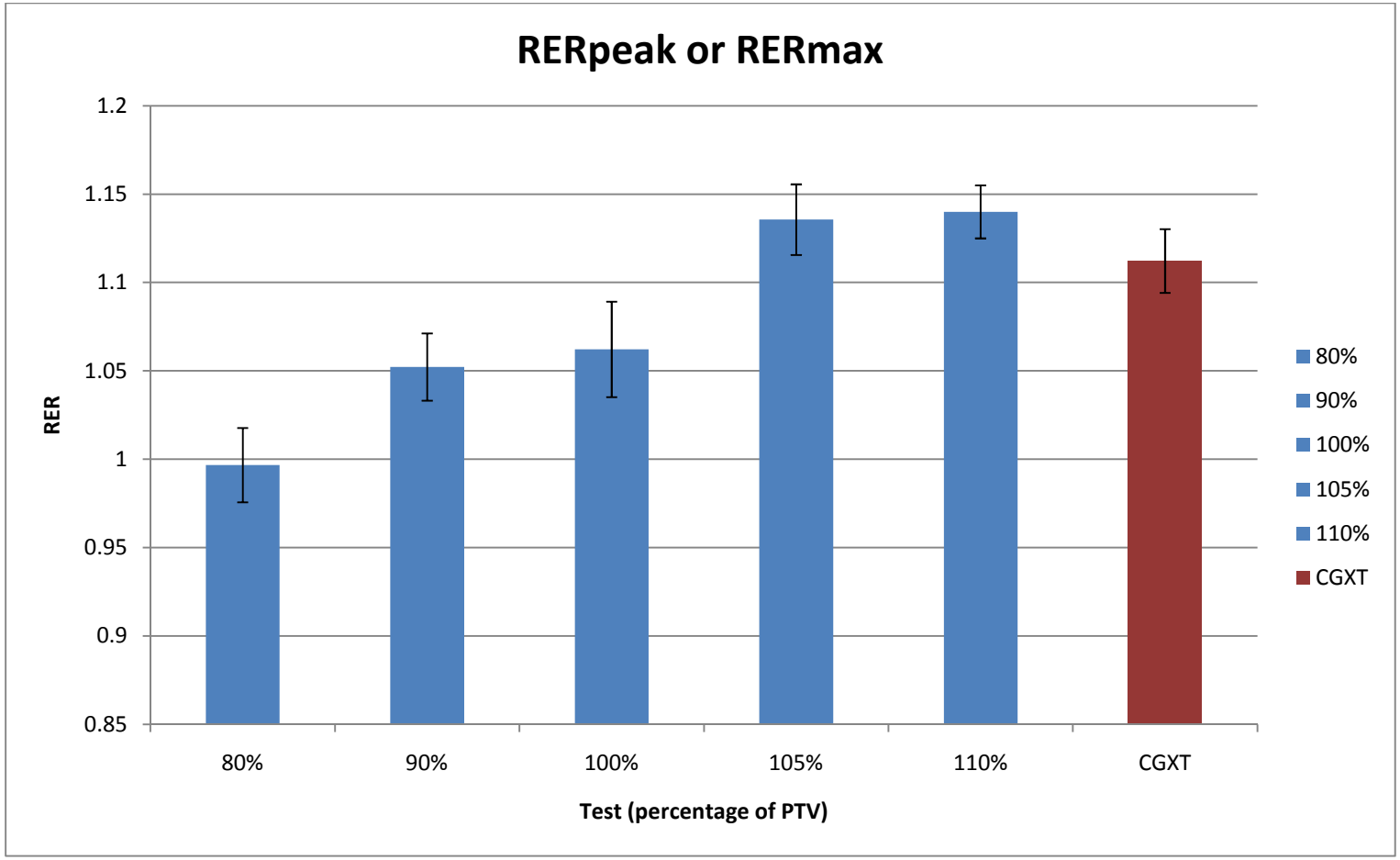


Figure 6, RER Comparisons Between CGXT and DGXT

Expressed as mean ± standard error

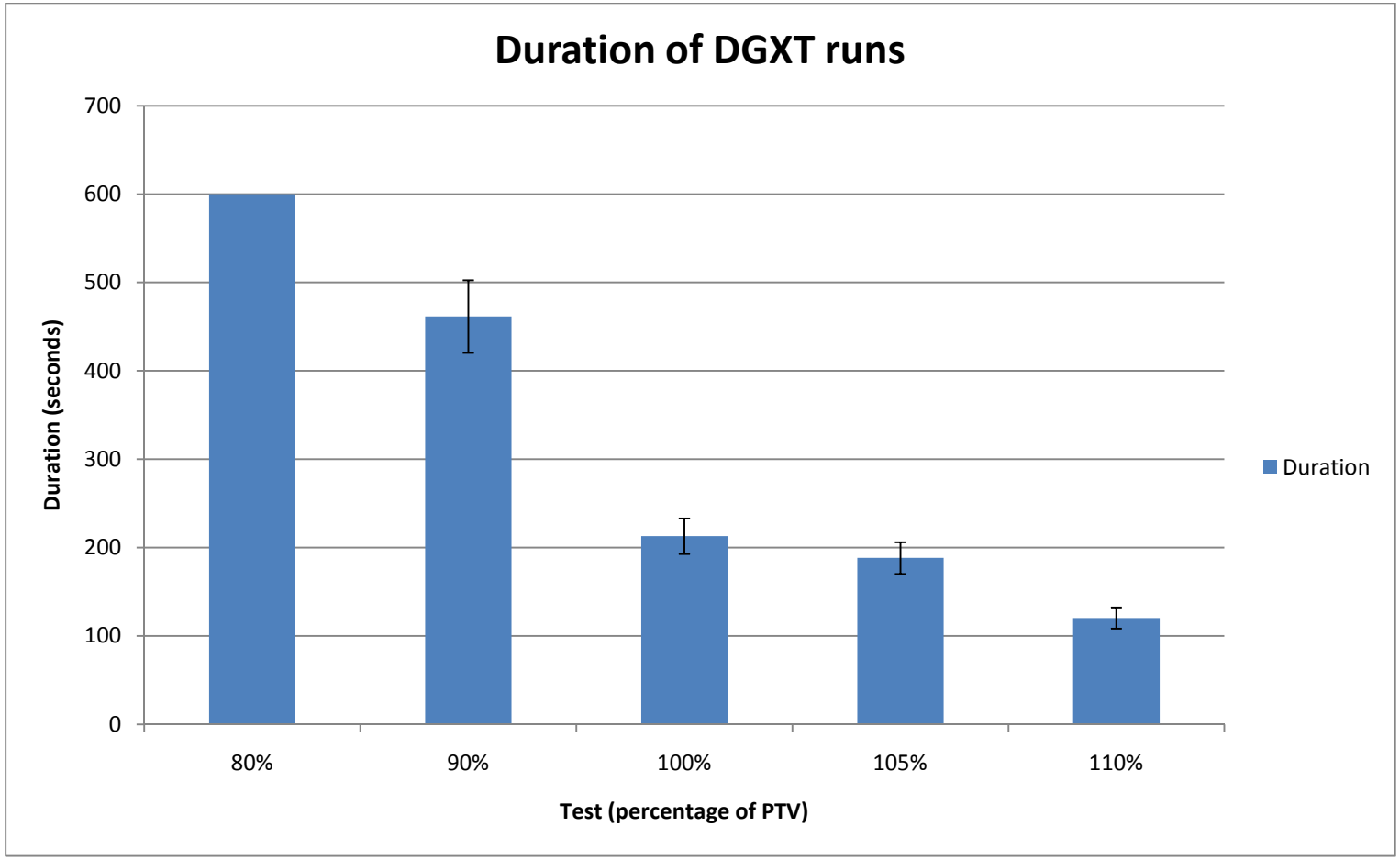


Figure 7, Duration of Each DGXT Run

Expressed as mean ± standard error

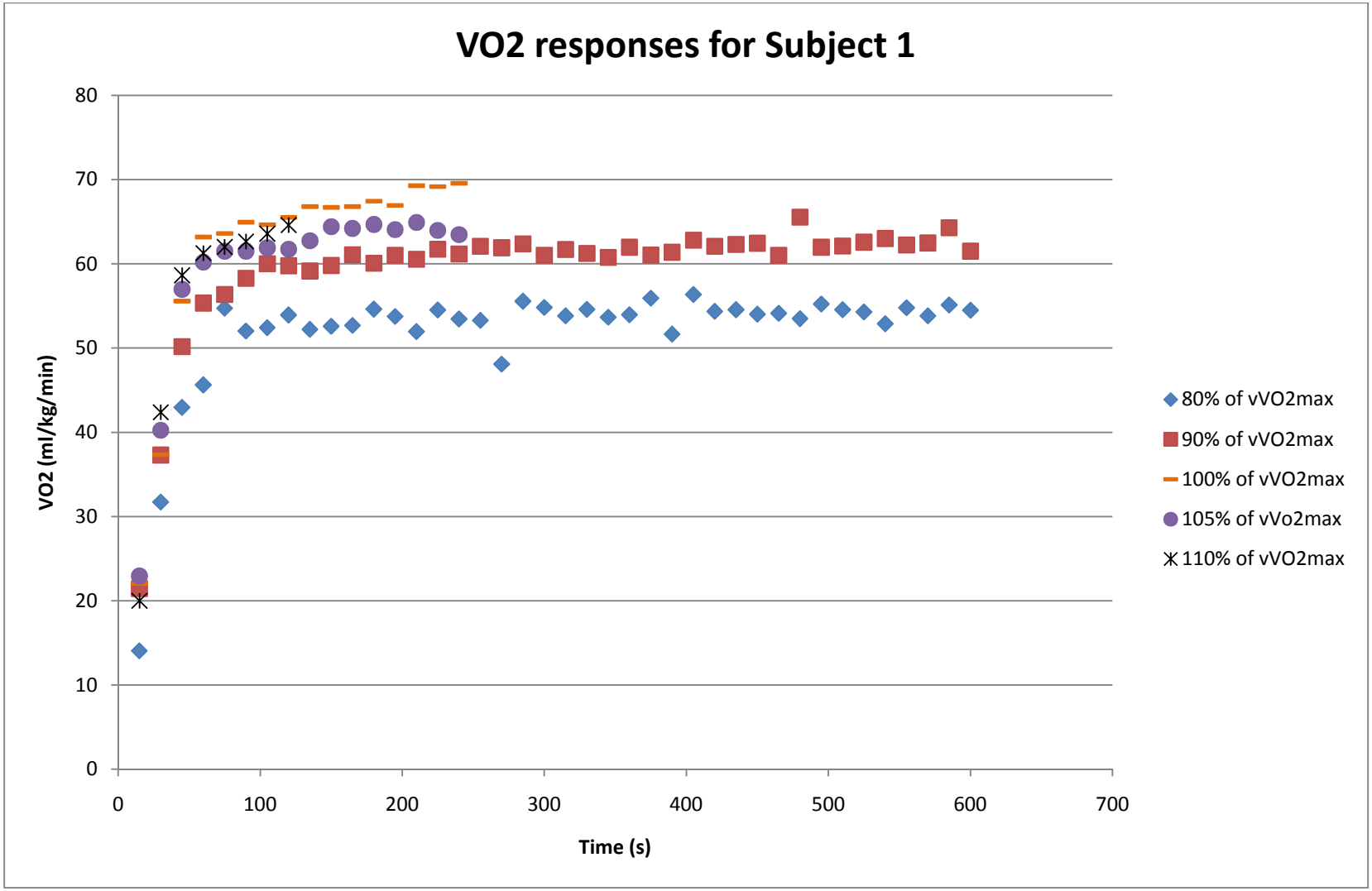


Figure 8, Subject 1 Time Course of the VO_2 Response for Discrete Continuous Speeds

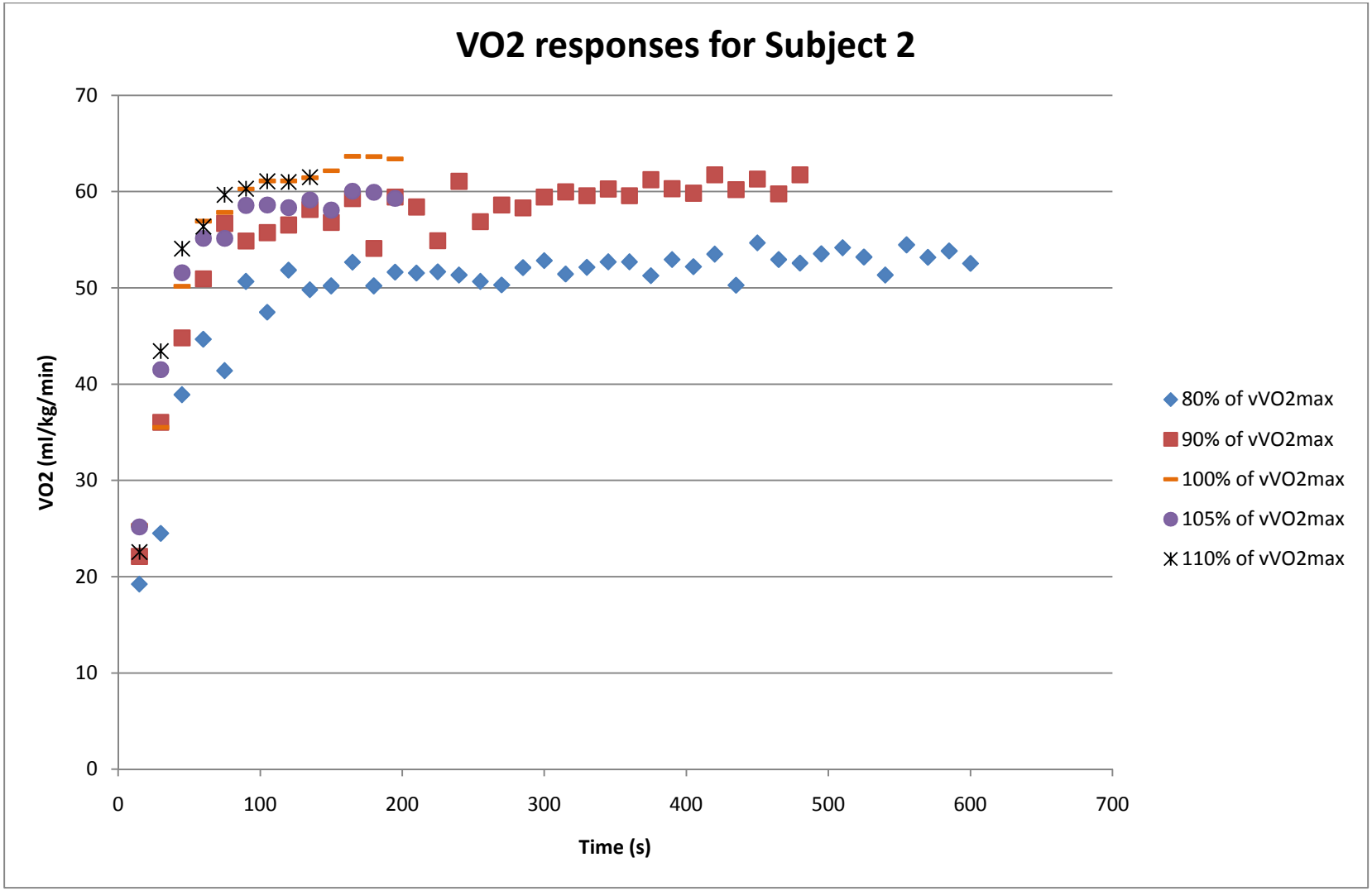


Figure 9, Subject 2 Time Course of the VO2 Response for Discrete Continuous Speeds

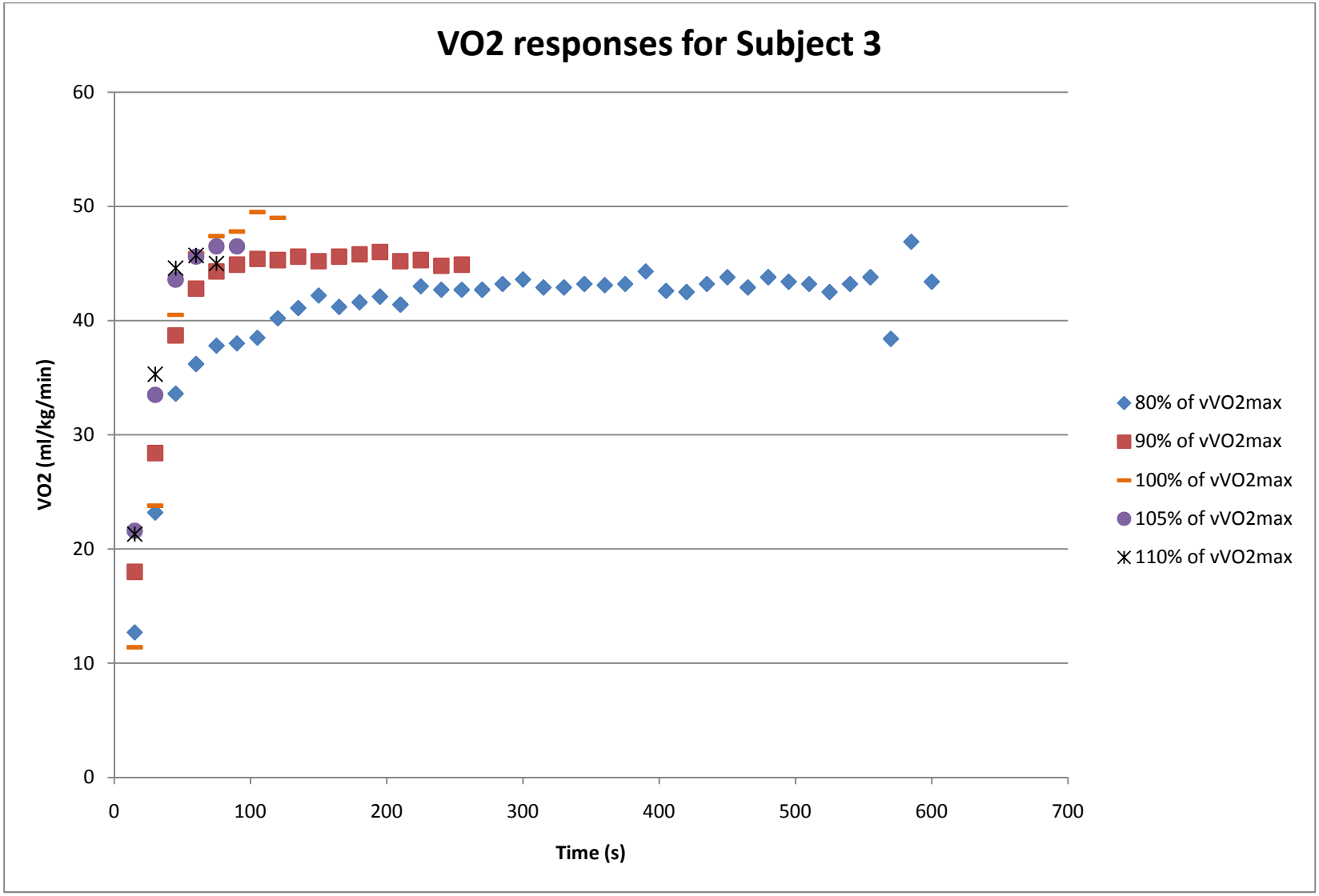


Figure 10, Subject 3 Time Course of the VO2 Response for Discrete Continuous Speeds

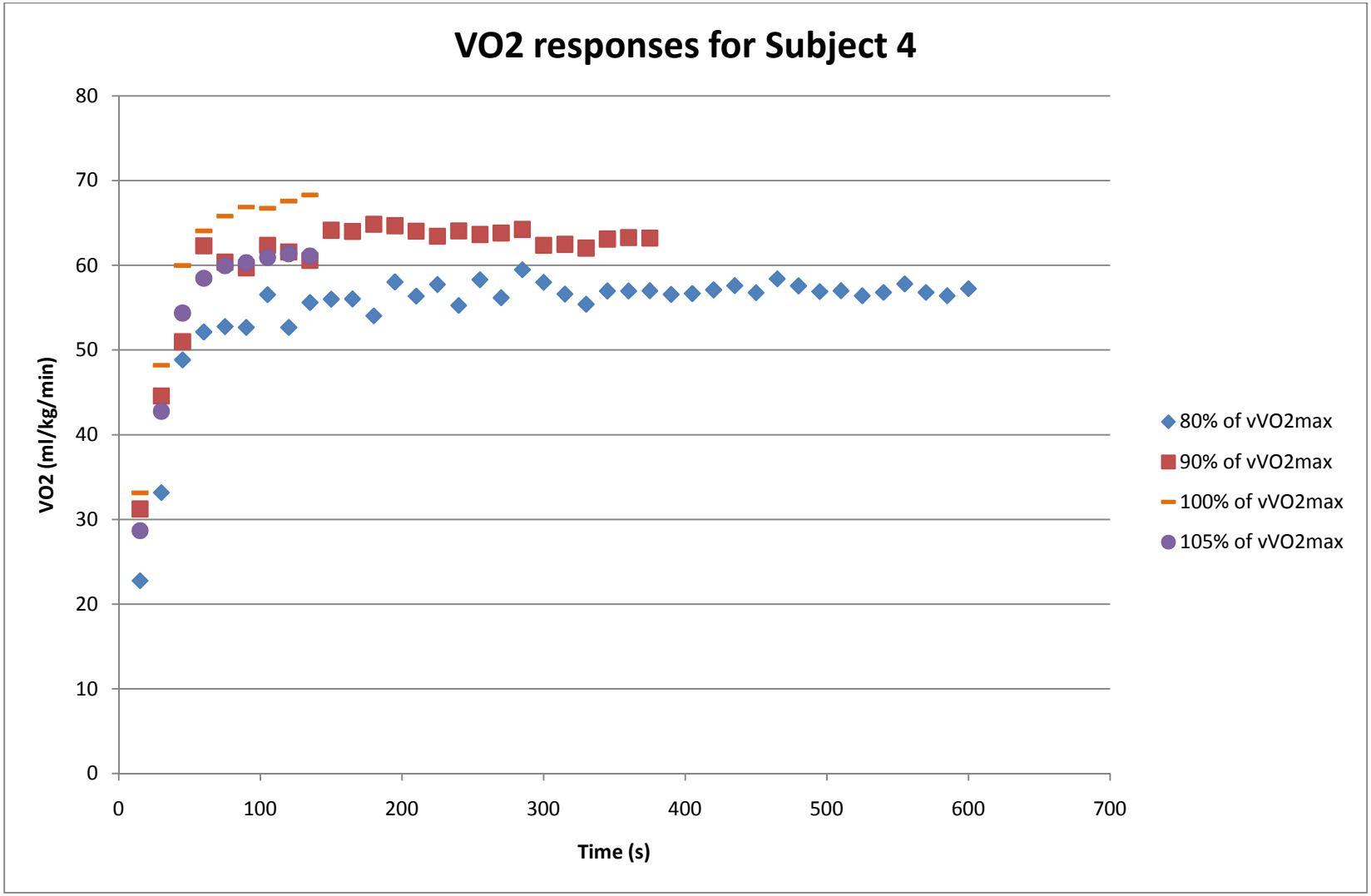


Figure 11, Subject 4 Time Course of the VO2 Response for Discrete Continuous Speeds

*Subject 4 had an invalid 110% of PTV run due to equipment malfunction

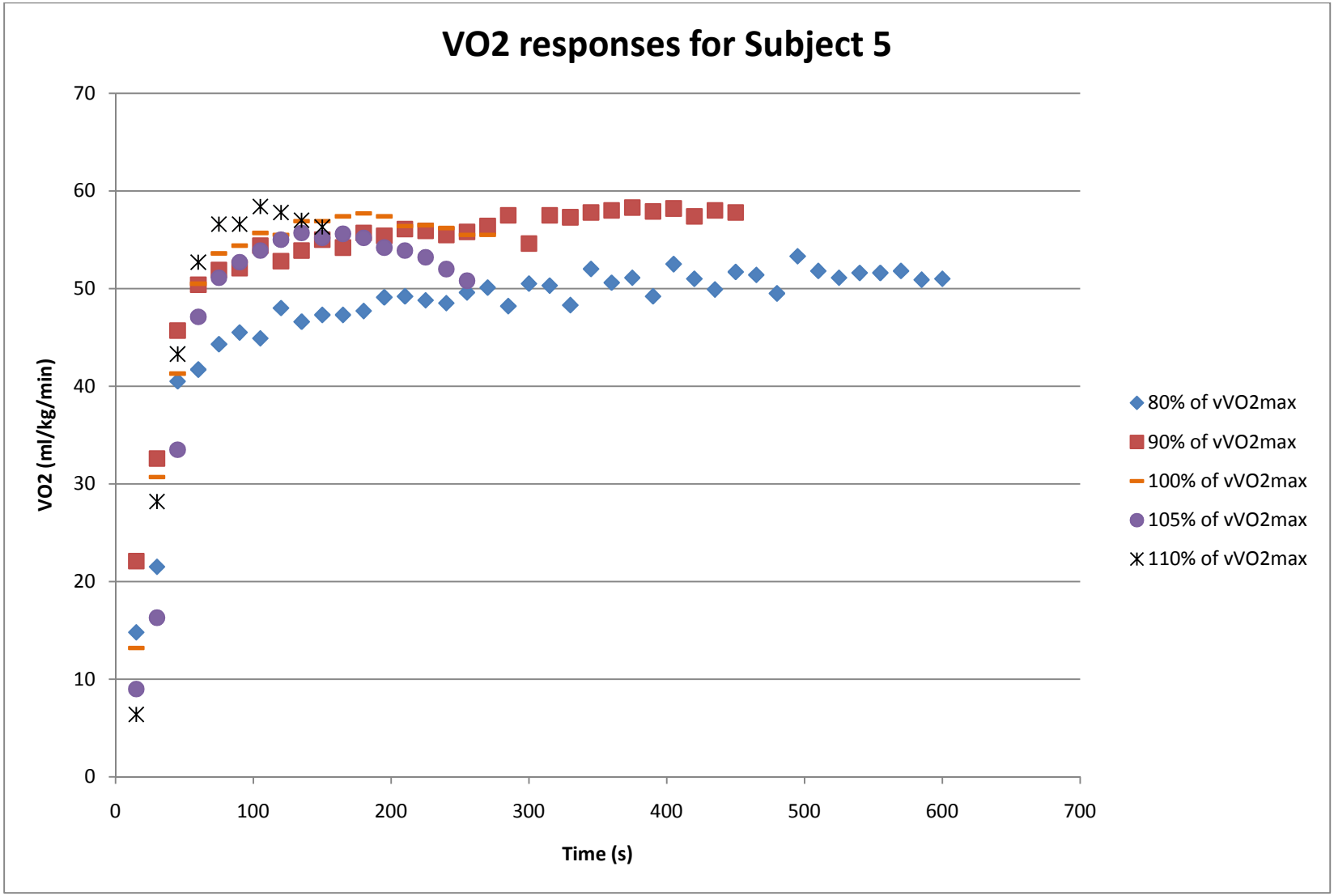


Figure 12, Subject 5 Time Course of the VO2 Response for Discrete Continuous Speeds

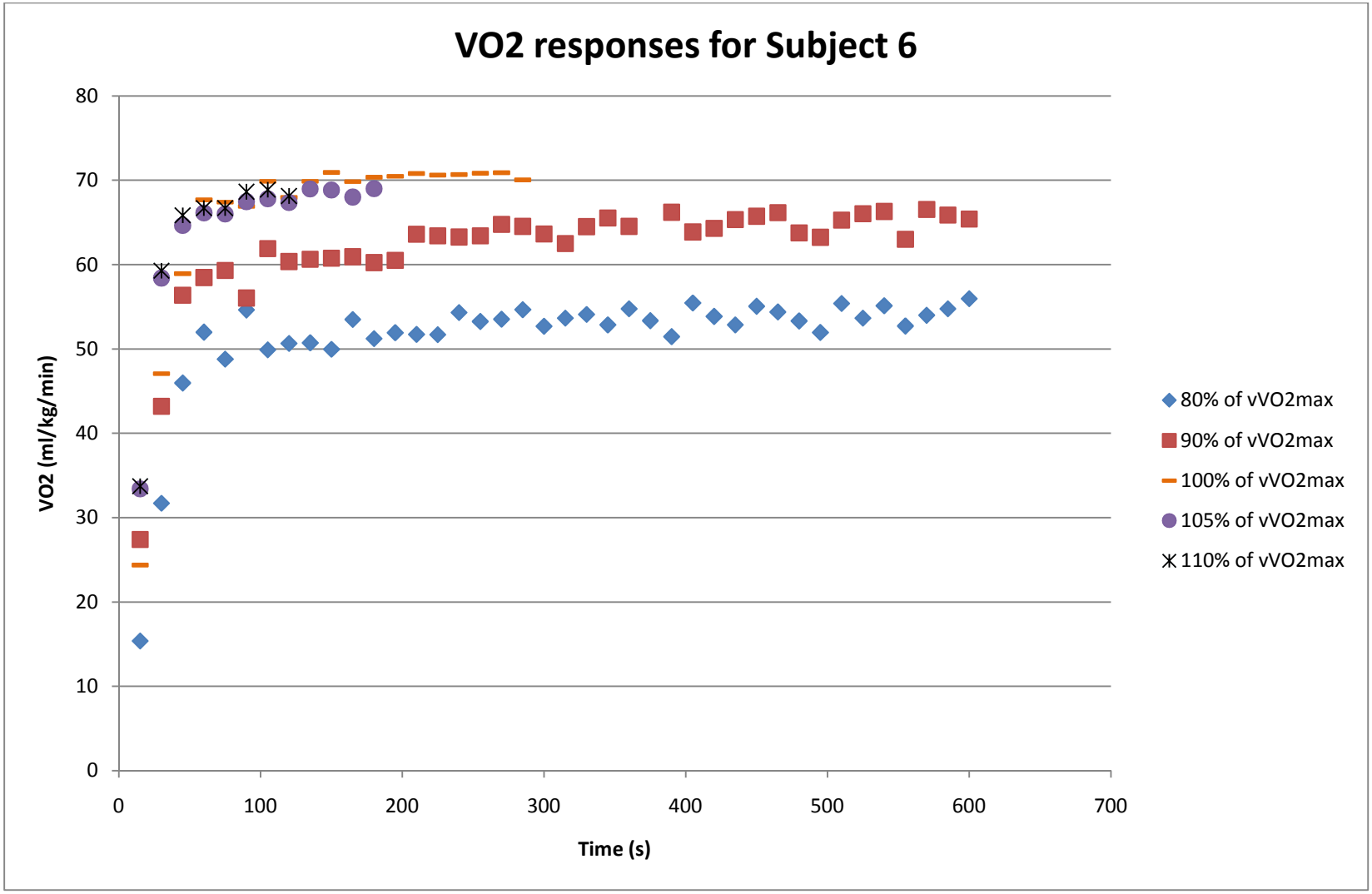


Figure 13, Subject 6 Time Course of the VO2 Response for Discrete Continuous Speeds

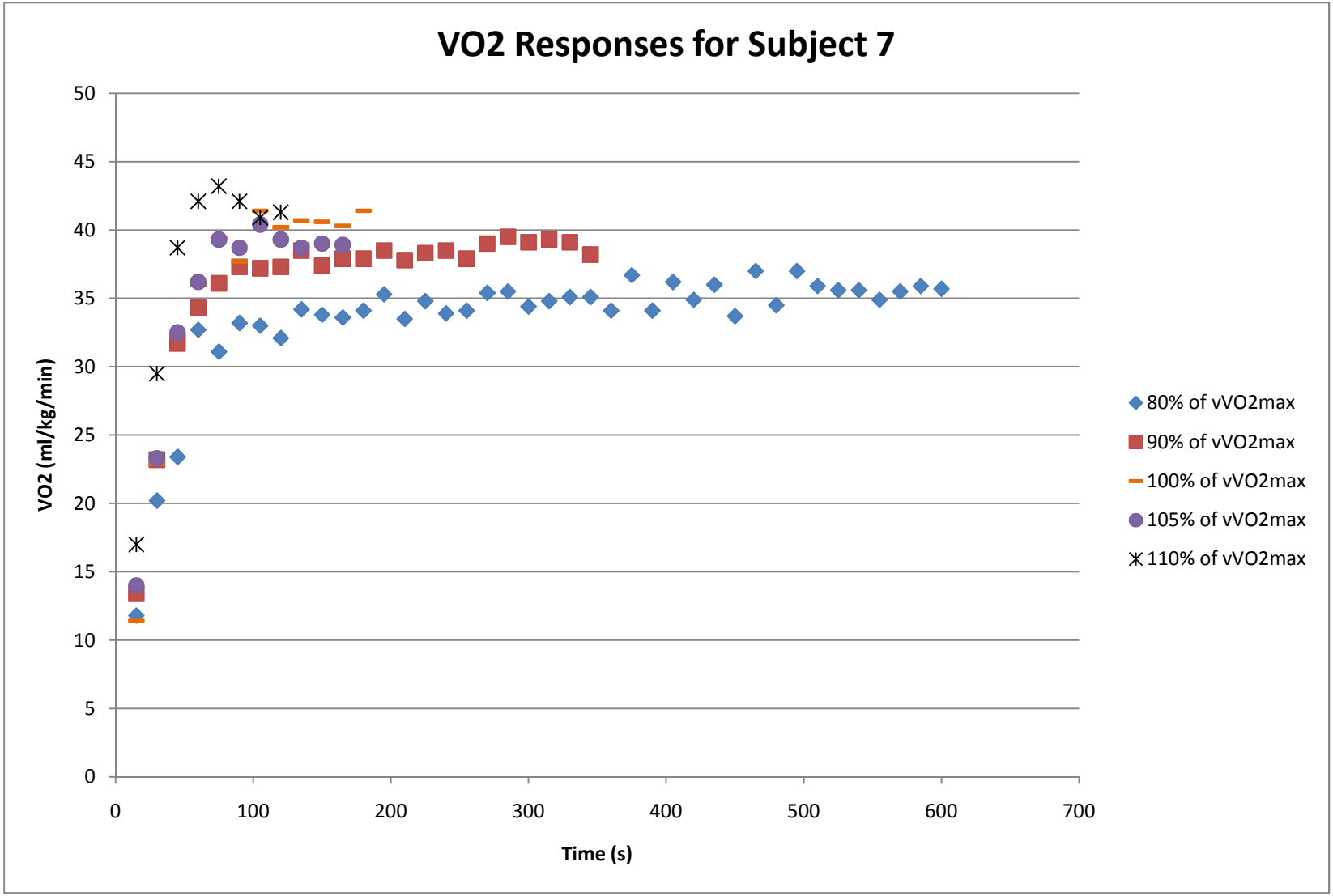


Figure 14, Subject 7 Time Course of the VO2 Response for Discrete Continuous Speeds

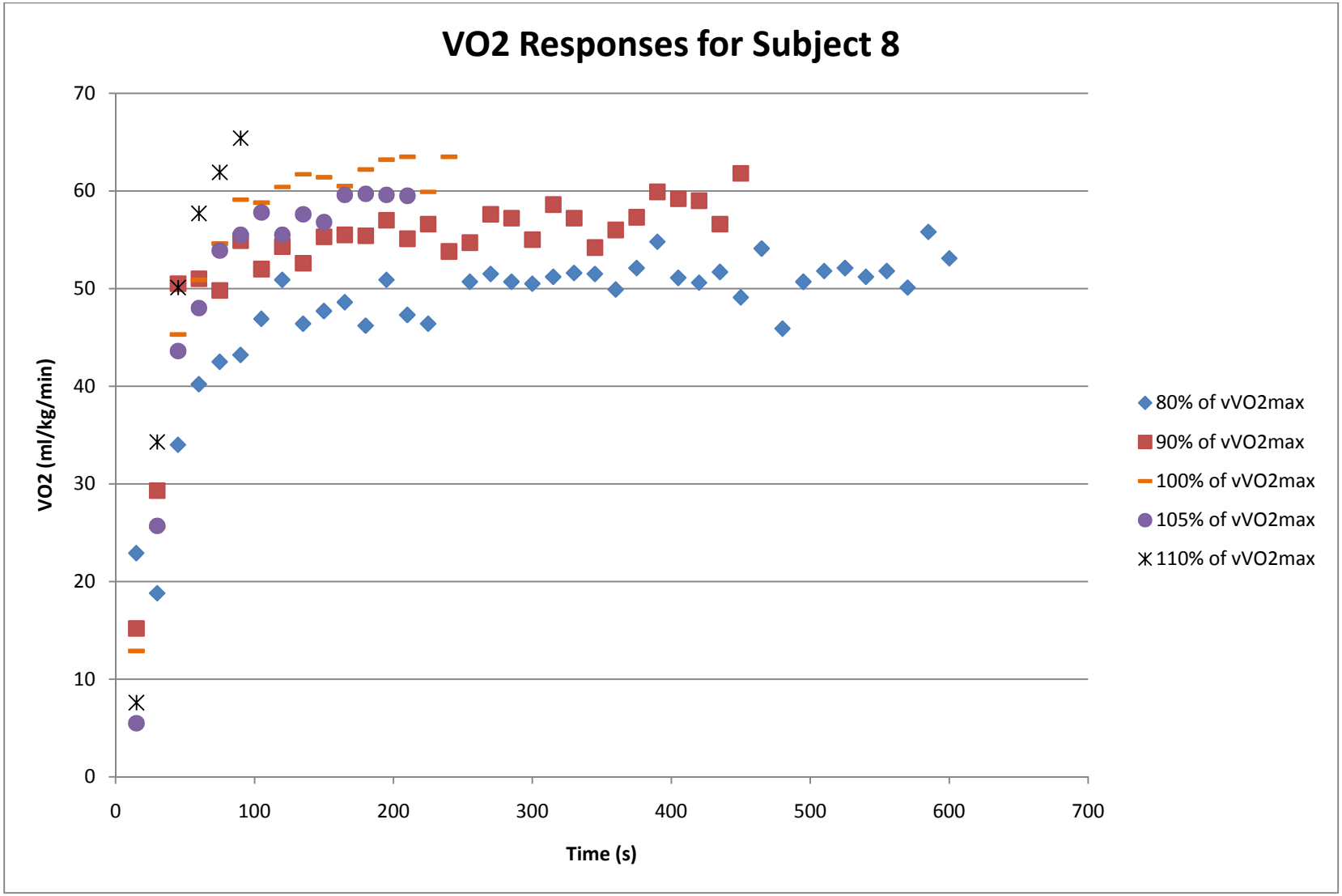


Figure 15, Subject 8 Time Course of the VO2 Response for Discrete Continuous Speeds

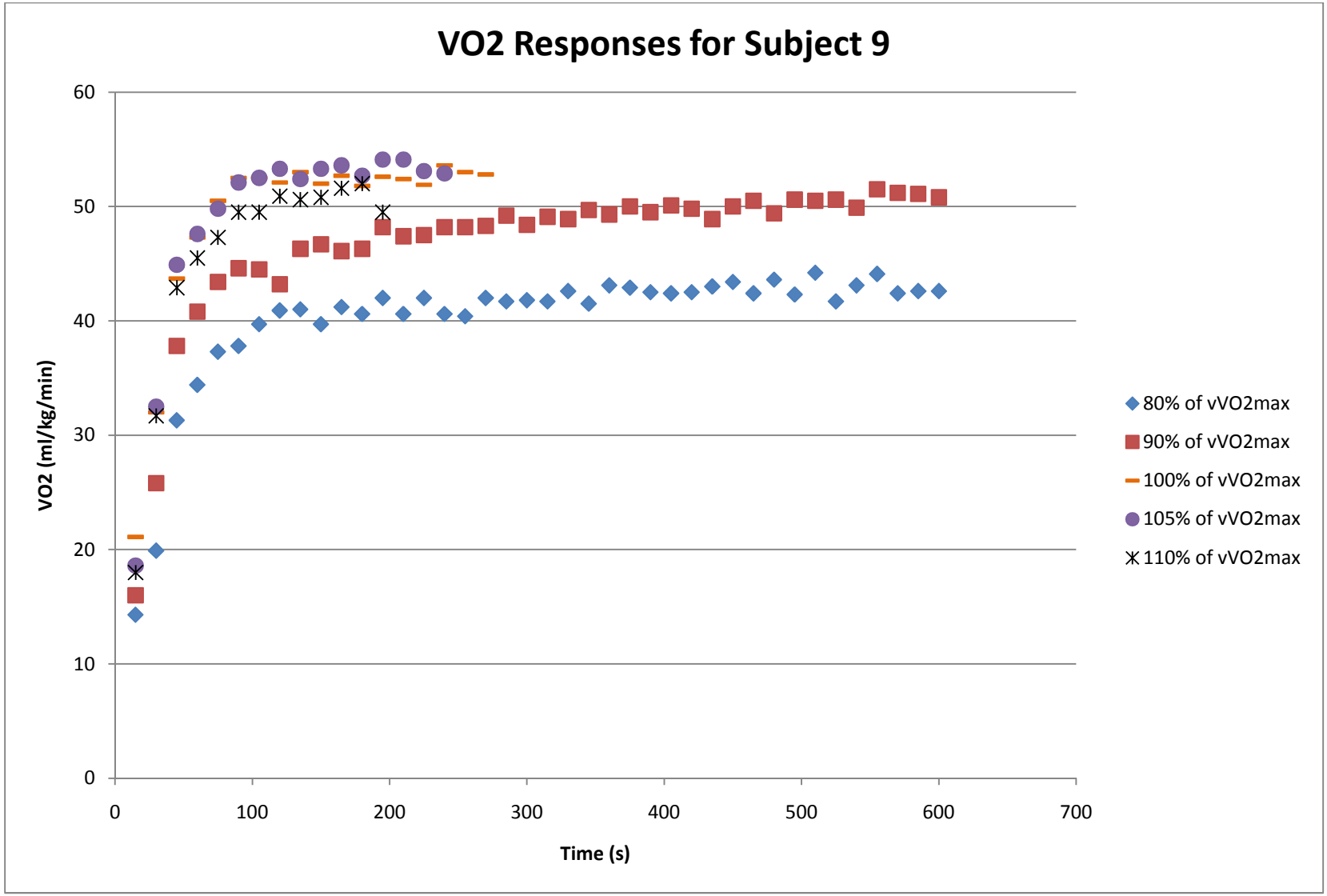


Figure 16, Subject 9 Time Course of the VO2 Response for Discrete Continuous Speeds

APPENDIX A

Screening Questionnaire:

1. Have any of the following occurred with your father or first-degree male relative before age 55, or with your mother or first-degree female relative before the age of 65: Myocardial infarction, coronary revascularization, or sudden death?

_____Yes _____No

2. Do you currently smoke, or quit smoking within the last 6 months?

_____Yes _____No

3. Has a doctor ever told you that you have hypertension, systolic blood pressure ≥ 140mmHg, diastolic blood pressure ≥90mmHg, or do you currently take antihypertensive medications?

_____Yes _____No

4. Has a doctor ever told you that you have hyperlipidemia ("High cholesterol") defined as LDL > 130 mg/dL, or been told you have HDL < 40 mg/dL, or are on lipid-lowering medication? If you have only been told total serum cholesterol, has it been >200mg/dL?

_____Yes _____No

5. Has a doctor ever told you that you have diabetes, or impaired fasting glucose defined as fasting glucose ≥ 100 mg/dL measured on two separate occasions?

_____Yes _____No

6. What is your height and weight?

Height (inches): *0.0254 = Height (meters):
Weight (lb.): /2.2 = Weight (kg):
Height (meters)*Height (meters) = [Height (meters)]^2:
Weight(kg) /[Height(meters)]^2 = BMI:
Is the participant's BMI > 30

_____Yes _____No

7. Do you run at least 15 miles per week on average, and have done so over the past 6 months?
_____Yes _____No

8. During exercise, do you experience chest discomfort, unreasonable breathlessness, dizziness, fainting, or blackouts?
_____Yes _____No

9. Do you take heart medications?
_____Yes _____No

10. Are you older than 35?
_____Yes _____No

If the participant answered "no" to all questions, except question 7, read the following text:
"*According to your screening, we have determined that you are eligible to participate in the study. We can set up a time with you in which you will be able to commit 30 minutes to an hour of your time for your first testing"*

If the participant answered "yes" to any question, except question 7, read the following test:
"According to your screening, we have determined that it might be unsafe for you to participate in this study given the presence of risk factors. Thank you for taking the time to contact us."

_____
Participant name

_____
Time and date of first meeting

_____
Date

APPENDIX B

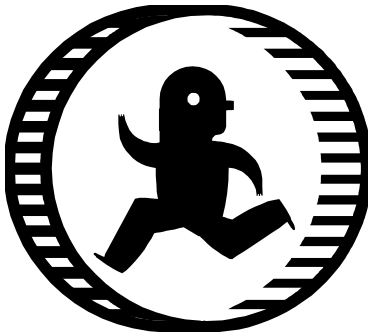
Sponsored by the Department of Kinesiology, Recreation, and Sports Studies

Are you a runner?

You can participate in a research study at the University of Tennessee, and get a free VO_{2max} test and body fat analysis in the process!

Requirements

- Run at least 15 miles a week regularly
- Be in good health, and 18-35 years old
- Willing to commit to 4 separate running tests
- Do interval training 1 or more days a week



Interested?

Contact Richie Castle at the number below to see if you are eligible

Richie Castle
865-974-5091
rcastle@utk.edu

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865-974-5091
rcastle@utk.edu
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rcastle@utk.edu
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rcastle@utk.edu

APPENDIX C

Research Team Member's Pledge of Confidentiality

As a member of this project's research team, I understand that I will be assisting in confidential fitness tests. The data and personal information in these fitness tests has been recorded from research participants who participated in this project on good faith that their test results and personal information would remain strictly confidential. I understand that I have a responsibility to honor this confidentially agreement. I hereby agree not to share any information in these fitness tests with anyone except the primary researcher of this project, his primary advisor, or other members of this research team. Any violation of this agreement would constitute a serious breach of ethical standards, and I pledge not to do so.

_____ _____

Research Team Member Date

APPENDIX D

Recruitment E-Mail

Dear Runner or runners,

I would like to invite you to participate in a study for the University of Tennessee looking to examine methods of testing aerobic fitness. If you choose to participate, you will receive free body fat, body mass index, and VO_{2max} testing. The testing consists of coming to our lab on the University of Tennessee campus for four separate days of testing. Testing will take 30 to 60 minutes for each day, and will consist of running at various high-intensity speeds to determine VO_{2max}.

To be eligible to participate you must be 18 to 35 years of age, healthy, and have been running an average of 15 miles a week for the past 6 months. If you would like to participate, please call Richie Castle at (865) 974-5091, or email me at rcastle@utk.edu.

Richie Castle, B.S.
Graduate Student in Exercise Physiology
University of Tennessee, Knoxville

APPENDIX E

INFORMED CONSENT FORM

TITLE: Why is there so much confusion about VO2 plateau? A re-examination of the work of A.V. Hill

Investigators: Richie Castle, B.S.
David R. Bassett, Jr., Ph.D.
Address:
Kinesiology, Recreation, and Sport Studies
322 HPER Building
University of Tennessee
1914 Andy Holt Ave., Knoxville, TN 37996-2700

Phone: (865) 974-5091

PURPOSE

You are invited to participate in a research study. The purpose of this study is to look at your rate of oxygen uptake near the end of a maximal exercise test to look for a plateau (i.e. leveling off) in oxygen uptake. You will be asked to participate in exercise testing on four separate days, while we study the effects of running speed on oxygen uptake.

PROCEDURES

On four separate days you will be asked to come to the Applied Physiology Laboratory in the Health, Physical Education & Recreation (HPER) building. Prior to your participation, you will be screened by the primary researcher to determine whether you have any risk factors that prevent you from taking part in this study. On the first day of testing, you will perform a maximal treadmill running test to determine your aerobic fitness. A researcher will measure your height, weight and body fat. Following these measurements you will undergo a maximal exercise test on a treadmill. This involves running on a treadmill until exhaustion while wearing a face mask, a vest housing two portable measurement devices, and heart rate monitor.

The next test will consist of a discontinuous exercise test. The laboratory test will consist of running on a treadmill at a single speed, resting, then repeating for faster speeds. While running, you will wear a face mask that will funnel all breathing through a mouth piece and chest harness that will house two light devices used in measuring oxygen content. In addition, the heart rate monitor will be worn around your chest. You will run for 10 minutes at a submaximal speed as a warm-up before running at each submaximal or maximal speed. Each 10 minute run will be separated by 15 minutes of rest, and the speed will be increased with each successive bout. Each bout will be performed for 10 minutes or until you are unable to continue, whichever comes first. The fastest speed will be equal to the fastest speed you attained on your first visit.

The final two tests will consist of you running at speeds that are approximately 5% and 10% faster than highest speed attained during the first test. Each test will be preceded by a 10 minute warm-up at a speed that is approximately 80% of the peak speed attained on the continuous run. The final two tests will be performed for 10 minutes until you are unable to continue, whichever comes first.

Participant initials_____

The total time commitment will be approximately 3 hours. One to six days of rest will be allowed between tests.

BENEFITS OF PARTICIPATION
By participating in this study, you will learn your current aerobic fitness level (VO_{2max}), body mass index, and percent body fat.

RISKS OF PARTICIPATION
Risks are similar to those experienced during a typical vigorous workout. Some risks include muscle soreness, dizziness, headache, leg discomfort, gastrointestinal discomfort, and a very rare possibility of a cardiac event. Sudden cardiac death during exercise among 18 to 35 year old persons could occur, but this is very rare. Researchers collecting data will be CPR/AED certified. Falling while running is the most likely injury. During running, one person will spot you, and there will be padding at the rear of the treadmill. During any part of the test, you may stop for any reason by signaling the researchers, or jumping off and straddling the treadmill belt. If the primary researcher feels it is unsafe for you to continue a test, he will terminate the test immediately. The University of Tennessee does not "automatically" reimburse subjects for medical claims or other compensation. If physical injury is suffered in the course of research, or for more information, please notify Richie Castle at (865) 974-5091 or rcastle@utk.edu.

CONFIDENTIALITY
Only the researchers will have access to your test results. All information will eventually be used for a research report, however, your private information will not be presented in the report.

CONTACT INFORMATION
If you have questions or concerns at any time during the course of the testing procedures or after completion of the testing procedures, you may contact Dr. David Bassett at (865) 974-8766. If you have questions concerning your rights as a participant, contact the Compliance Section of the Office of Research at (865) 974-3466.

PARTICIPATION
Your participation in this study is strictly voluntary. You have the option to withdraw from the study at any time without penalty. If you withdraw from the study, then all data will be given to you or destroyed.

AUTHORIZATION

By signing this informed consent form, I am indicating that I have read and understood this document and have received a copy of it for my personal records. I have been given the opportunity to ask questions about the research study. By signing this form I indicate that I agree to serve as a participant in this research study.

_____
Participant's name

_____ _____
Participant's signature Date

_____ _____
Investigator's signature Date

Vita

Richie Castle often spends his time wishing that he were Bruce Wayne and unsuccessfully picking up women at bars. It has not occurred to him that those two reasons may be linked.

Although aspiring to become a physician, life dealt him a different hand and he followed up on his undergraduate work and pursued a master's in exercise physiology. Be began the process arrogant and ignorant. As he learned more, the adage, "the more you know, the less you realize you know," rang true for him, and he learned the core of humility: no matter how much you know, there is always somebody that knows more.

He was accepted into Nova Southeastern University School of Osteopathic Medicine in February of 2011. Before you ask him, no he is not doing it for the money, and no he does not know what specialty he wants to do. However, should you ask him, he will be willing to see you as a patient in four years. Also, to be honest, he doesn't really understand the difference between osteopathic and allopathic medicine, but supposes he will in a couple of years.

He loves his mother who died just a day after defending his thesis. It was not unexpected, but the timing was. One of his pet peeves is when a person says, "this is the last thing I need right now," about an event that is never advantageous (e.g. when exactly would you need your car to break down?). His mother's death will never be a happy event, but he appreciates that the timing was as good as it was.

He is incredibly happy to finally become a doctor after several medical school rejections, hours of volunteer work, days spent on classes necessary for medical school and unnecessary for graduation, and answering the essay question "why do you want to become a doctor" written in ten similar but still intrinsically different forms. He is also happy to move. Knoxville is a college town and he graduated from college four years ago. Finally, he is happy to submit this monster of a learning experience. I'll close with a quote from my mother's husband (who enjoys driving for the sake of driving), "The thing about taking a trip, is that once I get where I'm going, there is nothing for me to do except pack it up and go home. You spend this time thinking the destination is the fun part, then I realize it was the drive."