ABSTRACT

Title of Thesis:	DEVELOPMENT OF A TRANSFER FUNCTION FOR MAXIMUM OXYGEN DEFICIT IN EXERCISE WHILE WEARING A RESPIRATORY PROTECTIVE MASK
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Successful innovation of respirator masks depends on accurate models of exercise performance during respirator wear. Any valid model must include oxygen deficit (OD), which is a vital indicator of the physiological changes that occur during the transition from rest to exercise. OD represents anaerobic metabolism and is related to performance time.

The goal of this research was to model the effect of a respirator on oxygen deficit. The following objectives were thereafter studied: (1) use experimental exercise data to calculate OD with a respirator; (2) determine the maximum OD and corresponding standard deviation values; and (3) develop a transfer function that accurately predicts OD in exercise while wearing a respirator.

The study results indicated that oxygen deficit was significantly affected by exercise intensity and performance time; at 85% maximal capacity, respirator wear was not a significant factor affecting OD. Notably, the transfer function developed will serve a valuable predictive purpose.

DEVELOPMENT OF A TRANSFER FUNCTION FOR MAXIMUM OXYGEN DEFICIT IN EXERCISE WHILE WEARING A RESPIRATORY PROTECTIVE MASK

by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2006

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Acknowledgements

I would like to extend my thanks to all of those who helped me to complete this work, including my committee for their guidance and my subject volunteers for their participation. Also, thanks to William H. Scott, Jr. for his help with exercise testing. I am additionally grateful to Dr. Richard McCuen for his unparalleled help in my modeling efforts and analysis. His help was more than I could have ever asked for.

I would also like to thank those who helped to keep me sane throughout this process, including my family, friends, and especially my husband. The support of these people helped to keep me on track and focused.

I dedicate this to those who aided in this accomplishment in any way. Thank you.

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Chapter 1: Research Introduction

1-1. Justification of Research

Respiratory protective masks are worn to protect the wearer from ambient conditions that may be detrimental to their respiratory health. In several occupations, respirators are a vital piece of equipment that enable the wearer to perform necessary tasks in line with their work. Proper design of respirators is, therefore, crucial.

A key step in the proper design of respirators, as well as in the regulation of occupational safety, is the modeling of exercise performance while wearing a respirator. A model that accurately predicts performance and performance time must include oxygen deficit, which is a measure of anaerobic capacity and ATP (adenosine triphosphate) re-synthesis. Oxygen deficit (OD) occurs during the transition from rest to exercise at any intensity, and thus, should be included in performance models.

A model was developed at the University of Maryland, College Park, to predict exercise performance while wearing a respirator (Chiou, 2004). The model includes the oxygen deficit, but prediction of this parameter is based on the performance of individuals who are not wearing respirator masks. This model is an extension of a previous model that used OD as the primary predictor of performance time (Coyne, 2001). Based on the lack of an appropriate means of predicting oxygen deficit for respirator wearers, the current model should be extended to include a transfer function to determine the maximum oxygen deficit (OD_{max}) that occurs during exercise performance while wearing a respirator; determination of OD_{max} is work-rate dependent.

Data should be collected for several individuals through experimental exercise tests to determine individual values of oxygen deficit for those wearing a respirator mask. Based on this data, relationships between OD, performance time, and work rate should be evaluated, and a transfer function may then be developed for use in predicting oxygen deficit in other individuals. This function will, thereafter, be available for future incorporation into the current model to ensure that a more accurate description of maximum oxygen deficit is included for respirator wearers.

1-2. Research Objectives

The goal of this research was to model the effect of a respirator on oxygen deficit. Based on this larger goal, the primary objectives of this research study were defined as follows:

1. Calculate the oxygen deficit during exercise while wearing a respirator mask by using data from experimental exercise tests. Thereafter, these values can be compared to oxygen deficit values determined from exercise tests completed without a respirator.
2. Determine the mean maximum oxygen deficit values and the corresponding standard deviations for exercise both with and without a respirator, and across a range of different work intensities;
3. Develop a transfer function that accurately describes the oxygen deficit developed during exercise with a respirator; this function will be available for future incorporation into a model of exercise performance while wearing a respiratory protective mask.

Chapter 2: Research Background

2-1. Introduction to Oxygen Deficit

The concept of oxygen (O_2) deficit was first introduced by Krogh and Lindhard (1920) as the difference between total O_2 uptake ($\dot{V}O_2$) at the commencement of exercise and O_2 uptake at the steady-state level of exercise (Figure 2-1.1). Quantitatively, the O_2 deficit represents the difference in total oxygen consumed during exercise and the theoretical oxygen consumption had steady-state metabolism begun immediately with exercise initiation (McArdle et al., 2000). The difference is attributable to the immediate use of adenosine triphosphate (ATP) for energy without the requirement of oxygen; oxygen is more heavily utilized as exercise continues (McArdle et al., 2000). Hence, the O_2 deficit represents anaerobic metabolism and the re-synthesis of ATP (Scott, 2000; Graham, 1996; McArdle et al., 2000; Medbo et al., 1988). As such, OD is used as a determinant of anaerobic capacity, "the greatest anaerobic energy production that an individual can obtain at any exercise bout performed to exhaustion" (Bangsbo, 1996).

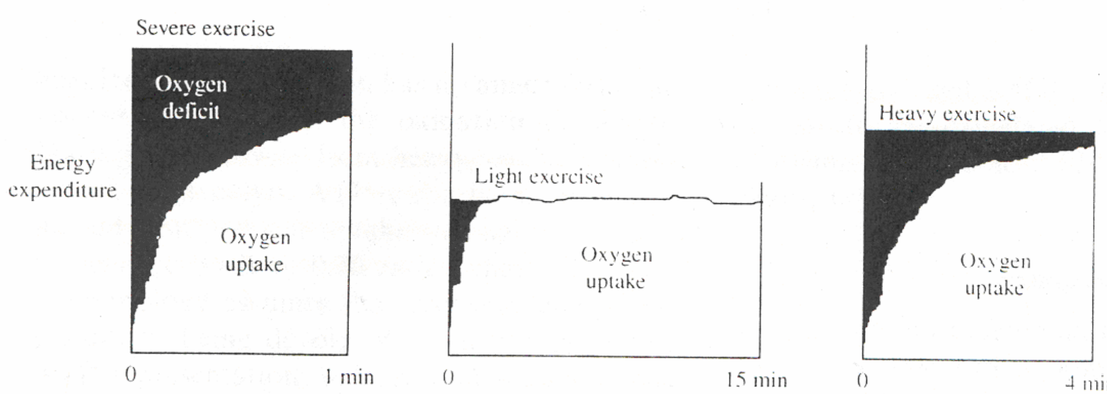


Figure 2-1.1. Oxygen deficits during different exercise intensities (Scott, 2000).

It was not until the late 1960s that accumulated oxygen deficit (AOD) was used as a measure of anaerobic capacity (Ericksson et al., 1973; Hermansen, 1969; Karlsson and Saltin, 1970). Saltin (1990), as well as Green and Dawson (1993), concluded that the O_2 deficit is the only measure that can potentially quantify anaerobic capacity. In fact, OD has been shown to be quantitatively similar to the anaerobic capacity determined from changes in anaerobic metabolites (Green and Dawson, 1993; Medbo and Tabata, 1993; Bangsbo et al., 1990).

The mean oxygen deficit is then calculated as the accumulated oxygen deficit divided by the exercise duration. It represents the mean rate of anaerobic energy release (Medbo and Burgers, 1990; Ramsbottom et al., 2001). The literature reports a range of mean maximal accumulated O_2 deficit values for humans, from 33 ml/kg/min in prepubescent males (Eriksson et al., 1973) to 80-85 ml/kg/min in sprint athletes (Medbo and Burgers, 1990; Medbo et al., 1988; Scott et al., 1991). Maximal OD values predicted for humans are ≈100 ml/kg/min (Saltin, 1987). Maximally accumulated O_2 deficit values of endurance athletes and untrained subjects are similar, ranging from 50 to 65 ml/kg/min (Medbo and Burgers, 1990; Scott et al., 1991); this similarity may be explained as a less efficient use of anaerobic energy transfer processes.

2-2. Additional Physiological Factors

2-2-1. Cyclic Process of Energy Production

The process of energy production and use is cyclical in nature, adding to the complexity of the issue of oxygen deficit. Glycogen, the storage form of carbohydrates, is used to maintain blood glucose levels. Glucose is an important sugar for energy metabolism, serving as an essential ingredient for the synthesis of ATP, which is chemical energy used for muscle activity (McArdle et al., 2000). During an anaerobic process termed glycolysis, glucose is broken down into pyruvate, with ATP simultaneously synthesized (McArdle et al., 2000).

During exercise, immediate energy is obtained from ATP and creatine phosphate stored in muscle. Creatine phosphate can provide energy rapidly and in the absence of O_2 for the re-synthesis of ATP (McArdle et al., 2000). In the early minutes of continuing exercise and during which anaerobic conditions exist, stored muscle glycogen is the primary energy source. Glycogen stored in the liver is converted to glucose, via a process known as glycogenolysis, and is then transported to active muscle for additional ATP production. Glycolysis must then occur to provide the necessary ATP for continued exercise (McArdle et al., 2000). Under anaerobic conditions, the pyruvate formed via glycolysis is converted to lactate, which is further used in the liver as part of the Cori cycle for the synthesis of glucose in a process known as gluconeogenesis (McArdle et al., 2000). As exercise continues, aerobic conditions ensue and additional methods are utilized for the production of glucose and ATP. Carbohydrate metabolism during exercise produces alanine, which is then used in the liver to make glucose via gluconeogenesis. Alanine is used in the alanine-glucose cycle to produce glucose that is released into the blood for delivery to the muscles for energy (McArdle et al., 2000).

ATP is utilized for energy and must then be re-synthesized to provide continued energy sources for sustained activities. Consideration of oxygen deficit requires consideration of this cyclic process, since oxygen deficit represents ATP re-synthesis as previously noted. Simultaneous forward and reverse processes of glycolysis and gluconeogenesis make the measurement of maximum oxygen deficit particularly challenging. What was sought here was not a characterization of each process and their interrelationships, but rather, the net effect of the processes for overall quantification that can be used as a limiting metric in exercise models.

2-2-2. Components of Oxygen Uptake

During graded exercise a point is reached at which the increase in minute ventilation increases disproportionately to the increase in $\dot{V}O_2$; this point is labeled the ventilatory threshold (VT) (McArdle et al., 2000). The VT is additionally important for defining the various components of oxygen uptake. Constant workload exercise below the VT is characterized by an initial rapid increase in $\dot{V}O_2$, which is representative of a fast component of oxygen uptake. The fast component is truncated upon the attainment of a steady state (Yano et al., 2004). However, for constant workload exercise above the VT, the $\dot{V}O_2$ response shows a secondary increase to maximum oxygen uptake ($\dot{V}O_{2\,max}$), which is indicative of a slow component (Scott, 1999).

The slow component of $\dot{V}O_2$ represents an additional energy requirement above that of steady state and is found to occur at exercise intensities that are defined as *severe* or *heavy* (Scott, 1999). Moreover, the final $\dot{V}O_2$ achieved after initiation of the slow component surpasses the estimated intensity-$\dot{V}O_2$ relationship (Yano et al., 2004; Scott, 1999). It should additionally be noted that the slow component of oxygen uptake has been found to be exercise intensity-dependent (Ocel et al., 2003; Jacobsen et al., 1998).

2-3. Methods of Determining O_2 Deficit

2-3-1. MAOD Method

The process that is now considered the "traditional" oxygen deficit method was presented by Medbo et al. (1988). The process incorporates ten bouts of exhaustive treadmill running at different submaximal exercise intensities in which $\dot{V}O_2$ is measured. The data produced from these tests are combined, and linear regression of the submaximal $\dot{V}O_2$ values and exercise intensity/treadmill speed is completed after forcing the data through a y-intercept of 5 ml/kg/min (representing resting oxygen uptake). The relationship between submaximal $\dot{V}O_2$ and exercise intensity is determined on an individual basis and extrapolation of this linear regression provides determination of O_2 demand (Medbo et al., 1988). The submaximal O_2 demand is used to define the intensity of an exhaustive bout of supramaximal exercise and is also considered the O_2 demand of the intense exercise. After completion of the supramaximal exercise, the extrapolated O_2 demand is multiplied by the exercise duration to define accumulated oxygen demand (AOD). The accumulated oxygen uptake is calculated by multiplying the O_2 uptake observed during the supramaximal exercise by the exercise time. Finally, the AOD is determined by subtraction of the accumulated O_2 uptake from the accumulated O_2 demand (Medbo et al., 1988) (Figure 2-3-1.1).

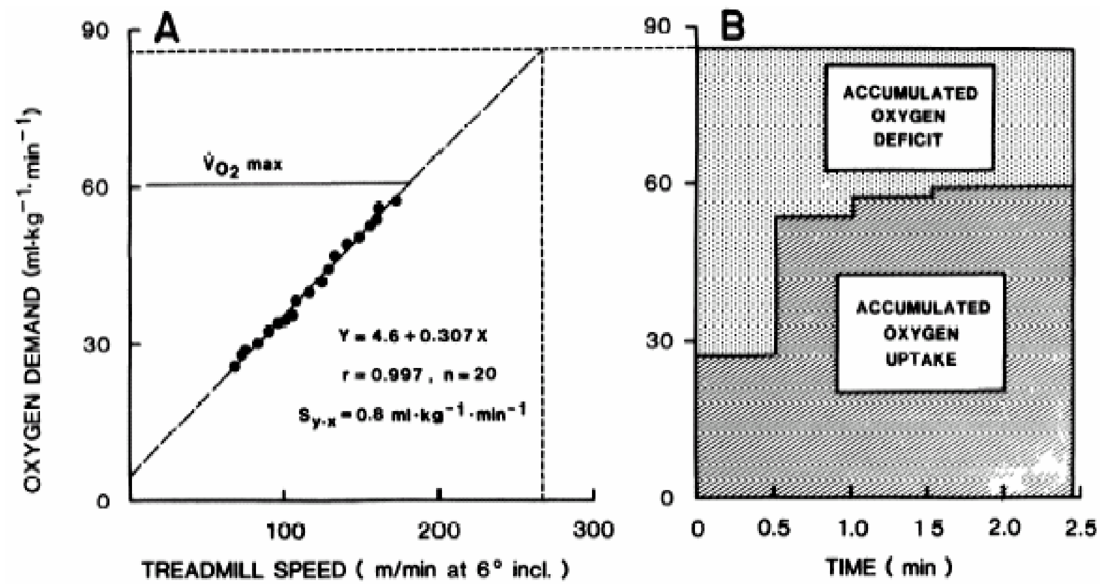


Figure 2-3-1.1. A) Relationship between exercise intensity (as determined by treadmill speed) and O_2 demand; B) accumulated oxygen deficit, calculated as the difference between accumulated oxygen demand and accumulated oxygen uptake (Medbo et al., 1988).

The duration of the supramaximal exercise bout is of concern, as duration of an anaerobic capacity test must be metabolically appropriate. This means that the test should be long enough to exhaust anaerobic metabolic processes, but should be brief enough to minimize energy influences from aerobic metabolism (Vandewalle et al., 1987; Gastin et al., 1995). This is to ensure that the immediate use of ATP is exhausted before oxygen is required for continued energy. Medbo et al. (1988) reported that exercise should be done at a severe intensity that provokes fatigue in approximately 2 to 4 minutes, while Saltin (1990) claimed that fatigue should occur within 2 to 15 minutes after the onset of exercise.

Despite the reliance on this "traditional" method, inherent limitations to its use exist. More specifically, the O_2 deficit method, or the MAOD (maximally accumulated oxygen deficit) method, is based on two primary assumptions:

1. The oxygen demand during supramaximal or intense exercise can be estimated from a linear relationship between oxygen uptake and exercise intensity during submaximal exercise; and

2. Supramaximal exercise produces a constant oxygen demand.

Bangsbo (1996) suggested that these assumptions may not be valid for a multitude of reasons, and as such, the O_2 deficit method may not be an appropriate means of determining O_2 deficit. However, this was not to say that the method was inadequate for the purposes of mathematical prediction of exercise characteristics.

The first assumption may be invalid, as it was reported that the relationship of power output and oxygen uptake is not linear from low to submaximal speeds; this nonlinearity may be due in part to the different musculature recruited at different times (Bangsbo et al., 1993). Moreover, evidence exists that strongly suggests that at high velocities in the severe intensity domain, the relationship between O_2 demand and velocity, and thus intensity, is curvilinear as opposed to linear (Hill et al., 2002). Therefore, based on the lack of a linear relationship, extrapolation may be inappropriate and may result in underestimated oxygen demands at higher intensities (Bangsbo, 1996; Hill et al., 2002). Ramsbottom et al. (1994) suggested, however, that the underestimations may be small. It should also be noted that different musculature is involved during different exercise intensities, leading also to different levels of lactate release; these physiological distinctions will differentiate lower exercise intensities from higher intensities (Bangsbo, 1996; Graham, 1996; Bangsbo, 1998).

The second assumption may also be invalid, as it has been suggested that energy production may vary throughout intense exercise (Bangsbo, 1996). Hill et al. (2002) questioned the validity of this assumption based on reduced efficiency as exercise continues, as fatigue begins to affect the subject and muscle fiber recruitment may change. Green and Dawson (1996) further stressed that anaerobic capacity should be mode-specific because of the amount of musculature involved.

Based on the invalidation of the assumptions used in the MAOD method, Bangsbo (1996) suggested that the O_2 deficit is an inaccurate measure of anaerobic metabolism during whole body exercise. Other studies also recognized that potential problems may exist in the assumptions of the O_2 deficit method (Hill et al., 2002; Bangsbo, 1998; Moore and Murphy, 2003). Despite such assertions that the O_2 deficit method is not valid, many studies have used the method and determined that OD may, in fact, be a useful estimate of anaerobic capacity (Scott et al., 1991; Ramsbottom et al., 2001; Doherty et al., 2000; Gardner et al., 2003; Gastin et al., 1995).

2-3-2. Additional Methods

Other methods have been used to determine the oxygen deficit in an attempt to either validate or further refute the O_2 deficit method. For example, Scott (1991) found significant correlations between the values obtained from the O_2 deficit method and other existing anaerobic tests, including Wingate power and treadmill work. Moreover, Hill (1996) found that OD could be measured without extrapolation to determine O_2 demand. The non-extrapolative procedure relies on an iterative least squares method to derive O_2 demand and deficit, using accumulated $\dot{V}O_2$, power, and time to exhaustion obtained from experimental, severe intensity exercise tests. Hill (1996) utilized the following equation:

$$O_2 \text{ deficit} = (O_2 \text{ demand} \cdot \text{power} \cdot \text{time}) - \text{accumulated } \dot{V}O_2 \qquad (2\text{-}3\text{-}2.1)$$

The method employed by Hill (1996) relied on three assumptions: 1) O_2 demand is a function of exercise intensity; 2) O_2 deficit in intense exercise is independent of the exercise duration, as long as the exercise lasts 1 to 16 min; and 3) O_2 demand, and thus efficiency, does not change during supramaximal exercise. Based on the results of this study, it was established that O_2 demand and deficit may be determined by utilizing several high intensity tests without extrapolating O_2 demand from submaximal exercise. Furthermore, the values obtained via this method were highly correlated with the conventional O_2 deficit method (Hill, 1996). Such results were verified in another study by Hill (2002).

In addition to the method used by Hill (1996), Whipp and Ward (1993) proposed a method in which O_2 deficit was determined as the product of $\dot{V}O_{2\,max}$ and the time constant (tau) of the $\dot{V}O_{2\,max}$ response. Hill (2002) compared this method to the conventional method of Medbo et al. (1988) and to Hill (1996). Comparisons showed that the values obtained using the Hill (1996) method and the Medbo et al. (1988) method were equal, while those from the Whipp and Ward (1993) method were lower than those of the other methods (Hill, 2002).

Further studies attempted to compare shuttle runs and all-out tests with the conventional MAOD method. Performance during high intensity shuttle runs showed a strong correlation with MAOD values (Ramsbottom et al., 2001; Moore and Murphy, 2003), as did results from all-out procedures that employed supramaximal all-out intensity exercise as opposed to constant intensity exhaustive exercise (Gastin et al., 1995). Gastin et al. (1995) also showed that the time required to reach maximal AOD is shorter for all-out exercise than for constant intensity exercise. Moreover, it is likely that the test best suited for maximal AOD determination is based on individual abilities, including energy production mechanisms, training type and quantity, and inherent physiological characteristics, such as musculature composition. For untrained individuals an all-out protocol with a set duration is likely more appropriate (Gastin et al., 1995).

2-4. Oxygen Deficit Differences

Accumulated oxygen deficit has been found to be a reproducible measure (Doherty et al., 2000; Ramsbottom et al., 1994), which allows for comparison of AOD values among different groups, as well as among individuals before and after training. Maximal O_2 deficit is increased after high-intensity training on account of improvements in anaerobic capacity (Green and Dawson, 1993; Ramsbottom et al., 2001). Similar improvement in AOD after training was observed in both men and women (Medbo and Burgers, 1990; Ramsbottom et al., 2001). The training-induced increase was associated with an enhanced ability to perform high intensity exercise at a greater volume due to a slower rate of oxygen deficit utilization (Ramsbottom et al., 2001). Furthermore, it was found that increases in oxygen deficit resulted in greater time to exhaustion when at the minimum speed at which $\dot{V}O_{2\,\max}$ was elicited (Renoux et al., 1999), enabling an increased ability to sustain exercise on account of an increase in anaerobic efficiency.

A reduction in O_2 deficit is associated with an improvement in endurance performance, as the smaller OD is associated with increased exercise duration (Demarle et al., 2001; McArdle et al., 2000). This is due to the aerobic nature of the activity, such that more of the energy cost is handled aerobically, as opposed to sprint-type activity that is anaerobic-based. Aerobic exercise requires a faster transition from immediate anaerobic metabolism, while anaerobic exercise longer utilizes pathways of anaerobic metabolism and thus, is more heavily influenced by oxygen deficit.

2-5. Modeling of Oxygen Deficit and VO_2 Kinetics

Multiple efforts have been made to model and simulate oxygen deficit during exercise (Yano et al., 2003; Demarle et al., 2001; Bearden and Moffatt, 2000; Barstow, 1994; Carter et al., 2000; Hill et al., 2003; Coyne, 2001; Chiou, 2004). Each model provided relevant information to the modeling question at hand, and thus, will be discussed briefly herein.

2-5-1. Yano et al. Model

Yano et al. (2003) used computer simulation to estimate $\dot{V}O_2$ kinetics, oxygen deficit, and oxygen debt in decrement-load exercise (DLE); oxygen debt is the additional oxygen uptake above the resting level that occurs during exercise recovery to return the body to pre-exercise conditions and to support the physiological changes occurring during the recovery process (McArdle et al., 2000). The purpose of the study was to establish if the difference between the O_2 debt and deficit produced during DLE was related to $\dot{V}O_2$ kinetics. OD was modeled by defining the oxygen debt per unit time, and then multiplying this value by the duration of time elapsed and summing the products:

$$Dt - \dot{V}O_2(t) = \sum [R\dot{V}O_2(t)n] \qquad (2\text{-}5\text{-}1.1)$$

where $Dt - \dot{V}O_2$ = oxygen debt per unit time and $R\dot{V}O_2(t)n$ = recovery $\dot{V}O_2$ values in constant-load exercises (Yano et al., 2003). Then,

$$O_2 deficit = \sum (Dt - \dot{V}O_2 \cdot \Delta t) \qquad (2\text{-}5\text{-}1.2)$$

where Δt = the duration of time elapsed (Yano et al., 2003). The results of the simulation indicated that oxygen deficit can be modeled similarly to oxygen uptake kinetics if the repayment of oxygen debt during decrement-load exercise was included (Yano et al., 2003).

2-5-2. Demarle et al. Model

Demarle et al. (2001) hypothesized that OD and the slow component of $\dot{V}O_2$ may be reduced after a program of specific endurance training. Moreover, these reductions may be responsible for an increase in performance time above the lactate threshold. In this study, oxygen kinetics were simulated using three models: a single exponential model and two double-exponential models. Oxygen deficit was defined according to the following equation:

$$DO_2 = (A_1 \times TD_1) + (A_1 \times \tau_1) \qquad (2\text{-}5\text{-}2.1)$$

where DO_2 = the oxygen deficit (ml), A_1 = the asymptotic amplitude of the fast component of $\dot{V}O_2$ (ml/s), τ_1 = the time constant of the fast component, and TD_1 = the time delay from the onset of exercise for the fast component of $\dot{V}O_2$ (Demarle et al., 2001). Demarle et al. (2001) showed that in a severe run, OD and the slow component were not related to the performance time. However, after a specific endurance training program, a decrease in OD was observed that was related to the observed increase in run time until exhaustion.

2-5-3. Bearden and Moffatt Model

Bearden and Moffatt developed a model that considered exercise as two phases for the calculation of the O_2 deficit. This approach was taken to account for the overestimations in recovery oxygen consumption that have been shown to occur using the traditional OD calculation (Bearden and Moffatt, 2000). In this model, oxygen kinetics were simulated using three models: a single exponential model and two double-exponential models, as in the model developed by Demarle et al.

The double monoexponential equation proposed by Bearden and Moffatt (2000) was as follows:

$$\dot{V}O_2(t) = B\dot{V}O_2 + A_1[1 - e^{-(t-TD_1)/\tau_1}] + A_2[1 - e^{-(t-TD_2)/\tau_2}] \qquad (2\text{-}5\text{-}3.1)$$

in which $B\dot{V}O_2$ = the baseline $\dot{V}O_2$, A_1 and A_2 = $\dot{V}O_2$ amplitudes for the fast and slow components, respectively, TD_1 and TD_2 = the time delays for the fast and slow components, respectively, and τ_1 and τ_2 = the time constants for the fast and slow components after their time delays, respectively. Equation 2-5-3.1 was then used in the Bearden and Moffatt (2000) model as part of the traditional calculation of OD:

$$O_2def_{Trad} = t(B\dot{V}O_2 + A_1 + A_2) - \int \dot{V}O_2(t)dt \qquad (2\text{-}5\text{-}3.2)$$

Bearden and Moffatt went on to conclude that an accurate model of O_2 deficit must include the slow component of $\dot{V}O_2$; the slow component is an oxygen requirement with a delayed onset from rest to exercise. This slow component makes the transition to heavy exercise essentially biphasic with two separate transitions that should be accounted for in the model: one immediate and one delayed (Bearden and Moffatt, 2000). Hence, Equation 6 was determined by Bearden and Moffatt to be invalid about the lactate threshold, as the traditional O_2 calculation is not biphasic in nature. Instead, a new means of calculating OD was developed by Bearden and Moffatt (2000) that accounted for the two distinct components of $\dot{V}O_2$:

$$O_2def_{New} = O_2def_{Trad} - (A_2 \times TD_2) \qquad (2\text{-}5\text{-}3.3)$$

2-5-4. Three-Phase Model

A three-phase exponential model is commonly used to describe oxygen uptake kinetics (Barstow, 1994; Carter et al., 2000; Hill et al., 2003). Phase I, the cardiodynamic component, occurs in the early seconds of exercise and reflects an initial increase in $\dot{V}O_2$. The early $\dot{V}O_2$ rise is caused by an increase in pulmonary blood flow with exercise onset, as cardiac flow increases in direct proportion to exercise intensity, increasing rapidly initially followed by a more gradual increase to steady-state levels (McArdle et al., 2000). The cardiodynamic component of the exercise response is followed by the primary component (phase II), which occurs approximately 10 to 20 seconds after exercise commencement. This phase of exercise is characterized by an exponential increase in $\dot{V}O_2$ to steady state (Hill et al., 2003). Phase III, termed the slow component, is observed during high-intensity exercise, is characterized by an additional rise in $\dot{V}O_2$ to a secondary steady state, and is typically manifested after approximately 90 to 110 seconds of exercise (Hill et al., 2003). This component is believed to be based on a shift in muscle fiber recruitment, in which the body shifts to an increased reliance on type II (predominately anaerobic) muscle fibers to meet the demands of heavy exercise and overcome fatiguing muscles (Carter et al., 2000). While not physiologically distinct, the three phases are modeled as such with each phase terminating at the onset of the subsequent phase.

The three-phase model was defined as follows (Barstow, 1994):

$$\dot{V}O_2 = \dot{V}O_2(0) + A_0^{on}\left(1-e^{-\frac{t}{\tau_0^{on}}}\right) \quad \text{Phase I (cardiodynamic component)}$$

$$+ A_1^{on}\left(1-e^{-\frac{\left(t-TD_1^{on}\right)}{\tau_1^{on}}}\right) \quad \text{Phase II (primary component)}$$

$$+ A_2^{on}\left(1-e^{-\frac{\left(t-TD_2^{on}\right)}{\tau_2^{on}}}\right) \quad \text{Phase III (slow component)} \qquad (2\text{-}5\text{-}4.1)$$

where $\dot{V}O_2(0)$ is the baseline value of $\dot{V}O_2$ at time t = 0; A_0^{on}, A_1^{on}, and A_2^{on} are the asymptotic amplitudes for each exponential term; τ_0^{on}, τ_1^{on}, and τ_3^{on} are the time constants; and TD_1^{on} and TD_2^{on} are the time delays for each exponential term. This equation does not consider that each phase is terminated at the beginning of the next. Further terms were defined (Barstow, 1994):

$$A_{0_n}^{on} = A_0^{on}\left(1-e^{\frac{-TD_1^{on}}{\tau_0^{on}}}\right),\; A_{1_n}^{on} = A_1^{on}\left(1-e^{\frac{-\left(TD_2^{on}-TD_1^{on}\right)}{\tau_1^{on}}}\right), \text{and } A_{2_n}^{on} = A_2^{on}\left(1-e^{\frac{-\left(t_f-TD_2^{on}\right)}{\tau_2^{on}}}\right).$$

As previously noted, each phase ends when the subsequent phase is initiated. More specifically, phase I ends at t $=TD_1^{on}$, phase 2 ends at t $=TD_2^{on}$, and phase three is terminated at time t = t_f . The asymptotic amplitudes are additive based on $A_{0_n}^{on}$, $A_{1_n}^{on}$, and $A_{2_n}^{on}$ (Figure 2-5-4.1).

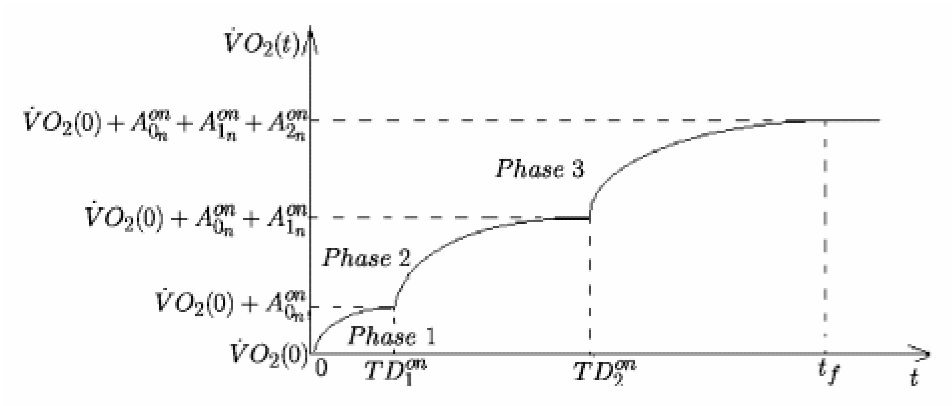


Figure 2-5-4.1. The three-phase model of oxygen uptake kinetics (Stirling et al., 2005).

2-5-5. Coyne Model

Coyne (2001) modeled the pulmonary effects of wearing respiratory protective masks during physical activity. The model was focused on steady-state exercise and, therefore, did not account for the transition from rest to exercise, which incorporates oxygen deficit. However, Coyne (2001) used oxygen deficit as a means of predicting performance time. Coyne's model is the fundamental model on which subsequent studies have been made in the Human Performance Lab at the University of Maryland, College Park, and as such, is of notable interest.

The model inputs were: 1) subject characteristics, including age, height, weight, and maximal oxygen consumption; 2) respiratory system characteristics, including the resistance and dead volume; and 3) respirator characteristics, including mass, dead volume, and the inhalation and exhalation resistances. Outputs of the model included oxygen consumption, minute ventilation, tidal volume, respiratory work, respiratory rate, times of inhalation and exhalation, oxygen deficit, and performance time (Coyne, 2001).

Coyne calculated the oxygen deficit as the difference between oxygen demand and actual oxygen consumption. Performance time was then calculated using the defined rate of OD development and an estimate of the maximal oxygen deficit:

$$PerformanceTime = \left(\frac{4.03}{O_2 DeficitRate} \right) \qquad (2\text{-}5\text{-}5.1)$$

where 4.03 liters was the maximum oxygen deficit found above the anaerobic threshold, as observed by Bearden and Moffatt (2000) and stated by Coyne (2001).

2-5-6. Chiou Model

Chiou (2004) expanded on Coyne's model to adjust oxygen deficit to include the fast and slow components of oxygen uptake. Moreover, Chiou added transient effects in an attempt to make the model a more precise estimate of physiological factors. Chiou first found physiological work rate, using external work rate and efficiency, then performed a linear regression on oxygen consumption and physiological work rate data. Subsequently, performance time was predicted using the equation put forth by Kamon (1972):

$$t_{wd} = 7200\ (\dot{V}O_{2\,max} / \dot{V}O_2) - 7020 \qquad (2\text{-}5\text{-}6.1)$$

in which t_{wd} = the performance time without masks. Transient oxygen consumption was then calculated, and oxygen deficit was determined using performance time and oxygen consumption according to the single-exponential equation proposed by Convertino et al. (1984):

$$OD = \dot{V}O_2(t_{wd}) * t_{wd} - \dot{V}O_2(t_{wd})[t_{wd} + \tau_{02} \exp(t_{wd}/\tau_{02})] \qquad (2\text{-}5\text{-}6.2)$$

While the Chiou (2004) model enabled the oxygen deficit to be calculated, improved model results were observed when work rate was used instead of the oxygen deficit to predict performance time. In addition, the model was fitted using data for 30% and 80% $\dot{V}O_{2\,max}$, which again does not model the transition from rest to exercise in which oxygen deficit is so influential. Thus, this current model at the University of Maryland, College Park, is limited in its ability to adequately describe the oxygen deficit parameter of the exercise response.

2-6. Analytical Processes

The research process incorporates a plethora of analytical processes, all of which should be thoroughly understood to provide the best research conclusion possible. Some of the analytical procedures relevant to this study will, therefore, be discussed.

2-6-1. Nonlinear Least Squares

The primary objective in modeling is defining the relationship that exists between independent or predictor variable(s) and dependent or criterion variable(s). Identification of this relationship allows the analyst to better fit the observed data with a predictive model equation or equation set. It is also possible to select model functions that more accurately reflect the physical processes. The fitting procedure will vary depending on the shape of the response curve; a nonlinear curve, as observed in the time response of oxygen uptake to exercise, is fit using a procedure referred to as nonlinear least squares (Ott and Longnecker, 2001). This technique is utilized for more complex model structures, with complexity indicating that the unknown values cannot be fit analytically, and instead, a numerical procedure must be employed (McCuen, 2003).

Optimizing a model to a set of data is based on minimizing the sum of the squares of the errors. Minimization involves defining an objective function, expressed as a function of the model itself, and thereafter numerically computing derivatives of the objective function and adjusting the unknown coefficients until those derivatives equal zero. The modeler is interested in the value of the unknowns where the derivatives are zero; these zero points must be found through an iterative process in numerical optimization (McCuen, 2003).

Using an iterative process, an optimum solution for each model coefficient is sought. More than one coefficient may present a problem in numerical optimization due to the importance and sensitivity of the coefficients. The process may be stopped when the more important coefficients have been optimized but the less important coefficients have not reached their optimal values; such is an approximately optimum solution (McCuen, 2003). Moreover, those values associated with the insensitive coefficients may not accurately reflect the physical processes for which the model is desired. These limitations to optimization require the modeler to have a fundamental understanding of the model and the physical processes under investigation (McCuen, 2003).

The modeler should have a good working knowledge of the model and the physical processes being studied for additional reasons. First, numerical optimization requires initial values of the unknowns to begin the iterative process. Second, the technique requires increment increases/decreases for each coefficient during the iterations (McCuen, 2003). Identifying appropriate initial values and incremental steps should be based on knowledge of the system at hand. Furthermore, the modeling process often requires compromising model accuracy and model bias; the modeler must decide what limitations in accuracy and bias are acceptable for the study at hand. Increased accuracy is associated with a minimum value of S_e/S_y, in which S_e is the standard error of estimate and S_y is the standard deviation of estimate (McCuen, 1993). Bias refers to the difference between the actual value and the long-term predicted result with an unbiased model consistently neither over- nor underestimating a predicted value (McCuen, 1993). Minimum standard error (S_e) and zero bias are often conflicting goals in fitting models, so compromising these criteria will often help to find an optimum solution (McCuen, 2003). Hence, knowing when valid coefficient values have been determined, while still maintaining good accuracy and bias, is an important part of the modeling process.

2-6-2. Assessing Model Reliability

The modeling process cannot be deemed complete without first performing an assessment of the goodness of fit and potential to reliably make predications about the system being investigated. The data used for model calibration are often additionally used to assess the model reliability. Some of the criteria used to assess model reliability include: (1) coefficient rationality; (2) the standard error of estimate, S_e; (3) the relative standard error, S_e/S_y; (4) the correlation coefficient, R; (5) the model bias, $\bar{e}$; and 5) the relative bias, $\bar{e}/\bar{y}$ (McCuen, 1993).

A rational model is characterized by reasonable or justifiable predictions provided by model use. Rationality can likely be considered the most important criteria for model assessment (McCuen, 1993). Understanding of the model and the underlying physical processes is important in evaluating model sensibility or rationality.

The standard error of estimate, S_e, is calculated according to (McCuen, 1993):

$$S_e = \left(\sum e^2/v\right)^{0.5} = \left(\sum\left(\hat{Y} - Y\right)^2/v\right)^{0.5} \qquad (2\text{-}6\text{-}2.1)$$

where $\hat{Y}$ is the predicted value, Y is the measured value of the random variable, and v is the degrees of freedom associated with the model. A model that makes "perfect" predictions will have a S_e equal to zero, indicating that the predicted values equal the measured values.

The correlation coefficient, R, is an additional index of how well the predicted and measured values agree. R^2 defines the amount of variance in the predicted variable that may be explained by the predictor variable, and is hence used as another indictor of model fit (McCuen, 1993). However, the correlation coefficient is technically applicable only to linear models and for purposes of this study, was replaced by a more suitable goodness of fit indicator for nonlinear models (i.e., S_e or S_e/S_y) (McCuen, 1993).

The model bias, as previously discussed, is a gauge of the difference between the long-term predicted value and the true value. An unbiased model will consistently provide predicted values close to the measured value (McCuen, 1993).

Model accuracy is defined by the ratio S_e/S_y, as previously noted. This ratio signifies the improvement in the prediction accuracy due to the predictive model equation. When near 0.0, the model drastically improves the prediction accuracy over predictions based on the mean, whereas values near 1.0 indicate little improvement by the model in prediction accuracy as compared to the mean (McCuen, 1993).

Hence, it is important that the model reliability or goodness of fit is evaluated before the model is determined complete and ready for use. A model put to use before or without assessing its reliability, is ultimately of little worth.

2-6-3. Evaluation of Differences

The analysis of variance (ANOVA) is completed to assess whether the differences in the sample means are statistically significant as compared to the variation that exists between samples (Ott and Longnecker, 2001). In other words, this statistical method tests for the significance of the effect of the independent variable on the predicted variable (McCuen, 1993). ANOVAs are performed to assess whether resultant differences are due to treatment or group effect, or simply random noise (Ott and Longnecker, 2001).

The simple (single factor) analysis of variance is an ANOVA that considers only variation due to the independent variable and that associated with sampling error. This test is one of the more popular statistical tests used in data analysis, and is highly applicable to a wide range of research fields (Roscoe, 1969). The simple ANOVA has basic assumptions that are required for its use, including that the samples are independent random samples collected from normally distributed and equally variable study populations. The normality assumption may be ignored for large sample sizes (Roscoe, 1969).

Results of the ANOVA may be interpreted by evaluating the p-value, defined as the level of significance of the statistical test. ANOVA procedures are often run at the 5% (0.05) significance level, meaning that the *p*-value is compared against 0.05 to assess statistical difference. More specifically, a *p*-value of ≤ 0.05 indicates that a statistically significant difference exists between the variables being analyzed.

2-6-4. Confidence Interval Estimation

The nature of physiology and the human body is variable, resulting in a range of values for physiological parameters across a given population. Since a single parameter value will not adequately represent a physiological response, it is imperative that a range of predictive values be formulated to better describe the response of the larger population. Confidence interval estimation is used to define such a range using values measured from the sample population.

Point estimates are the specific values from the sample data that are used for estimation of population parameters (Ott and Longnecker, 2001; McCuen, 1985). Based on these point estimates, confidence intervals may be developed for these same parameters. The confidence interval indicates the probability of the true population value for the particular parameter occurring within that range (Ott and Longnecker, 2001). The smaller the interval, the more likely the population value is correct and thus, the higher the accuracy (McCuen, 1985). The confidence coefficient for 95% confidence expresses the proportion in which repeated sampling would encompass the parameter being estimated 95% of the time, and is found according to the following equation:

$$CI = \bar{y} \pm 1.96\sigma_{\bar{y}} \qquad (2\text{-}6\text{-}3.1)$$

where *CI* = the confidence interval, $\bar{y}$ = the sample mean, and $\sigma_{\bar{y}} = \sigma/\sqrt{n}$, for which σ = standard deviation and *n* = sample size (Ott and Longnecker, 2001). Using this equation, lower and upper confidence limits may be calculated to define an appropriate estimate range. Graphically connecting these limits across the experimental treatments provides confidence "belts," which allow for inference of intermediate treatment values (Ott and Longnecker, 2001).

Chapter 3: Experimental Procedures

3-1. Sample Size Determination

The appropriate determination of sample size is imperative for a successful study, as the sample size must provide a sufficient amount of data while maintaining research restraints. The sample size is a compromise between the desired accuracy of the statistic as a predictor of the population value and the time necessary to achieve such accuracy (Ott and Longnecker, 2001).

The researcher must define two factors for the calculation of sample size: the tolerable error, which is the width of the confidence interval, and the level of confidence (Ott and Longnecker, 2001). The researcher must carefully choose these values, as a large confidence interval will result in an imprecise measure of the population mean and a low confidence level will likely result in an erroneous confidence interval. However, that is not to say that a narrow confidence interval and a high confidence level of Type II error are optimal, for these conditions may require an unreasonably large sample size (Ott and Longnecker, 2001). Typically, the confidence level is set at 90% to 95% and therefore, α = 0.10 to 0.05. However, the tolerable error is dependent on the problem context and should therefore, be chosen according to the study (Ott and Longnecker, 2001).

Sample size is calculated according to the following formula:

$$n = \frac{(z_{\alpha/2})^2 \sigma^2}{E^2} \qquad (3\text{-}1.1)$$

where n = sample size, z = the statistical z value at the designated α, σ = the standard deviation, and E = half the confidence interval width = half the tolerable error (Ott and Longnecker, 2001). However, use of equation 3-1.1 requires previous knowledge of the population variance (σ^2) or the standard deviation (σ), both of which were unknown prior to initiation of this study. Sample size was instead determined based on precedent set for human subject tests in the Human Performance Lab at the University of Maryland. A minimum of ten subjects is the general rule for experiments conducted in this academic research lab; thus, ten was chosen as the sample size for this experimental study.

Retrospective analysis with a tolerable error set equal to the standard deviation revealed that 15 subjects would be necessary to complete this research at the 95% confidence level. Moreover, post-analysis indicated that use of 10 subjects for study completion resulted in the work being accomplished at the 88% confidence level. This should be taken into account for possible future study expansion.

3-2. Subject Recruitment

Ten untrained subjects were recruited from the student population at the University of Maryland, College Park. Some of the subjects were enlisted using a subject database stored in the Human Performance Lab in the Biological Resources Engineering Department, while others were found through day-to-day interactions within the campus community. Subjects were chosen based on voluntary agreement to participate in the study, with the understanding that participation was not monetarily compensated. Subjects were recruited following submission to and approval of the research protocol by the University of Maryland Institutional Review Board (Appendix A-1).

Subjects were required to be healthy, free of pulmonary and cardiovascular ailments, and fall within the age range of 18 to 40 years old; this age range was chosen to help eliminate the influence of age-induced reductions in physical ability and characteristics. In addition, the American College of Sports Medicine (ACSM) in the Guidelines for Exercise Testing and Prescription (6^{th} edition, 2000), states that vigorous physical exercise is appropriate for asymptomatic individuals between the ages of 18 to 40 years, and that medical clearance is not required for this group prior to initiating a vigorous exercise program. This project did not provide medical clearance for prospective participants, and as a result, it was mandatory that individuals selected to participate did not require medical clearance and were at minimal risk for cardiovascular events while performing vigorous exercise.

3-3. Subject Orientation

All study participants received an orientation to the research project in which they were provided with a basic explanation of the test procedures and methods being used. Volunteers were given a written informed consent document outlining these procedures and methods and were asked to read and sign this document before being allowed to further participate (Appendix A-2).

All study volunteers were also asked to complete several questionnaires to better assess their health and medical ability to participate in the project. The first questionnaire was a brief medical history document intended to gather information concerning the individual's current and previous health background (Appendix A-3). The second assessment was the Physical Activity Readiness Questionnaire (PAR-Q) given to determine if exercise was appropriate for the volunteer without a medical clearance (Appendix A-4). Both the medical history and physical activity questionnaires were utilized to screen individuals deemed at risk for cardiovascular events when performing vigorous physical activity. Subjects were screened for any cardiovascular risks, such as chest pain when exercising or heart palpitations; any indication of a possible cardiovascular risk would result in subject exclusion from the research study for safety purposes. It was initially determined that participants should be administered the Spielberger State-Trait Anxiety Inventory to assess the subject's anxiety disposition in general and prior to commencement of each exercise test. However, this information was later deemed less important than other data to be collected and, therefore, the Spielberger State-Trait Anxiety Inventory was not given in the interest of better focusing data collection efforts.

During this orientation, all volunteers were provided the opportunity to ask any questions they had regarding this study. All subjects were informed that they were free to ask questions throughout the duration of the study and, moreover, were free to withdraw from the project at anytime without incurring any penalty. Such a request of withdrawal could be made verbally or through written communication. In addition, subjects were notified of their right to confidentiality in this study, with subject numbers serving as identifiers as opposed to names or other descriptors.

3-4. Maximal Oxygen Consumption Test

A maximal oxygen consumption ($\dot{V}O_{2\,\max}$) test was completed by each subject to determine their maximal aerobic capacity, a value used to define the work rates of the subsequent exercise tests (75%, 85%, 100%, and 115% $\dot{V}O_{2\,\max}$). All subject testing occurred in the Human Performance Laboratory at the University of Maryland, College Park.

3-4-1. Test Procedure

Participants were first asked to warm-up on a Quinton motorized treadmill for approximately five minutes at 50 to 60% of his/her age-predicted maximum heart rate. Immediately following this warm-up period, subjects were asked to briefly stretch in order to avoid possible muscle injury during the test. Next, the participants were seated and fitted with a Hans-Rudolph half-piece breathing mask for the collection of expiratory air. A hose was then connected to the exhalation valve of the mask to collect expired gas. The hose was connected to a mixing chamber, which was, in turn, connected to a pneumotach. A mass spectrometer was connected to this gas analysis system via a capillary tube attached to the collection hose; the mass spectrometer was necessary for supplying information regarding expired gas content. This airflow collection system also included a computer for gas analysis and data display. A DAS-8 analog-to-digital converter board was utilized, in addition to a custom-designed computer program already in use in the Human Performance Lab for gas data collection and thirty-second average output.

At least one minute of baseline $\dot{V}O_2$ data was collected with the subjects in a seated position. The subjects were then asked to stand and straddle the treadmill belt. When the belt began to move, subjects were asked to carefully step onto the belt and begin walking at the appropriate pace; the pace was gradually increased until the treadmill speed and grade were ramped to the levels required to elicit the desired work rate (50-60% of the volunteer's age-predicted maximum heart rate response).

The moment at which the treadmill speed and grade reached the necessary levels to elicit this response marked the beginning of the $\dot{V}O_{2\,\max}$ test. This work rate signified the initial stage of the test and was continued for approximately three minutes.

At the completion of this stage, a new work rate was selected and the participants were required to work at this new intensity for another three minutes. Work rates were subsequently modified every third minute during the maximal aerobic assessment test until reaching $\dot{V}O_{2\,\max}$. The work rate increases were calculated to exhaust the subject's aerobic system in approximately 9 to 15 minutes. In addition, the increase in work rate was achieved only through an increase in treadmill speed. The treadmill grade was set at 2.5% for each $\dot{V}O_{2\,\max}$ test and each exercise test thereafter for enhanced comparison and result interpretation.

The test sessions were discontinued upon reaching $\dot{V}O_{2\,\max}$, a point at which oxygen uptake fails to increase, or may slightly decrease, despite increases in exercise intensity (McArdle et al., 2000). This termination point was more specifically defined by a rise in the oxygen consumption rate of <150 ml/min in response to a new work rate (McArdle et al., 2000). Additionally, the tests were terminated if the participants reached his/her age-predicted maximal heart rate, if the individuals displayed a response that contraindicated continued assessment (e.g., paleness in the face, extreme difficulty breathing), or if the participants reached volitional fatigue despite motivation from the test administrator. If the tests were ceased prior to reaching $\dot{V}O_{2\,\max}$, a decision was made based on the data collected as to whether the data was usable or if the subject should return to complete another graded exercise/

$\dot{V}O_{2\,max}$ test. None of the ten subjects required a second test to assess their aerobic capacity.

Throughout the tests, heart rate data were collected using Polar (Polar Electro Inc.; Lake Success, New York) heart rate monitors worn by the subject. Expired gas data were also collected throughout, as was the participant's rating of perceived exertion (RPE). The Rating of Perceived Exertion is a subjective scale that is used to identify the effort the subject believes that he/she is giving in the exercise test. The scale is ranked 6 to 20 with a rating of 6 indicating a lack of exertion, increasing gradually until reaching a rating of 20, which corresponds to maximal exertion. In an exercise test, the RPE scale is held up as the subject exercises and he/she is asked to indicate the rating by pointing to the level of exertion that he/she feels appropriate. Subjects are notified that there is no correct answer, so they may respond as they deem fitting. The RPE value is then called out by the test administrator to ensure that the correct rating is recorded. The RPE given by the subject is then used as an indication of the subject's ability to continue, enabling the test administrator to adjust the work rate stages required to elicit $\dot{V}O_{2\,max}$ in the time desired. The data collected during the maximal oxygen consumption tests were recorded electronically and using hard copy data sheet (Appendix A-5). Demographic information for all subjects was also collected at this time (Table 3-4-1.1).

Table 3-4-1.1. Demographic information for the study participants.

Subject #	**Gender**	**Age**	**Weight (kg)**	**Height**	$\dot{V}O_{2\,max}$ **(L/min)**
001	M	42*	93	5' 8"	4.59
145	M	35	93	5' 10"	3.96
358	F	24	66.2	5' 6"	2.20
359	M	25	84	5' 10"	3.57
379	F	22	63.5	5' 4.5"	1.74
401	F	25	50	5' 4"	2.80
414	M	24	93.5	6' 0"	3.17
419	M	21	69	5' 8"	2.82
420	M	21	75	5' 7"	3.66
422	M	21	75	5' 9"	2.72

* Subject deemed able to participate based on extensive athletic involvement (aerobic and anaerobic activities). Subject did not have cardiovascular risk factors as identified in the medical history questionnaire or the PARQ. Moreover, subject reported no physician – identified reasons for not exercising and was additionally notified of the risks of study participation. Involvement was deemed conditional, with any signs of subject distress serving as cause for ceasing further participation.

3-4-2. Test Analysis

The subsequent oxygen deficit exercise tests were based on $\dot{V}O_{2\,max}$; each test being conducted at a percent intensity of $\dot{V}O_{2\,max}$ (75%, 85%, 100%, and 115% $\dot{V}O_{2\,max}$). In order to proceed with these tests, it was first necessary to determine the work rates (kJ/min) and treadmill speeds that would elicit these percent intensities.

The first step in this process was to define the metabolic cost per stage in the $\dot{V}O_{2\,max}$ test. The metabolic rate, or physical metabolic cost of exercise, was defined using the equation presented by Gagge and Nishi (1983):

$$\dot{M} = 21.14\dot{V}O_2(0.23RQ + 0.77) \qquad (3\text{-}4\text{-}2.1)$$

where $\dot{M}$ = metabolic rate or cost (kJ/min) and RQ = the respiratory exchange ratio (known also as RER, unitless). The RER, which is measured using the gas analysis program previously noted, is the ratio of carbon dioxide (CO_2) produced by the body to oxygen consumed; a ratio closer to or above 1.0 indicates heavy or anaerobic activity in which CO_2 accumulates (McArdle et al., 2000). The maximum $\dot{V}O_2$ for each stage and the corresponding RER were used to compute the stage metabolic cost. The metabolic cost for each stage was then compared to the metabolic cost associated with the subject's $\dot{V}O_{2\,max}$ to find the stage fraction of $\dot{V}O_{2\,max}$.

The metabolic cost was graphed versus the associated stage fraction of $\dot{V}O_{2\,max}$ (kJ/min versus %$\dot{V}O_{2\,max}$). A generally linear relationship existed between these two parameters (for a subject-specific intensity range), and the equation that relates these factors was determined for each subject (Appendix A-6). This equation was then used to extrapolate the metabolic cost of each of the desired exercise intensity conditions. Finally, the treadmill speeds for each intensity condition were calculated by substituting metabolic cost for work rate in the external work rate equation presented by Aoyagi et al. (1995):

$$\dot{W} = 0.06 m_{tot} g v \sin\theta \qquad (3\text{-}4\text{-}2.2)$$

where $\dot{W}$ = the external work rate (kJ/min), m_{tot} = the mass of the body plus clothing (kg), g = the acceleration due to gravity (9.81 N/kg), and θ = the angle of treadmill inclination as compared to the horizontal (= arctan *Grade*/100, degrees, = 0.0250 since the treadmill slope was held constant).

3-5. Maximal Oxygen Deficit Tests

3-5-1. Data Collection Program

The program used for gas collection and analysis in the maximal oxygen consumption tests provided 30-second averages as output values. The smoothing effect of averaging is often a desirable attribute, although data averaging, especially in regards to biological data, often removes inherent variability that exists within the system (Robergs and Burnett, 2003). For a more accurate representation of the oxygen uptake response during exercise, and in turn a more precise estimate of the oxygen deficit developed, instantaneous gas collection was determined to be the most desirable option.

A LabView (National Instruments Corporation; Austin, Texas) program (Koh, 2005) was employed for instantaneous data collection. The program uses expired gas flow, and carbon dioxide and oxygen contents of the gas as measured by the mass spectrometer to determine oxygen consumption. The fundamental equation within the program was defined by McArdle et al. (2000):

$$\dot{V}O_2 = \dot{V}_E\left[\left(\frac{\%N_{2_E}}{79.04\%}\times 20.93\%\right) - \%O_{2_E}\right] \quad (3\text{-}5\text{-}1.1)$$

where $\dot{V}O_2$ = volume of oxygen consumed per minute and $\dot{V}_E$ = expired air volume per minute. However, the LabView program calculates the percentage of nitrogen (N_2) using O_2 and CO_2 values. The program has a sampling rate of $1/100^{th}$ of a second and provides several output parameters, including time, O_2 and CO_2 concentrations, exhalation flow, and $\dot{V}O_2$.

In showing that the instantaneous program was reliable, the LabView program was calibrated against the standard 30-second average program used in the Human Performance Lab. To do so, the $\dot{V}O_2$ values from the thirty-second program were compared against instantaneous $\dot{V}O_2$ values averaged over the same time period. The two sets of $\dot{V}O_2$ values were graphed versus one another to assess the correlation between the two gas analysis programs (Figure 3-5-1.1). The two programs have a highly linear relationship and are strongly correlated, having an R^2 value of 0.95. Thus, the LabView program was deemed valid and suitable for use in collecting reliable instantaneous gas data.

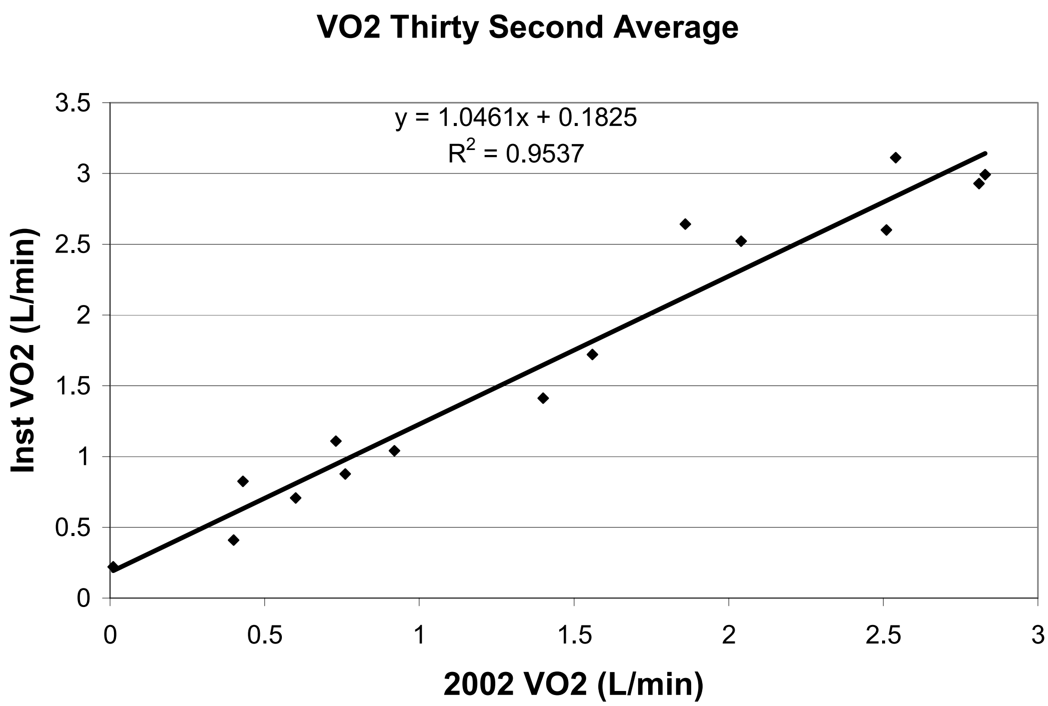


Figure 3-5-1.1. Calibration graph for gas collection programs (Koh, 2005).

While the average program and the instantaneous program were found to be highly correlated, it was also necessary to assess whether a delay existed in the gas concentration analysis. Any delay in the concentration reading can produce an offset in the $\dot{V}O_2$ reading for the duration of the exercise test and will require that the offset be accounted for in all subsequent calculations. To determine if a delay existed, the CO_2 and flow values were graphed versus time, and the times of the peaks were defined and compared against one another (Figure 3-5-1.2). The peak times showed that CO_2 concentration peaks an average of 0.48±0.12 seconds after the air flow peaks. An ANOVA on the peak times indicated that the peak times were not significantly different ($p = 0.91$), and therefore, it was not necessary to account for a delay in the instantaneous data analysis. The times of the CO_2 peaks should correspond to the times of the O_2 peaks as based on the principles of gas expiration and expiratory measurement. Hence, the strong correlation between CO_2 peak times and flow peak times likewise indicates strong agreement between O_2 and flow. It is this relationship that is of key interest, as the lack of a difference between peak times provides confidence in the $\dot{V}O_2$ as measured and reinforces that there is no need to account for a delay in the instantaneous data analysis.

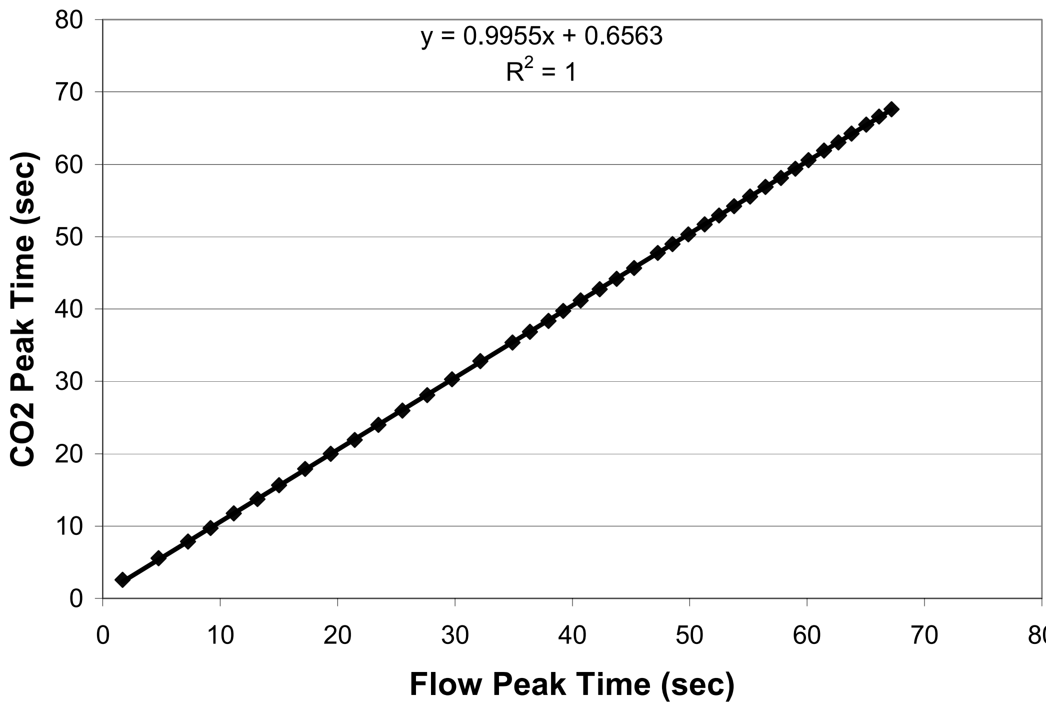


Figure 3-5-1.2. Delay calculation graph for Koh (2006) LabView program.

3-5-2. Pre-Test Metabolic State

Each individual has a specific minimum energy requirement for sustenance of metabolic activities while the body is awake though inactive. Measurement of oxygen uptake prior to exercise initiation allows for inference of the metabolic activities occurring within the body. A subject's baseline $\dot{V}O_2$ will affect his/her metabolism during exercise; the higher the baseline $\dot{V}O_2$, the more elevated his/her metabolism during exercise based on an increased energy requirement throughout (McArdle et al., 2000).

It was, therefore, important that each subject try to maintain a consistent pre-test metabolic state for each exercise test to avoid inconsistencies in the oxygen uptake responses. A relatively consistent baseline $\dot{V}O_2$ throughout the exercise test sessions would indicate that any differences in the O_2 uptake response were not based on initial conditions, but rather on the exercise itself. Research participants were asked to keep a log of their physical activity and diet for 24 hours prior to each exercise test session (Appendix A-7). This information was used as a spot check to ensure that there were no dramatic changes in the food type/ amount consumed or in the amount/ type of activity completed by the study participant. A significant difference would alter the subject's metabolic conditions, indicating that the test may need to be rescheduled for another day to avoid metabolic inconsistencies.

The menstrual cycle of the female volunteers was also monitored for metabolic purposes. While the phase of the menstrual cycle has been shown to have little or no influence on aerobic performance, studies have shown improvements in the performance of high-intensity exercise that occur during the luteal phase of the female cycle (Lebrun, 1993; Hall et al., 1981). The luteal phase begins immediately following ovulation and ends before the onset of menses (Lebrun, 1993). It was determined that the female participants should complete all of the exercise tests for this study in the same two weeks of their cycle. More specifically, the participants should not complete the tests during menses, but rather during the first two weeks of their next cycle. Consistency within the menstrual cycle was the objective to ensure that there would not be metabolic changes due to menstruation.

A final means of reducing any influence of metabolic differences on the final oxygen deficit results was to define rules of consistency for testing times. Subjects were asked to complete each exercise test on a separate day, initiating each test at approximately the same time of day (± 2 hours) according to the procedure followed by Carter et al. (2000). Maintaining such a schedule would help minimize the effects of prior exercise tests on the current test, while additionally minimizing the effect of any diurnal changes in metabolism. Should time constraints require that a second test be conducted on an exercise trial day, subjects were asked to sit for an hour between tests to allow for recovery of energy stores; this decision was also made according to the procedure outlined by Carter et al. (2000). Subjects were additionally asked to wear similar clothing for each session to eliminate thermoregulatory differences.

3-5-3. Test Procedures

Each study participant was asked to complete five exercise tests, performed in a randomized order, to define the maximal oxygen deficit occurring across a range of exercise intensities. The subjects completed tests on a Quinton motorized treadmill at 75%, 85%, 100%, and 115% of their pre-determined $\dot{V}O_{2\,max}$. Four of the five sessions were completed with the subject wearing a military-style (M40) respirator mask, while the remaining exercise test was performed with the subject wearing a Hans-Rudolph breathing mask. The M40 worn by the subjects weighed 0.78263 kg with the "standard" filter attached; this filter imposes a resistance of 0.749 $cmH_2O/L/sec$ when measured at a typical resting flow rate of 6 liters/min (Johnson et al., 2005). The dead volume of the mask was not measured; the dead volume refers to the air that is present in the mask, but not taking part in gas exchange (Johnson, 1999; Johnson, 1991). This volume was not measured because it may vary from subject to subject and test to test, as this parameter is based on breath flow patterns and any seal leaks due to improper fit (Saatci et al., 2004).

Exercise was completed at each of the four intensities while wearing the M40 respirator, although the Hans-Rudolph mask was worn only for a second exercise session at 85% $\dot{V}O_{2\,max}$; replication of the 85% test was done to examine the effect of the respirator mask on oxygen deficit at a commonly studied intensity. It should be noted that the original study protocol called for three additional exercise sessions in which the Hans-Rudolph mask would be worn for exercise at the three remaining intensities; these tests were later deemed unnecessary for meeting the objectives of this research and were eliminated. All tests were conducted in the same manner, the only difference being the mask condition and the work rate used.

After arriving in the Human Performance Lab, subjects were asked to sit for 15 to 20 minutes in an attempt to return to resting metabolic conditions, or as close to baseline as possible. A warm-up or stretching period was not allowed prior to exercise in order to ensure that the OD obtained was a maximal value for each test; warm-up or stretching by the volunteers would exhaust part of the ATP stores being drawn from at the beginning of exercise, thereby reducing the measured OD. Study participants were then fitted with a M40 military-style negative pressure respirator mask that had been adjusted for standard conditions (containing the standard filter) (Figure 3-5-3.1a). If the exercise test was the Hans-Rudolph condition, subjects were instead fitted with a Hans-Rudolph half-piece breathing mask for collection of expiratory gases (Figure 3-5-3.1b).

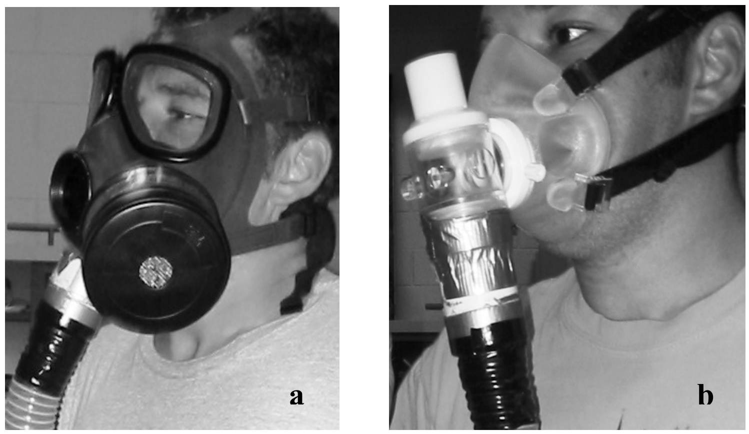


Figure 3-5-3.1. a) Military-style M40 negative-pressure respiratory mask;
b) Hans-Rudolph half-piece breathing mask.

The mask exhalation valve (M40 or Hans-Rudolph) was then connected to a hose identical to that used in the $\dot{V}O_{2\,max}$ test. The hosing was connected directly to the pneumotach instead of the mixing chamber; the mixing chamber was removed from the gas collection system because of the desire to collect instantaneous breath data. Again the mass spectrometer was connected to the system by a capillary tube attached to the hosing. Two computers were connected to this airflow collection system, one running the standard 30-second average analysis program and the other operating the instantaneous LabView program. The 30-second program was used only to spot check the $\dot{V}O_2$ response to ensure that the test was proceeding as expected; irrational values would imply that a problem existed in the gas collection set-up.

The subjects were then seated and asked to breathe normally for at least two minutes while baseline $\dot{V}O_2$ data were collected. Afterward, the participants were asked to stand and straddle the treadmill belt. The treadmill was turned on and the subjects were instructed not to step onto the belt until the treadmill speed and grade reached that required for the test. All of the tests were conducted with the treadmill at 2.5% grade for enhanced comparison across all subjects and intensity conditions. Once the treadmill speed and grade reached that defined for the specified exercise intensity, subjects were given an instruction to step onto the treadmill belt whenever they were ready to begin. Since the speed was often quite high, the volunteers were asked to be cautious when stepping onto the belt and were asked to adjust to the pace as quickly and smoothly as possible. Data logging and timing of the tests were initiated once the subjects stepped onto the moving belt.

All exercise tests proceeded until volitional fatigue, although motivation was given to the subjects throughout the tests to help ensure that the subjects continued exercise as long as possible. When the subjects were not able to proceed with exercise, data logging was stopped, the treadmill was slowed, and the time duration of the test was recorded. Upon termination of the tests, subjects were asked to complete a five-minute cool-down to ensure subject safety.

A Polar heart rate monitor was worn by all subjects to collect heart rate data throughout exercise. Rating of Perceived Exertion and Breathing Apparatus Comfort scales were taken periodically during each test to provide subject feedback on the exercise intensity and subject-perceived mask comfort. The BACS (Breathing Apparatus Comfort Scale) is a subjective scale used to measure the subject-perceived mask comfort. The BACS is rated from 0 to 8; a rating of 0 is indicative of mask conditions that are "very, very uncomfortable," whereas a rating of 8 is used to signify that the respirator is "very, very comfortable." Again, subjects were informed that there was no incorrect answer when identifying a BACS rating, and the rating was obtained in the same way as the RPE score. The data collected from these exercise tests were recorded electronically and using a hard copy data sheet (Appendix A-8).

Chapter 4: Analytical Procedures and Results

4-1. Breath-by-Breath Conversion

The high sampling rate of the instantaneous LabView program resulted in a large amount of expired gas data collected for each exercise test. The instantaneous data incorporated both the inspiratory and expiratory components of breathing and, therefore, had to be converted to show the oxygen uptake response. The conversion process was used to convert the 3,035,562 data points collected into the 15,428 breaths taken by the subjects over the course of all of the oxygen deficit tests. The breath-by-breath conversion process, described hereafter, was used for each exercise test.

The gas data were imported into Microsoft Excel (2003) and a graph of $\dot{V}O_2$ (liters per minute, L/min) versus time (seconds) was generated for the test (Figure 4-1.1). Depending on the length of the test, graphing may have been done using multiple sequential series to accommodate all of the data. The resulting graph provided a visual representation of each breath taken, including the inspiratory peaks and the pause between subsequent breaths (Figure 4-1.2).

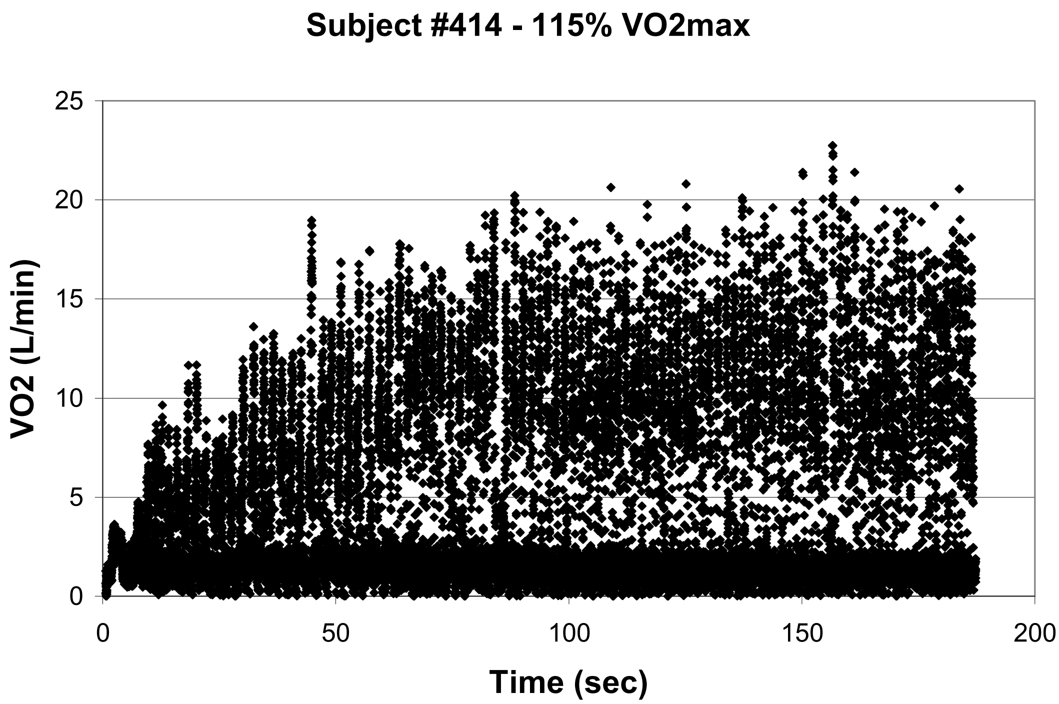


Figure 4-1.1. Example of the instantaneous breath data graphed for a single study participant.

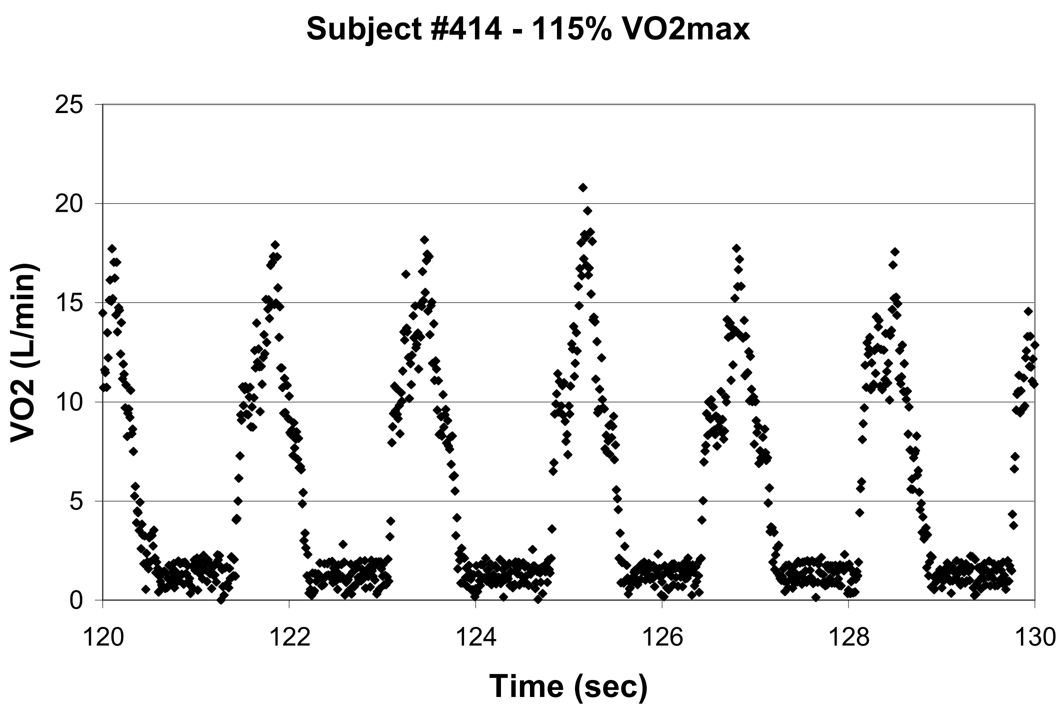


Figure 4-1.2. Instantaneous breath data magnified to show breath components.

In order to define the oxygen uptake that occurred within each breath, If-Then statements were used in the Excel worksheet to define the beginning and end of each inspiratory increase. The point representing the breath beginning was defined as the time of the lowest $\dot{V}O_2$ value that occurred before an increase to peak $\dot{V}O_2$ after the relatively constant $\dot{V}O_2$ values experienced during exhalation; theoretically this point symbolized the onset of inhalation. Likewise, the end of the inspiratory rise was identified by finding the time of the lowest $\dot{V}O_2$ value occurring after a decrease from peak $\dot{V}O_2$. The If-Then statements were used to compare $\dot{V}O_2$ values to find the lowest points before and after each inhalation. An offset in the breaths also had to be accounted for if the points of exhalation were above zero liters per minute (L/min); exhalation values should approximately equal zero L/min based on the idea that no oxygen uptake occurs during this breath component. The offset in exhalation $\dot{V}O_2$ was accounted for by averaging the exhalation uptake range and allowing only points above this average to be defined as the inhalation start and stop points. Finally, the end of the breath was defined as the last time point before the start of the next breath, or next inhalation; theoretically this point signified the end of expiration.

Using the beginning and ending of the inspiratory rise to define each inhalation, the points within each inhalation were used for integration purposes to find the $\dot{V}O_2$ volume occurring within each rise. The integration process utilized the upper sum method, a precursor technique to the Trapezoidal Rule and Simpson's Rule, to calculate the area under each inhalation (Ellis and Gulick, 1994). The premise for this method is that the overall area under a curve may be approximated by defining intervals within the range considered and circumscribing rectangles in the intervals; the upper sums of the areas of the circumscribed rectangles were then calculated to find the overall area under the curve. The upper sum was found according to the following equation given by Ellis and Gulick (1994):

$$U_f(P) = M_1\Delta x_1 + M_2\Delta x_2 + ... + M_n\Delta x_n \qquad (4\text{-}1.1)$$

in which M = $\dot{V}O_2$ (L/min) and Δx = the time between sample points ($\Delta x_1 = \Delta x_2 = \Delta x_n$ = 0.01 = the gas collection sampling rate). All M values within each inspiratory rise were summed for the specified inhalation and multiplied by the sampling rate Δx.

The time of each breath was calculated by subtracting the breath start time from the breath end time. Finally, the upper sum for each inhalation was divided by the corresponding time length of the breath to find the breath-by-breath oxygen uptake per unit time. When necessary, unit conversions were made within all of the breath-by-breath conversion calculations for consistency. Upon completing these calculations for each breath within a dataset, the resulting breath-by-breath $\dot{V}O_2$ values were graphed versus the associated breath start time to give the final breath-by-breath oxygen uptake response for the exercise test (Figure 4-1.3).

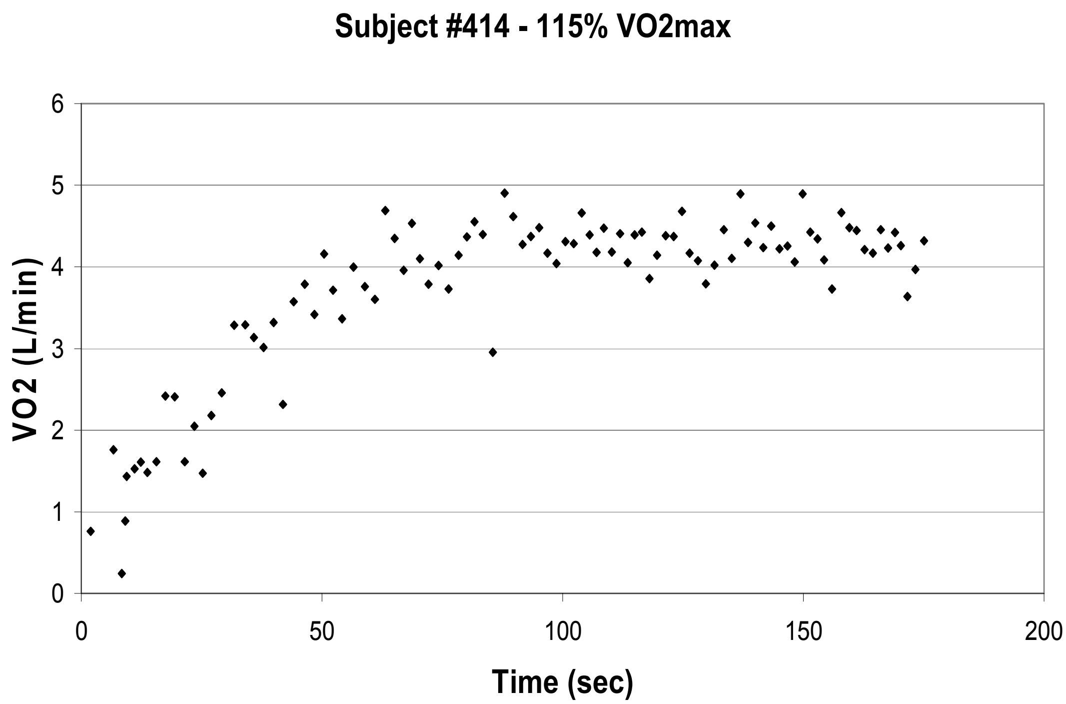


Figure 4-1.3. Breath-by-breath data as converted from raw exercise data.

4-2. Fitting of Nonlinear Equations

4-2-1. Model Considerations

In attempting to define the appropriate model to fit to the collected data, it was first necessary to ascertain those characteristics that must be considered for model accuracy. Upon examining the data, two primary factors were found to be of utmost importance when selecting a model: (1) the variability observed in the oxygen uptake response, as a large amount of noise was observed in each dataset; and (2) a decrement in $\dot{V}O_2$ that occurred near the end of exercise in some of the subject responses.

Breath-by-breath data is inherently variable, reflecting both biological variability and variability that is associated with a high sampling frequency (Myers et al., 1990; Robergs and Burnett, 2003). Individuals also exhibit personal breathing patterns, resulting in additional variability in breath-by-breath data over a given population (Benchetrit, 2000). Additional inconsistencies in $\dot{V}O_2$ data may be due to imprecision or limitations in the gas collection and analysis equipment, or the calibration process used for set-up (Robergs and Burnett, 2003). It was, therefore, important that the variability of the data be considered in any model used for analysis. Moreover, data smoothing or breath averaging were not utilized in the modeling process, as these methods may actually remove unevenness due to true biological variability and artificially alter the $\dot{V}O_2$ response (Robergs and Burnett, 2003).

A decrement toward the end of the test session in the oxygen uptake response was observed in some of the exercise tests, although this phenomenon was not consistently observed; not all of the subjects showed an obvious decrement, nor was this decrease seen for specific exercise intensities. Hoogeveen and Keizer (2003) studied the incidence of $\dot{V}O_2$ overshoot after it had been observed in prior exercise tests, conducted in two independent laboratories in which they worked, although never reported. The concept of the overshoot in oxygen uptake is in contrast with the traditional exponential $\dot{V}O_2$ response. Hoogeveen and Keizer (2003) studied the $\dot{V}O_2$ response in 15 subjects during constant-load exercise, finding that a $\dot{V}O_2$ overshoot occurred in the first two minutes, namely 55 to 90 seconds, of exercise before the volunteers reached steady state; all but three of the study participants showed this response.

Hoogeveen and Keizer (2003) suggested several possible explanations for the overshoot phenomenon. The first possible explanation was that a sudden increase in exercise intensity may instigate an exaggerated immediate increase in ventilation to meet the physiological demands on the body, although the change in cardiac output that accompanies the intensity increase does not match that of ventilation. Another rationalization is that a sudden increase in cardiovascular dilation may occur, which would enhance muscle perfusion for faster and increased oxygen extraction (Hoogeveen and Keizer, 2003). Individuals might initially increase oxygen uptake to meet the estimated work demand, but upon reaching this level realize that such a level of uptake is not required to perform the work successfully and $\dot{V}O_2$ is decreased; however, this explanation introduces the question of where the additional oxygen is stored following this transition. Perhaps individuals become more efficient as exercise continues and oxygen uptake may decrease. It is also possible that the subjects exhibit a change in body posture near the end of exercise, which would cause a change in the oxygen demands of the musculature. Regardless of the physiological rationale, the decrements in end $\dot{V}O_2$ reflect a change in the energy sources and transfer mechanisms being utilized and should be considered in any model used to define oxygen deficit.

4-2-2. Model Used

While the three-phase model and a single-exponential model were originally attempted for modeling of the exercise data, it was determined that the data as a whole did not fit these models and a new model was sought. Taking into consideration the breath-by-breath variability and possible end-exercise $\dot{V}O_2$ decrements, a FORTRAN program was developed to model the data using a nonlinear equation. The model was based on the following equation:

$$\hat{y} = \dot{V}O_2 + C_1 t^{C_2} e^{-C_3 t} \qquad (4\text{-}2\text{-}2.1)$$

where $\hat{y}$ = the oxygen uptake ($\dot{V}O_2$) response, $\dot{V}O_2$ = the oxygen uptake averaged from 2 minutes of baseline data (L/min); C_1, C_2, and C_3 = coefficients to be optimized by the model; and t = time (sec). C_1 controls the scale of the ordinate with the magnitude of the $\dot{V}O_2$ response increasing with increasing C_1. The parameter C_2 controls the rate of climb of the response curve with the $\dot{V}O_2$ response rising higher as C_2 increases. The parameter C_3 is a scaling factor that varies with time; as C_3 increases, the $\dot{V}O_2$ ($\hat{y}$) values are lessened because of the exponential term $e^{-C_3 t}$. C_3 can cause a downslope in the curve; the curvilinearity of the response is controlled by a combination of C_2 and C_3. Therefore, an increase in C_1 or C_2 is positively associated with an increase in $\dot{V}O_2$, whereas C_3 has an inverse relationship with $\dot{V}O_2$. Moreover, the peak of the response curve occurs at a time of C_2/C_3, so a downslope will occur if the test duration exceeds that of the coefficient ratio.

Two models were run using the data, each identical in the equation used (Equation 4-2-2.1) although one required that the $\dot{V}O_2$ be set to the measured average baseline value and the other optimized the baseline $\dot{V}O_2$ to better match the data. For some cases, the measured average baseline value did not agree with the $\dot{V}O_2$ values measured at the onset of exercise, presenting a discrepancy in the modeled response; therefore, the option was to allow the initial $\dot{V}O_2$ to be optimized. The measured $\dot{V}O_2$ baseline values were compared to those optimized by the second model to determine if optimization of the baseline $\dot{V}O_2$ was preferable for fitting of the data with the nonlinear model. The error between the two sets of values was determined and the average error calculated (Appendix B-1). The results denoted an average error of 0.01 between the measured and optimized baseline $\dot{V}O_2$ values, which indicates that the measured baseline model is unbiased. The statistical deviation of the errors is 0.20, which indicates the precision of the measured values relative to the model estimates, this level of precision was deemed acceptable in the interest of using actual data as measured from the subjects. An ANOVA run on the two sets of $\dot{V}O_2$ values indicated that there was no statistically significant difference between them ($p = 0.71$). A decision was then made to use the model in which the baseline $\dot{V}O_2$ was set to the measured average value; the decision was made to use actual data, as opposed to theoretical optimum values, for improved applicability.

Finally, the model program using Equation 4-2-2.1 and set $\dot{V}O_2$ values was applied to each set of exercise data. The program used an iterative process to define the optimum solution for each of the coefficients. Initial values were approximated and the incremental steps were set to ten percent of the initial value estimates. After iteration, the program provided values for goodness-of-fit statistics (e.g., accuracy and correlation), optimized values for each coefficient, and information relaying which of the coefficients was most important in defining the response curve was additionally provided; a typical set of results is presented (Table 4-2-2.1). Model results were obtained for all subjects, across all of the exercise intensities and mask conditions (Appendix B-2), and graphed for visual comparison against the breath-by-breath graphs (Figure 4-2-2.1, Appendix B-3). The graphed model results showed strong visual correlation to the breath-by-breath data, so only the model results are presented in their entirety (Appendix B-4).

Table 4-2-2.1 Model results for subject #414 across intensities and mask conditions.

	414						
	C1	C2	C3	$\dot{V}O_2$	Se/Sy	R	C2/C3
75% M40	0.7672	0.2770	0.0005	0.44	0.7733	0.6362	554.0000
85% M40	0.3720	0.4084	0.0007	0.37	0.7099	0.7060	583.4286
100% M40	0.1555	0.6800	0.0023	0.42	0.5655	0.8267	295.6522
115% M40	0.0967	0.9914	0.0086	0.46	0.3533	0.9369	115.2791
85% M40	0.3720	0.4084	0.0007	0.37	0.7099	0.7060	583.4286
85% Hans	1.6770	0.1197	0.00001	0.39	0.8254	0.5667	11970.0000

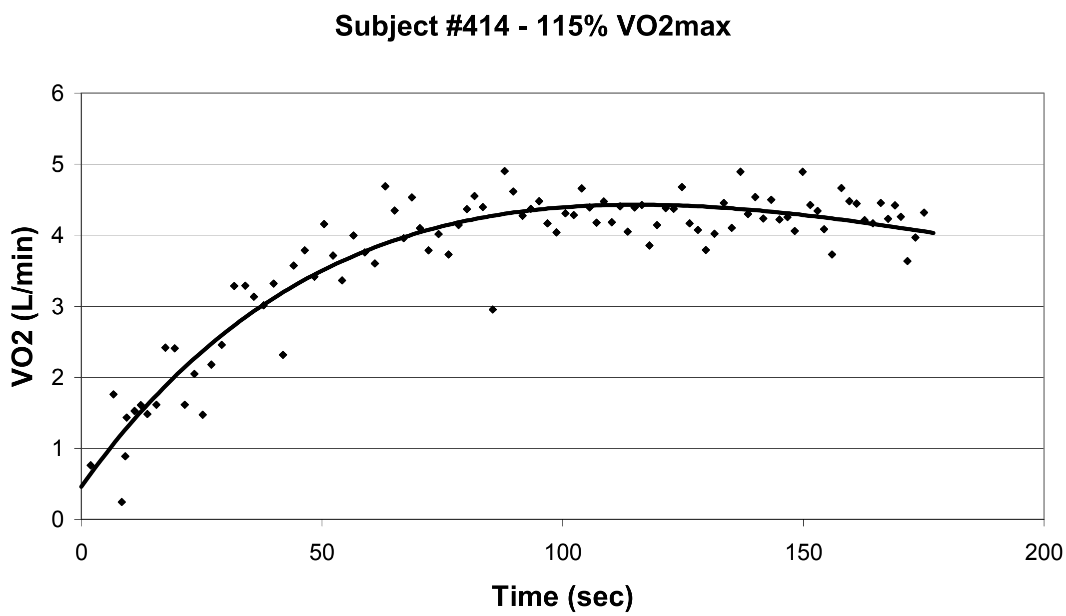


Figure 4-2-2.1. Model results for subject #414 for exercise at 115% $\dot{V}O_{2\,max}$ while wearing an M40.

<u>*4-3. Assessment of Model Reliability*</u>

4-3-1. Coefficient Rationality/ Trends

As previously noted, the rationality of model coefficients is likely the most important measure of model assessment. Rational values provide rational predictions of the phenomenon under consideration. In order to assess rationality of the model, the values of C_1, C_2, and C_3 had to be examined, recalling that C_1 controls the magnitude of the ordinate, C_2 controls the rate of climb of the response curve, and C_3 causes a downward slope in the curve. The peak of the response curve occurred at a time of C_2/C_3; this parameter was very important in assessing model rationality. A decrease in C_2/C_3 indicated that the subject was reaching his/ her oxygen uptake peak at an earlier point in the exercise test. This decrease in time was to be expected as exercise intensity increases, for which oxygen deficit values were also expected to increase. The C_2/C_3 ratio should, therefore, be negatively correlated with oxygen deficit.

Initially, the model coefficients indicated a generally decreasing trend for the C_2/C_3 parameter with increasing exercise intensity, though some of the data sets provided C_2/C_3 ratios inconsistent with this trend (Appendix B-2). The correlation between OD values (to be later discussed) and C_2/C_3 values was not always consistent, with an R value of -0.15935 indicating little correlation. Due to the lack of a consistent trend in the peak ratio and the poor resultant correlation, some of the data sets were rerun using the model to obtain different coefficient results. Re-analysis was completed in light of response surface analysis. Response surfaces represent the relationship that exists between the fitted coefficients and the objective function under consideration (McCuen, 2003). These tools provide information regarding the extent of interaction between the coefficients, optimal coefficient solutions, and the stability of this optimum solution. In fitting the model coefficients in nonlinear regression, the objective is to descend over the response surface to a point of minimum S_e/S_y (highest accuracy) (McCuen, 2003). Hence, using response surfaces it is possible to show that slightly altering the value of the coefficients may do little to change the model accuracy and correlation.

Only those sets for which the peak ratio trend was not consistent were re-analyzed. The model was rerun by holding the C_2 and C_3 values constant at levels that would provide a C_2/C_3 value consistent with the expected decreasing trend; the C_1 coefficient would then be optimized by the model. Comparison of the resulting accuracy and correlation values was then completed to determine if the goodness-of-fit of the model to the data was affected. Very small decrements in the resultant correlation were deemed acceptable in the interest of more rational coefficient values, more specifically peak values consistent with the originally observed and generally expected trend, while larger values indicated that the reruns were not appropriate. The results of the new coefficient values were obtained (Appendix B-5) and new graphs of the results were created where appropriate (Appendix B-6). This practice of using adjusted coefficients was justified because the response surface of the model was very flat near the optimum. The extreme variation in the breath-by-breath measurements introduced considerable uncertainty in the coefficients.

The peak ratios indicated reasonable values and trends in the expected direction according to increasing exercise intensity. The ratios generally decrease with increasing intensity and typically increase with removal of the respiratory mask during exercise; increasing values with the Hans-Rudolph breathing mask are anticipated based on an uninhibited breathing ability by the subjects. The correlation between the oxygen deficit values (to be later discussed) and the new C_2/C_3 ratio values was improved to an R value of -0.24623, which is also in the expected direction of the physiological relationship. Based on these findings, the new coefficient values were used in the subsequent calculation of oxygen deficit for each exercise test and in the determination of a transfer function to describe this exercise phenomenon.

4-3-2. Goodness-of-Fit Statistics

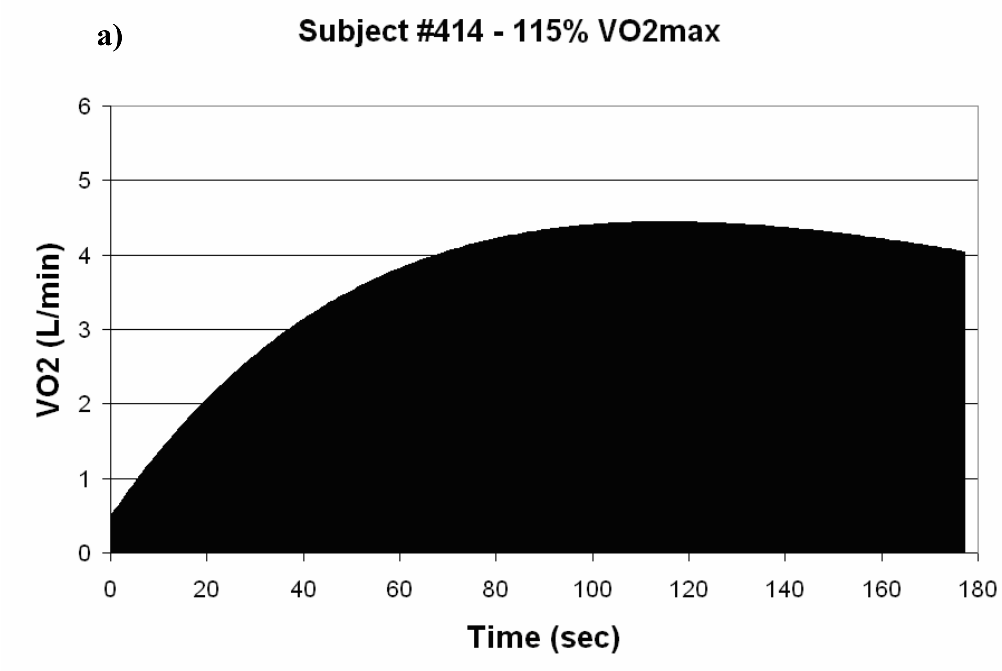
The goodness-of-fit statistics for a given model are also important in assessing model reliability. The two statistics of primary consideration for the current model were accuracy (S_e/S_y) and correlation (R). As previously noted, S_e/S_y values of 0.0 are most desirable; the closer the accuracy estimate to zero, the more significant the improvement in prediction accuracy using the model. The correlation coefficient, R, is used to determine the degree of agreement between the predicted and measured values; larger values indicate an increase in agreement and are, thus, more desirable. Less emphasis was placed on this statistic, however, since this indicator is most useful for linear models.

The model results (Appendix B-5) indicated low to relatively moderate accuracy estimates. These low values were not deemed problematic based on the high variability observed in the breath-by-breath data. The moderate goodness-of-fit statistics do not really suggest a mediocre model, as the model passes through the center of the data, and the model is intended to represent $\dot{V}O_2$, not the breath-by-breath physiology of the subject. As to the previous discussion, breath-by-breath data are highly variable due to both biological variability and error introduced by experimental collection and analysis. The variability in these data likely reduces the fit of any model applied, presenting difficulty in an absolute model fit because of data variability. A low number of data points and a large range of variability are likely explanations for the lower accuracy estimates obtained for some of the data sets. It should be noted, however, that the model results show moderate to relatively high correlation values. These values are positive indicators of a reasonable model, although the fact that the model is nonlinear should be considered.

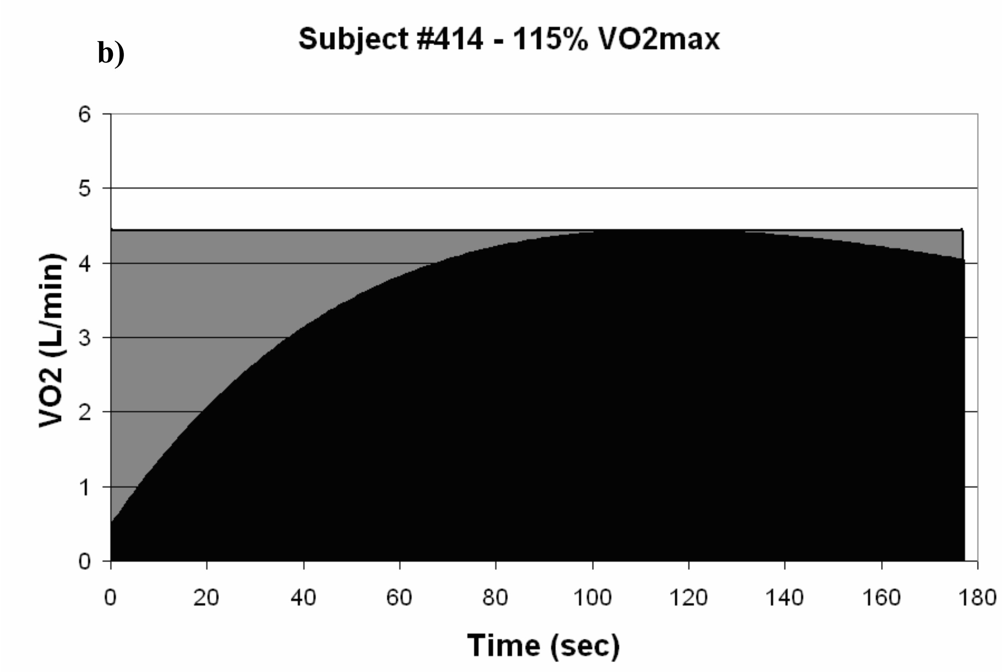
4-4. Calculation of Oxygen Deficit

The analytical process continued with the calculation of the OD developed by each subject in the exercise tests. The coefficients obtained using the nonlinear model were entered into the model equation (Equation 4-2-2.1) to determine the defining function of the oxygen uptake response curve for each exercise test. Using Mathematica 5.2 (Wolfram Research Inc.; Champaign, Illinois), each model curve was explicitly integrated over the length of the test. Integration over the exercise performance time provided the area under the oxygen uptake response curve, signifying the $\dot{V}O_2$ of the exercise test (Figure 4-4.1.a). Oxygen deficit is, however, defined as the difference between $\dot{V}O_2$ at the beginning of exercise and $\dot{V}O_2$ occurring at steady-state (Krogh and Lindhard, 1920; McArdle et al., 2000). This definition implies that the area above the curve, as opposed to below it, up to the steady-state or peak $\dot{V}O_2$ level, is the oxygen deficit. Therefore, the value of the steady-state or peak $\dot{V}O_2$ was multiplied by the corresponding exercise performance time to define the absolute maximum oxygen uptake possible in liters (Figure 4-4.1.b). The associated integrated $\dot{V}O_2$ (Figure 4-4.1.a) was then subtracted from the absolute max uptake (Figure 4-4.1.b) to define the accumulated oxygen deficit for the exercise; schematically, this is the area above the curve, constrained by the level of the steady-state $\dot{V}O_2$ (Figure 4-4.1.c). This value included the difference occurring at the end of the test if a decrement in $\dot{V}O_2$ was observed.

a)



b)



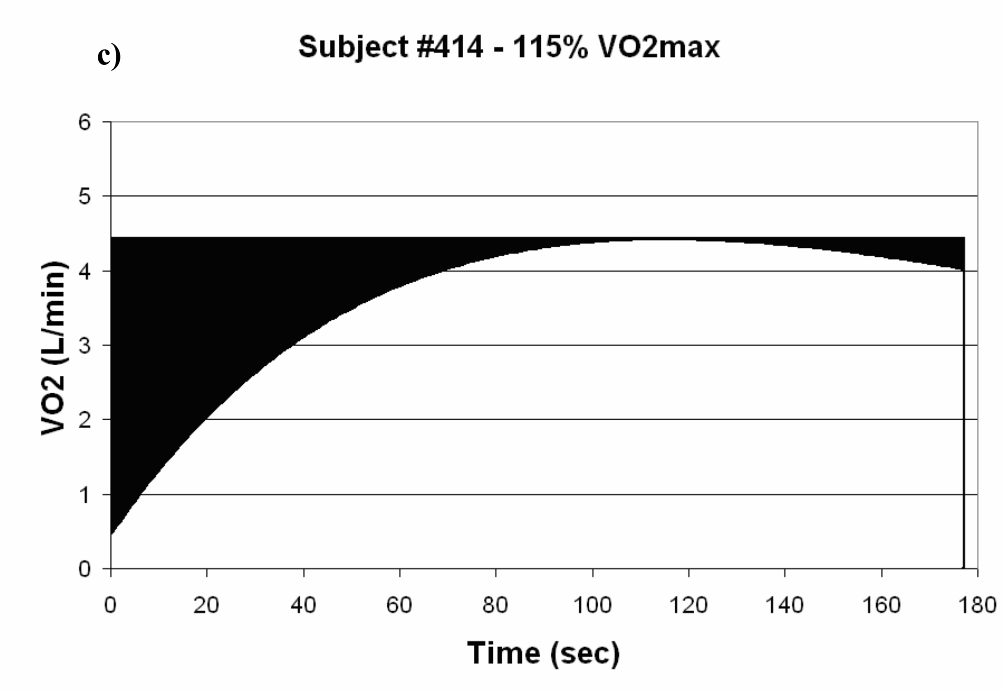


Figure 4-4.1. a) Total $\dot{V}O_2$ of the exercise test, determined by integrating the model curve over the exercise performance time; b) maximum oxygen uptake possible, found by multiplying the peak or steady-state $\dot{V}O_2$ by the exercise duration time; c) the oxygen deficit developed in the test, calculated by subtracting the total exercise $\dot{V}O_2$ (a) from the maximum $\dot{V}O_2$ possible (b).

The mean oxygen deficit was found by dividing the accumulated oxygen deficit by the exercise duration. Finally, the mean OD was divided by the weight of the subject (in kilograms) to provide an independent means of comparison. OD values were defined for each subject for each intensity and mask condition (Table 4-4.1) utilizing time and unit conversions where necessary.

Table 4-4.1. Oxygen deficit (OD) values calculated for each exercise test (in ml/kg/min).

	M40				85%	
	75%	**85%**	**100%**	**115%**	**M40**	**Hans**
001	33	34	36	43	34	44
145	37	52	44	45	52	39
358	8	11	23	24	11	9
359	19	22	N/A	49	22	53
379	11	19	24	29	19	28
401	15	20	22	30	20	17
414	20	28	37	41	28	18
419	23	24	41	42	24	28
420	24	47	38	42	47	27
422	13	33	39	32	33	35
Avg	20.3	29.0	33.8	37.7	29.0	29.8
Std Dev	9.32	12.80	8.42	8.25	12.80	13.34

It should be noted that use of this procedure is technically applicable only to the submaximal and maximal exercise tests. This limitation is based on the fact that during supramaximal exercise, $\dot{V}O_2$ requirements cannot be attained even at the maximum level of physical exertion. Hence, for supramaximal (e.g., 115% $\dot{V}O_{2\,\max}$) exercise conditions, OD should be calculated using an extrapolated $\dot{V}O_2$ value in lieu of the peak $\dot{V}O_2$ value. This procedure, however, was not utilized herein because some of the subjects attained higher peak $\dot{V}O_2$ values during this condition than those values extrapolated for 115% $\dot{V}O_{2\,\max}$ using their maximal oxygen uptake test data; this discrepancy between peak and extrapolated $\dot{V}O_2$ values was observed for approximately half of the study participants. In an effort to be consistent in all oxygen deficit calculations for the supramaximal condition, the procedure previously described using the peak $\dot{V}O_2$ of the test was employed for all 115% $\dot{V}O_{2\,\max}$ OD calculations.

Before continuing with the analytical process, the oxygen deficit values were re-calculated, disregarding any $\dot{V}O_2$ decrement occurring toward the end of exercise. This was done to determine if the end $\dot{V}O_2$ decrease made an important contribution to the OD. To calculate these OD values, the model curve was explicitly integrated from zero to the time of the peak $\dot{V}O_2$ (time of C_2/C_3); this represented the area under the curve. The peak $\dot{V}O_2$ value was then multiplied by C_2/C_3 to define the maximum O_2 uptake possible up to that point in the test. Finally, the area under the curve was subtracted from the maximum $\dot{V}O_2$ possible to give the accumulated oxygen deficit occurring only from exercise commencement to steady-state (Figure 4-4.2). These new values (Appendix B-7) were compared to the previously-calculated OD values; comparison revealed that the two sets of OD values were highly correlated (R^2 = 0.99) and no significant difference existed between the two sets (p = 0.6670). While most of the newly-calculated values were identical to those previously determined, some of the new OD values were higher than the first. This variation was likely due to rounding differences carried, and possibly augmented, throughout the calculation process. It was, therefore, concluded that the drop in $\dot{V}O_2$ observed in some of the exercise tests did not make a significant contribution to the total accumulated oxygen deficit. However, in the interest of being most comprehensive, the initial OD values calculated using any observed $\dot{V}O_2$ decrement were used for the subsequent analyses.

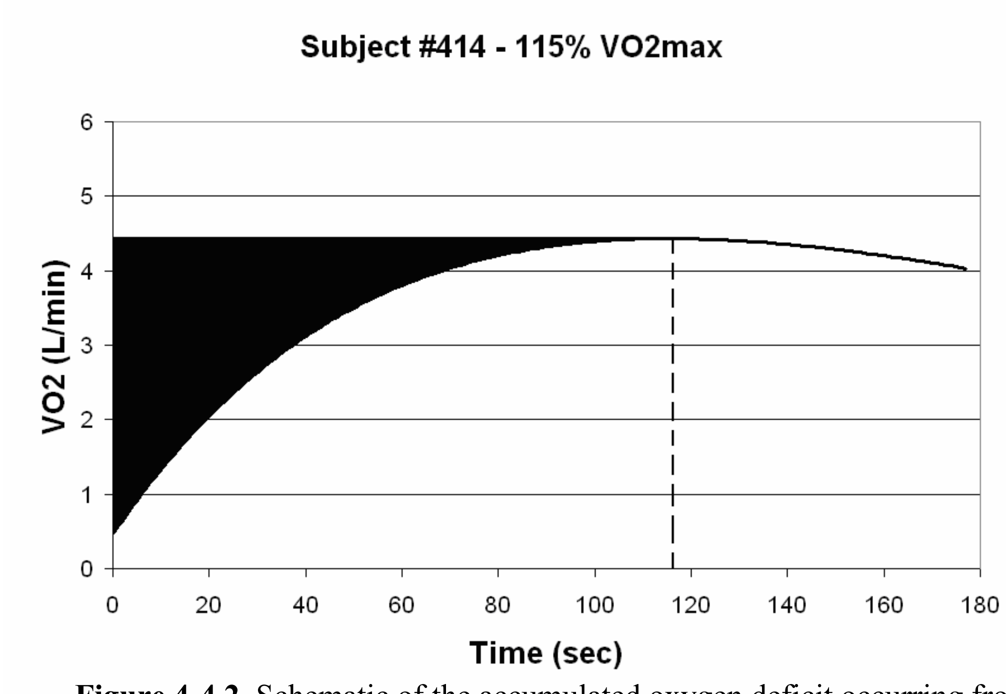


Figure 4-4.2. Schematic of the accumulated oxygen deficit occurring from exercise initiation to steady-state exercise.

4-5. Interpretation of Oxygen Deficit Values

Determination of oxygen deficit values is meaningless without analysis and interpretation of the calculation results. Several different analyses were performed to assess the importance of OD on exercise.

4-5-1. Comparison to Published Values

First, the oxygen deficit values calculated were compared to those published in the literature to evaluate if those calculated were reasonable. The values reported in the literature range from 33 ml/kg/min in prepubescent males (Eriksson et al., 1973) to 80-85 ml/kg/min in sprint athletes (Medbo and Burgers, 1990; Medbo et al., 1988; Scott et al., 1991). Moreover, maximally accumulated O_2 deficit values of endurance athletes and untrained subjects are reported to range from 50 to 65 ml/kg/min (Medbo and Burgers, 1990; Scott et al., 1991). The values obtained in this study were generally lower than those reported for untrained subjects. This difference may be attributable to the method used to calculate the OD. The literature reported values determined using the MAOD method, to which the results of other methods were compared. However, the method used herein was not found in the literature and may perhaps have contributed to the difference in the overall values.

Moreover, AOD values for lower work rates have not been reported. It should be noted that the values obtained for the 115% $\dot{V}O_{2\,max}$ condition were relatively close to those reported in the literature. This was reasonable considering that the published values were measured under severe or heavy exercise conditions; 115% $\dot{V}O_{2\,max}$ may be considered such a condition. Since the 115% $\dot{V}O_{2\,max}$ values were slightly lower than, though relatively similar to, published values, it should be expected that the lower exercise intensities would result in lesser AOD values.

4-5-2. ANOVA Results

Multiple ANOVAs were performed to assess the statistical importance of oxygen deficit on exercise performance. The first ANOVA was used to compare the OD values occurring across the different exercise intensities. The results indicated that there was a statistically significant difference in oxygen deficit across the varying exercise intensities ($p = 0.0028$), for which an increase in exercise intensity was likewise associated with an increase in OD. Subsequently, an ANOVA was performed to ascertain the influence of the M40 respiratory mask on exercise; a resulting p-value of 0.89 denoted that no statistically significant difference existed in the oxygen deficit developed in the different mask conditions. Finally, an ANOVA was completed to compare OD to the performance time of the corresponding exercise test (Table 4-5-2.1). Results of the procedure showed a statistically significant difference in performance time and oxygen deficit values (p = 7.09E-10) with shorter duration tests being generally associated with higher oxygen deficit values.

Table 4-5-2.1. Oxygen deficit values (ml/kg/min) versus performance time (min).

	75%		85% M40		85% Hans		100%		115%	
Subject	**Time**	**OD**	**Time**	**OD**	**Time**	**OD**	**Time**	**OD**	**Time**	**OD**
001	4.07	33	1.91	34	7.51	44	1.14	36	1.62	43
145	11.28	37	3.60	52	10.55	39	2.24	44	2.07	45
358	17.22	8	21.45	11	23.24	9	3.97	23	1.54	24
359	12.59	19	6.02	22	4.92	53	N/A	N/A	1.15	49
379	23.80	11	1.96	19	5.77	28	1.62	24	1.27	29
401	11.62	15	18.87	20	54.75	17	3.12	22	1.21	30
414	15.48	20	13.22	28	16.36	18	6.43	37	2.95	41
419	17.33	23	20.07	24	19.21	28	5.90	41	2.39	42
420	18.74	24	6.52	47	23.69	27	5.74	38	3.88	42
422	27.30	13	13.52	33	15.96	35	6.26	39	2.90	32
Avg	15.94	20.3	10.71	29.0	18.20	29.8	4.05	33.8	2.10	37.7
Std Dev	6.62	9.32	7.66	12.80	14.55	13.34	2.10	8.42	0.92	8.25

4-5-3. General OD Trends

The oxygen deficit values showed that women (subjects #358, 379, and 401) generally had lower OD values than their male counterparts, with the female subjects having an average OD value of 19.3 across all exercise tests as compared to an average OD value of 34.8 for the male participants. Statistical analyses showed that the male OD values were significantly different than those developed by the female subjects (p = 0.00). Additionally, both men and women showed statistically significant differences in OD across exercise intensity (p = 0.001 for men; p = 0.002 for women). The data for both men and women indicated that no statistical difference existed in the oxygen deficit developed in the different mask conditions (p = 0.93 for men; p = 0.84 for women), whereas a statistically significant difference was found when comparing performance time to OD (p = 0.00 for men; p = 0.002 for women). Perhaps this is based on differences in normal exercise activity or perhaps a physiological rationale can account for this difference. It is highly likely that the variation is associated with lean body mass differences. A more specific rationale, physiological or otherwise, to explain this observation is currently unknown and should be further researched.

In regards to OD changes with exercise intensity, a general trend of increasing oxygen deficit with increasing exercise intensity was observed in the subject data. This indicated that the subjects generally utilized intramuscular ATP sources more heavily at the onset of exercise at higher intensities. For seven of the ten subjects, a clear increasing trend was observed. For the remaining three subjects, a single intensity condition disrupted the trend; this inconsistency may be due to subject motivation during the exercise test session. A change in subject motivation, either adding to or lacking in motivation, for a test may dramatically alter the oxygen deficit attained as based on the exercise performance time and the peak $\dot{V}O_2$ reached; the value of the peak has great influence on the OD developed.

The magnitude of the OD values is indicative of the subject efficiency during exercise in regards to metabolism and overall performance. Those subjects with lower overall oxygen deficit values were likely better equipped to perform aerobic activity, implying that these subjects more heavily utilized ATP generated through aerobic metabolism. Conversely, those individuals with higher OD values across all intensities probably excel in more anaerobic-type exercise, relying more on anaerobic metabolism to generate the ATP necessary to perform the work. This is not to say, however, that all of the subjects are not capable of performing work for which they are not physiologically better equipped, as training would probably greatly affect performance.

In comparing the OD values developed in exercise with and without an M40 respiratory mask, no specific trend was observed. Half of the subjects exhibited an increase in oxygen deficit while wearing a Hans-Rudolph breathing mask as opposed to an M40 mask; such a difference may be accounted for by the higher $\dot{V}O_2$ values generally attained without respirators. For the other half of the subjects, the respirator OD was higher than that achieved without the mask; it is possible that these subjects were more heavily impacted by the mask condition. The large degree of variability observed when assessing mask differences may indicate that the presence of any respirator effect is only incidental. To better assess mask limitations, or the lack thereof, it may be useful in future work to allow the subjects to become more comfortable with the mask before any exercise tests are initiated. If subjects are given the opportunity to acclimate to the mask before beginning the study, the issue of mask discomfort or distress will be eliminated, leaving only physiological explanations for oxygen deficit differences.

A comparison was also made between the OD developed and the Rating of Perceived Exertion (RPE) value as indicated by the subject at the onset of exercise. The initial RPE values (Appendix B-8) were used in place of the terminating RPE values because these values should provide a more realistic assessment of how hard the individuals perceived they were working, whereas the terminating values were likely to be very similar toward the end of each exercise test as fatigue set in. The correlation between the initial RPE and the OD developed was poor (R = 0.12). It was expected that the RPE increase with increasing exercise intensity, and should therefore, showed a better correlation to the OD. However, the lack of correlation may indicate that the subjects might not have used the scale properly or that the scale is not the most appropriate indicator of work. Perhaps a motivational scale would be a better tool to assess subject perceived work and willingness to continue exercise.

Overall, the results indicated that while generally increasing with increasing intensity, the oxygen deficit values were highly individualized and based on subject efficiency and physiological energy source preferences. Motivational differences among subjects may be additionally important in accounting for individual values. Reproducibility of these values may provide additional future information and explanation.

4-6. Determination of a Transfer Function

A transfer function to describe the changes in oxygen deficit occurring across exercise intensities while wearing an M40 military-style respirator mask was, thereafter, defined. The function is important for being able to adequately predict the oxygen deficit developed by a subject for a given set of exercise conditions (mask and intensity). The function must consider the variable nature of physiology and must, therefore, include a range of predictive values to better describe the population response.

The transfer function was defined by first identifying sample means and standard deviations for the oxygen deficit values calculated for each exercise intensity in the M40 mask condition. The values were defined as: (1) 20.3 ± 9.3 ml/kg for the 75% M40 condition; (2) 29.0 ± 12.8 ml/kg for the 85% M40 condition; (3) 29.8 ± 13.3 ml/kg for the 85% Hans-Rudolph condition; (4) 33.8 ± 8.4 ml/kg for the 100% M40 condition; and (5) 37.7 ± 8.2 ml/kg for the 115% M40 condition. The Hans-Rudolph values were not incorporated into the transfer function, as they are irrelevant when discussing the OD developed during respirator wear, but are important when examining the effect of the respirator. Confidence intervals were then calculated according to Equation 2-6-3.1. The confidence interval values were connected to define confidence "belts" for inference of intermediate exercise intensities (Figure 4-6.1). Trend lines were subsequently fit to the means and confidence belts to define equations that may be generally used to define intermediate intensity oxygen deficit values (Figure 4-6.2).

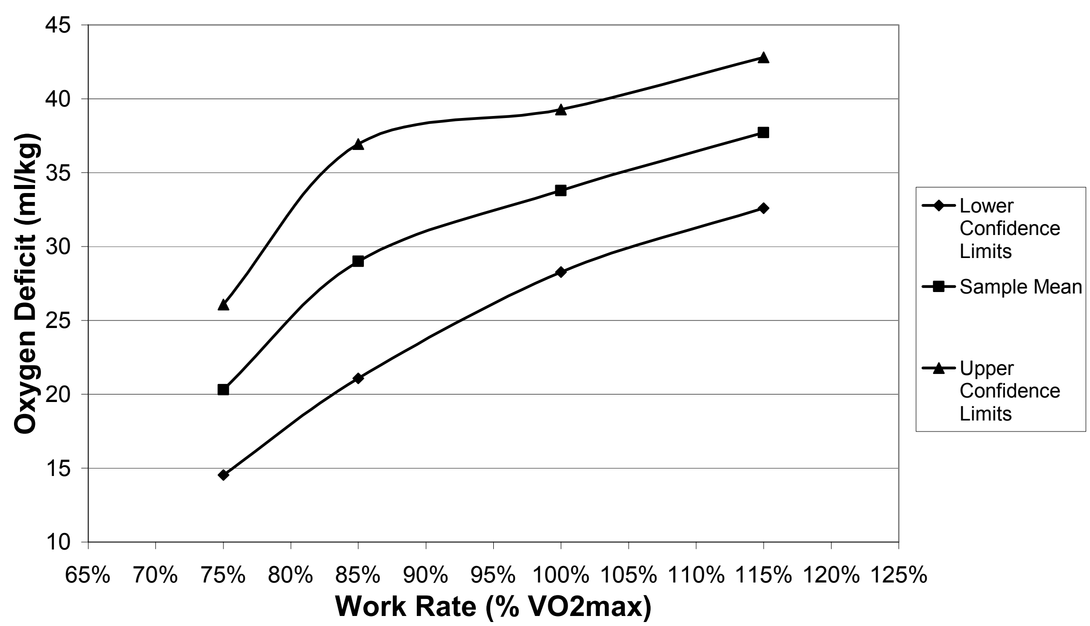


Figure 4-6.1. Sample means and the corresponding confidence limits for oxygen deficit values developed over a range of exercise intensities.

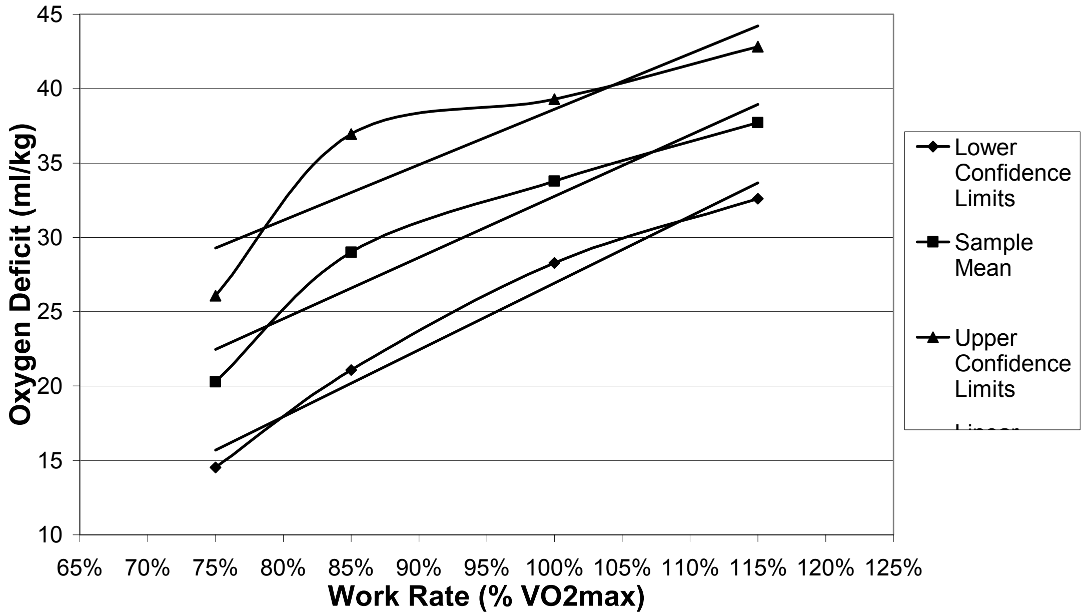


Figure 4-6.2. Sample means and the corresponding confidence limits for oxygen deficit values developed over a range of exercise intensities with added trend lines.

The linear functions defining the oxygen deficit response for exercise completed across multiple intensities while wearing an M40 respirator mask were as follows:

a) Upper confidence limit: OD = $37.348(\dot{V}O_2/\dot{V}O_{2\,\max}) + 1.2619$ ($R^2 = 0.8206$);

b) Sample mean: OD = $41.128(\dot{V}O_2/\dot{V}O_{2\,\max}) - 8.3628$ ($R^2 = 0.9223$); and

c) Lower confidence limit: OD = $44.908(\dot{V}O_2/\dot{V}O_{2\,\max}) - 17.988$ ($R^2 = 0.9731$).

A transfer function was similarly computed to define the predictive relationship between oxygen deficit and performance time. Confidence intervals were subsequently calculated and connected to define "confidence belts" to better determine the predicted exercise performance times associated with intermediate oxygen deficit values (Figure 4-6.3). The resulting curves were best fit and defined by exponential functions that may be later used for predictive purposes (Figure 4-6.4).

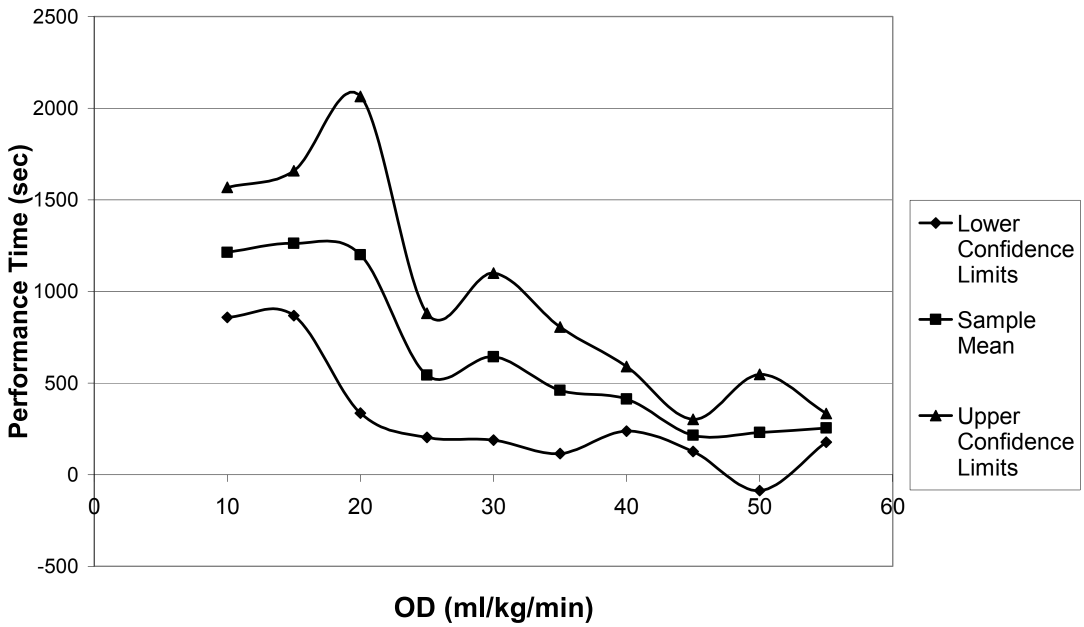


Figure 4-6.3. Sample means and the corresponding confidence limits relating exercise performance time to oxygen deficit.

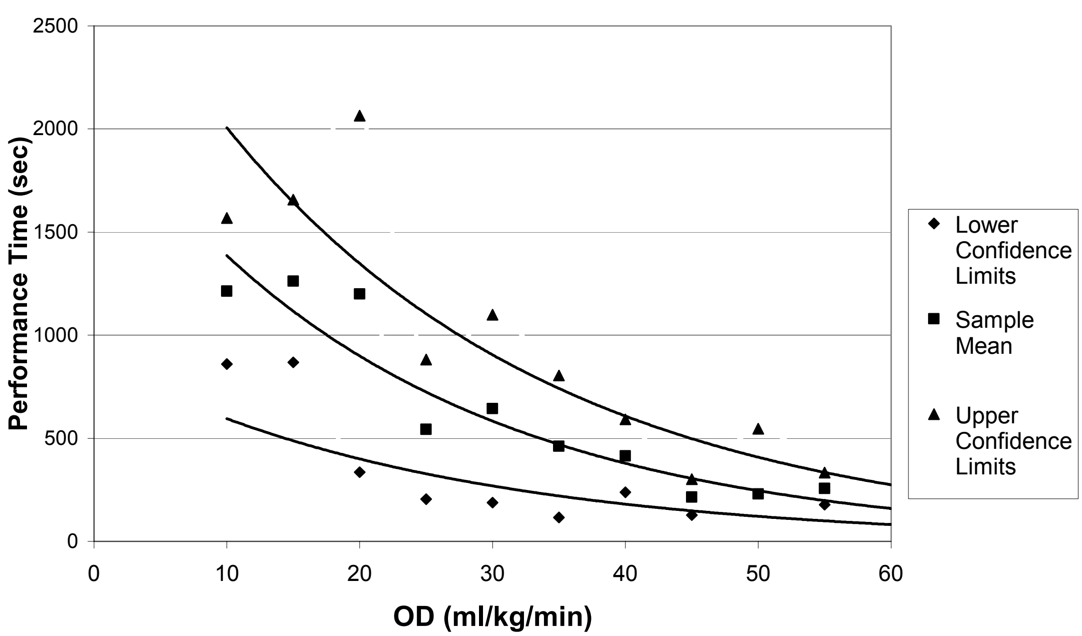


Figure 4-6.4. Sample means and the corresponding confidence limits relating exercise performance time to oxygen deficit with added trend lines.

The exponential functions defining the expected performance time based on the oxygen deficit developed during exercise while wearing an M40 respirator mask were identified as follows:

a) Upper confidence limit: Perf. Time = $2987.6e^{-0.0398*OD}$ ($R^2 = 0.8285$);

b) Sample mean: Perf. Time = $2136.2e^{-0.0433*OD}$ ($R^2 = 0.9037$); and

c) Lower confidence limit: Perf. Time = $885.68e^{-0.0398*OD}$ ($R^2 = 0.6155$).

The data were subsequently broken down into subgroups to define the male OD responses versus those OD values developed by the female subjects. Separate transfer functions (Appendix B-9) were then developed to define the predictive relationships between work rate and OD developed, and OD and exercise performance time; these functions will be valuable in future modeling for enhanced predictive abilities.

Chapter 5: Discussion

5-1. Conclusions

This study was undertaken to define the effect of exercise intensity and respirator wear on the development of oxygen deficit, a measure of an individual's anaerobic capacity. A model developed in the Human Performance Laboratory in the Biological Resources Engineering Department at the University of Maryland, College Park, is lacking in predictive ability for this exercise parameter. The results of this study were intended to fill the existing gap in knowledge.

The overall goal of this research was to model the effect of a respirator on oxygen deficit. To fulfill this goal, three primary objectives were defined. The objectives of this research were to: (1) use experimental exercise data to calculate oxygen deficit with a respirator; (2) determine the maximum oxygen deficit and standard deviation values from the same exercise data; and (3) develop a transfer function that accurately predicts oxygen deficit developed during exercise completed while wearing a respirator.

5-1-1. Research Findings

The model used in this study was developed to accurately model breath-by-breath data collected during exercise testing, accounting for the large variability observed in the subject data and decrements in oxygen uptake observed near the termination of exercise in some of the tests. The curves identified in the model were subsequently used to calculate the oxygen deficit accumulated during exercise. The oxygen deficit values determined in this work were found to generally increase with increasing exercise intensity, a trend expected as based on increasing peak $\dot{V}O_2$ attained during exercise. A decrement in $\dot{V}O_2$ was observed near the end of exercise in some of the exercise tests, although this drop was found to not significantly contribute to the total oxygen deficit.

The results of this research showed oxygen deficit values that were slightly lower than those previously reported in the literature, though this difference may be attributable to the method of oxygen deficit calculation employed. The oxygen deficit values calculated were found to be significantly affected by exercise intensity ($p = 0.0028$), although no statistically significant difference was found between mask conditions ($p = 0.89$). However, a significant difference was observed between oxygen deficit and performance time ($p = 0.00$), with an inverse relationship existing between the two exercise parameters. There was little correlation ($R^2 = 0.014$) found between the initial rating of perceived exertion identified by the subject during exercise and the OD developed. This lack of correlation was unexpected, as harder work perception at the onset of exercise was anticipated for tests of increasing intensity. The RPE scale may be augmented with an additional indicator of subject motivation, as motivational issues may have been the cause of some of the OD discrepancies found in this work.

5-1-2. Model Utilized

The model employed in this analysis was developed when the collected data did not show the characteristics of the three-phase model response curve; namely, three exponential increases were not seen, but rather, a decrement in near-end $\dot{V}O_2$ was occasionally observed. The model equation was defined as follows:

$$\hat{y} = \dot{V}O_2 + C_1 t^{C_2} e^{-C_3 t} \qquad (4\text{-}2\text{-}2.1)$$

where $\hat{y}$ = the oxygen uptake ($\dot{V}O_2$) response, $\dot{V}O_2$ = the oxygen uptake averaged from 2 minutes of baseline data (L/min); C_1, C_2, and C_3 = coefficients to be optimized by the model; and t = time (sec). Increasing C_1 increases the scale of the $\dot{V}O_2$ curve, which in turns increases oxygen deficit by increasing the area above the curve. Increasing C_2 causes the response curve to increase in magnitude and the time to peak $\dot{V}O_2$ to increase; again, the area above the curve will increase. Conversely, increasing C_3 causes the curve to go down and the time to peak $\dot{V}O_2$ to occur earlier; the oxygen deficit will then decrease.

A physiological rationale for the model is herein hypothesized, and should be further analyzed in future work. It is conjectured that C_1 is the aerobic capacity of the individual, accounting for subject body type, endurance, and general fitness. The aerobic capacity or $\dot{V}O_{2\,max}$ for each subject is represented by the scale of the response curve and responds in the manner identified for C_1. C_2 likely represents the anaerobic metabolic efficiency of the subject. As the oxygen demand is increased, there is an increased initial reliance on anaerobic metabolic pathways to meet immediate physiological needs; an increased efficiency in anaerobic metabolism and transport pathways enables the body to meet higher work demands at an earlier time before transitioning to aerobic metabolism. The parameter C_3 is hypothesized to be the rate of type II muscle (anaerobic) fiber fatigue; an increase in the rate of fiber fatigue requires aerobic metabolism earlier to meet energy demands and limits the performance capacity possible. An increase in the rate of fiber fatigue would be associated with a decrease in total oxygen deficit.

5-1-3. Transfer Functions Developed

Using the OD values calculated a transfer function was developed to allow for inference of oxygen deficit values at intermediate exercise intensities for exercise performed while wearing a respirator. A second transfer function was determined to allow for prediction of exercise performance time using oxygen deficit as a predictor. In this way, the work rate may be used to predict the OD developed, from which the exercise performance time with a respirator may be ascertained. These functions are available for incorporation into the model that has been developed at the University of Maryland, College Park to predict exercise performance with a respirator. This model, and hence these functions, may serve as useful tools in respirator design and innovation.

The confidence intervals for both functions indicate little expected population variation at the lowest and highest exercise intensities, though a larger variation is predicted for the intermediate intensities. This is rational, as at lower intensities the body is able to work for a longer duration, while at higher intensities subjects are limited by physiological constraints. The intermediate intensities are, therefore, more highly influenced by subject motivation and willingness to continue exercise. The intermediate variation is further supported by the fact that motivation is highly subject-dependent. Again, this reinforces the need to determine subject motivation both prior to and during exercise.

5-2. Future Work

The results of this study indicated several possible facets for future study. Two primary focus areas emerged as key areas of future work. The first recommendation is to examine the reproducibility of oxygen deficit while wearing a respirator. Oxygen deficit has been shown to be a reproducible measure (Doherty et al., 2000; Ramsbottom et al., 1994) without a respirator, and, thus, should be reproducible under respirator wear conditions. Reproducibility efforts may also help to eliminate the inconsistencies observed in deficit trends. The second key focus area is to further verify the model used for analysis in this work. Additional exercise tests with additional subjects will help to ascertain if this model is the best suited for optimization of oxygen deficit exercise data. The model may be verified or altered using additional exercise data. Supplementary study may be done at additional exercise intensities to verify the transfer function developed through this research.

The fit of the data to this model may also be compared to the fit to other models, such as the three-phase model, by using force-fitting methods to fit the data with other models. The measurement system used to collect the data prevented collecting the data necessary to fit the three-phase model. Breath-by-breath measurements include random variation that is as large as the systemic variation associated with the second and third phases. To model this effect, it would be necessary to include a component that modeled the breath-by-breath variations. It may also be useful to reanalyze the data collected using minimal breath averaging versus breath-by-breath conversion; this will enable the degree and influence of the variability imposed by the breath-by-breath method to be better assessed.

As previously noted, a motivational scale may be created and used to assess subject motivation prior to and during exercise. Motivational differences may explain the discrepancies in oxygen deficit observed. Additionally acclimatizing the subjects to the respirator prior to study commencement may help eliminate baseline variations observed. Another option to help reduce baseline $\dot{V}O_2$ variations is to measure the subjects in the ready position on the treadmill, rather than in the seated position since oxygen demands of the musculature will change based on position.

Other possible work that may stem from this research includes further studying physiological differences between subjects in an attempt to provide physiological explanations for the results obtained herein. The differences between men and women seen in this study should be examined, as should body makeup differences observed between subjects. Muscle biopsies may provide additional interesting information in attempting to explain subject oxygen deficit values.

Appendices

A-1. Research Protocol

The Effects of Respiratory Protective Masks on Maximum Oxygen Deficit

Abstract: A key step in the proper design of respirators, as well as in the regulation of occupational safety, is the modeling of exercise performance while wearing a respiratory mask. A model that accurately predicts performance and performance time must include oxygen deficit, which occurs during the transition from rest to exercise at any intensity. A current respirator model being developed at the University of Maryland, College Park includes oxygen deficit as based on performance of individuals not wearing respiratory masks. Therefore, experimental data should be collected to ascertain oxygen deficit values during exercise with a respiratory mask to be incorporated into the current model.

Purpose: This project is intended to determine oxygen deficit values during exercise at several different exercise intensities (75, 85, 100, and 115% $VO_{2\ max}$). Exercise at each intensity will be completed for each respirator condition, namely with a military-style respiratory mask or a Hans-Rudolph breathing mask.

1. Subject Selection:

a) Who will be the subjects, how will you persuade them to participate, and how many do you expect to participate? If you plan to advertise for subjects, please include a copy of the advertisement.

We plan to recruit 10 participants from the University of Maryland, College Park. A portion of this sample will be drawn from a database stored in the Human Performance Laboratory located in the Biological Resources Engineering Department. Additional subjects will be selected through day-to-day interaction within the campus community. All participation will be voluntary.

b) Will the subjects be selected for any specific characteristics (e.g. age, sex, race, ethnic origin, religion, or any social or economical qualifications)?

We will be selecting subjects between the ages of 18-40 years.

c) State why the selection will be made on the basis or the bases given in 2(b)?

The selection criteria stipulated in 2(b) reflects a desire to recruit individuals who are at minimal risk while taking part in vigorous physical activities. Vigorous exercise may induce life-threatening cardiovascular responses in older populations with known cardiovascular diseases; therefore, this group may not be ideal for this project. The American College of Sports Medicine

(ACSM) in the Guidelines for Exercise Testing and Prescription (6th edition), states that vigorous physical exercise is appropriate for asymptomatic individuals between the ages of 18-40 years, and that medical clearance is not required for this group prior to initiating a vigorous exercise program. This project will not provide medical clearance for prospective participants, and as a result, it is important to select individuals (aged 18-40 years) who do not require medical clearance and are at minimal risk for cardiovascular events while performing vigorous exercise.

2. Describe precisely what will be done to the subject.

Orientation

All participants will be asked to report for a one-hour orientation session. An investigator will be present at this session to explain the test procedures and methods applicable to this project. Volunteers will be provided with a written informed consent document outlining these procedures and methods. Participants will be asked to read and sign this document before being allowed to take part in this study.

Volunteers will be asked to complete several questionnaires. The first questionnaire will be a brief medical history document designed to provide investigators with the individual's present and past health background. Next, the subject will be administered a Physical Activity Readiness Questionnaire (PAR-Q) to determine whether exercise is appropriate at this time without first seeking medical clearance. The American College of Sports Medicine, in the Guidelines for Exercise Testing and Prescription, suggests administering this questionnaire to asymptomatic individuals prior to instituting vigorous exercise programs. The medical history and physical activity questionnaires will be used as screening tools to exclude individuals who are at risk for cardiovascular events when performing vigorous physical activities. The Spielberger State-Trait Anxiety Inventory will be the final questionnaire administered to volunteers, providing investigators with information on the individual's present and general anxiety disposition. These questions provide feedback on anxiety and are not intended to diagnose any psychological state.

All participants will be provided the opportunity to have any questions regarding this study answered at this time or throughout the duration of the remaining test sessions.

Maximal Aerobic Capacity

All participants will undergo a maximal oxygen consumption assessment using a Quinton motorized treadmill. First, participants will be allowed to warm-up on the treadmill for approximately 5 minutes at 50-60% of his or her age-predicted maximum heart rate, followed immediately by a brief stretching period. Next, the volunteer will be seated and fitted with a Hans Rudolph breathing mask for the collection of expiratory air. The test will begin with the treadmill speed and grade gradually ramped to the desired work rate (50-60% age-predicted maximum heart rate response) with this moment signifying the initial stage and lasting approximately 3 minutes. At the completion of this stage, a new work rate will be selected and the participant will be required to work at this intensity for another 3 minutes. Work rates will be modified every third minute during the maximal aerobic assessment period. The session will be terminated if the participant fails to display a sufficient rise in oxygen consumption rate (<150 ml/min) to correspond to the new work rate, if the individual reaches his or her age-predicted maximal heart rate, if the individual displays a response that contraindicates continued assessment (e.g. irregular EKG tracings), or if the participant requests that the session be terminated. The maximal aerobic assessment will last approximately 9-15 minutes.

A Polar heart rate monitor will be used to assess heart rate responses during the session.

Test Conditions

Participants will be asked to report to the lab on 8 separate days to exercise on a Quinton motorized treadmill at one of 4 different exercise intensities (75, 85, 100, and 115% VO_{2max}). Test sessions may or may not be completed on consecutive days, as based on subject availability. Due to the large number of test sessions and a desire to run the test at the same point in the metabolic cycle (i.e. same place in the menstrual cycle for women), it may be necessary to run some of the tests on consecutive days. Four of the eight sessions will be done with the subject wearing a military-style respiratory mask, while the remaining four will be run while wearing a Hans Rudolph breathing mask. All tests will be run in the same manner, the only difference being the mask condition and the work rate used. The sessions will be ordered based on randomization of exercise intensities. Moreover, randomization within each intensity block will be completed to determine the order of the mask condition (with or without). This process is being followed to negate the effect of any learning curve associated with the activity.

Test sessions will not include warm-up or stretching periods directly prior to commencement of the exercise. This is to ensure that the oxygen deficit obtained is maximal for each test, as such periods would exhaust part of the ATP stores that are drawn from at the beginning of exercise. Warm-up increases metabolic rate and affects ATP storage. This procedure will alter the major variable outlined for this project. Studies in healthy subjects have failed to confirm cardiovascular abnormalities during sudden strenuous exercise (ACSM Guidelines, p. 141). Therefore, it would appear reasonable to perform strenuous activities without a warm-up period. It should be noted that subjects will be informed of the risk of muscle injury or cardiovascular abnormalities that may occur from completing these test sessions without prior warm-up.

After arriving in the Human Performance Lab, subjects will be asked to sit for 15-20 minutes in an attempt to return to resting conditions, or as close to baseline as possible. The subjects will then be fitted with a M40 military-style negative pressure respiratory mask that has been adjusted for standard conditions (contains the standard filter); should the test session not call for wearing of the military-style mask, the participant will be fitted with a Hans Rudolph breathing mask for collection of expired air. All of the tests will be run on a treadmill at 2.5% grade until volitional fatigue; only the speed of the treadmill belt will be adjusted to elicit the specific work rate desired. The grade will be held constant during the exercise tests for enhanced comparison and result interpretation. The speed of the treadmill will be set to the appropriate level to elicit the specified work rate, and the treadmill will be turned on while the subject is straddling the belt. Data logging and timing of the test will initiate once the subject steps onto the moving belt. When the subject is no longer able to proceed with the test as based on his or her volitional fatigue, data logging will stop, the treadmill will be slowed before coming to a stop, and the time duration of the test will be recorded. It is important to note that for all exercise tests, a short cool-down period will follow completion of the test to ensure subject safety and return to physical baseline. Each cool-down period will last approximately 5 minutes.

A Polar heart rate monitor will be used to provide heart rate responses during the exercise sessions. Rating of Perceived Exertion and Breathing Apparatus Comfort scales will be taken periodically during each test to provide investigators with subjective feedback regarding the independent variables (e.g. exercise intensity and subject-perceived mask comfort). Tests will be run at approximately the same time of day in an attempt to ensure that physiological conditions are constant and any diurnal cycles are not influencing the results obtained. All of the procedures listed above will be employed for all exercise test sessions, namely all respiratory mask conditions (with or without) and at all exercise intensities.

At the 75 and 85% VO_{2max} exercise intensities, it is anticipated that exercise will last approximately 15-20 minutes; at the higher intensities (100 and 115% VO_{2max}) it is expected that exercise will last only 30 seconds–3 minutes. A single test condition will last up to approximately 30-45 minutes; therefore, this project will necessitate that individuals commit 6-7 hours to fulfill the requirements (1 orientation session with a maximal aerobic capacity test and 8 test conditions) outlined in this study. Participants are free to withdraw from this project at anytime without incurring a penalty. This request may be expressed to an investigator through verbal or written communication.

3. Risks and Benefits: Are there any risks to the subjects? If so, what are these risks? What potential benefits will accrue to justify taking these risks?

Risks

Vigorous physical exercise may produce undesired cardiovascular responses in at-risk populations, leading to possibly life-threatening situations. The medical history and physical activity questionnaires will be used as screening tools to exclude this at-risk group. An Automated External Defibrillator (AED) will be available for use should a cardiovascular incident arise during test sessions. Investigators are trained and certified in the use of the AED.

There is a risk of muscle injury occurring from beginning exercise without a proper warm-up period. As exercise will be completed in this study without warm-up periods, muscle injury is possible, though subjects will be continually monitored in an effort to maintain subject safety throughout the duration of this study.

Benefits
Participants will not receive monetary benefits from taking part in this study; however, individuals will be provided with test results upon completion of this project.

Confidentiality
All participants will be assigned an identification number and will be referred to by this descriptor in any presentation or publication of test findings. All files will be stored and maintained in the assistant investigator's office with access permitted to only those individuals directly responsible for the collection and analysis of test data.

Information and Consent Form
An investigator will meet with each participant to explain the test procedures and methods applicable to this project. The participant will be provided with a written informed consent document outlining these procedures and methods. Volunteers will be asked to read and sign this document before being allowed to participate in the investigation.

Conflict of Interest
Investigators do not have a conflict of interest in this project.

HIPPA Compliance
This investigation will not be using protected health information. Identification numbers will be assigned to help ensure the patient's anonymity. Investigators plan to adhere to the guidelines outlined by the University of Maryland at College Park regarding any sensitive information.

Research Outside of the United States

a) Did the investigators previously conduct research in the country where the research will take place? Briefly describe the Investigators' knowledge and experience working with the study population.

   Not applicable. All research is taking place in the United States.

b) Are there any regulations, rules or policies for human subjects research in the country where the research will take place? If so, please describe and explain how you will comply with the local human subject protection requirements.

   Not applicable. All research is taking place in the United States.

c) Do you anticipate any risks to the research participants in the country where the research will take place, taking into account the population involved, the geographic location, and the culture? If so, please describe. Risks could include physical, psychological, social or economic risks. Do you anticipate that subjects who participate in this research will be placed at risk of criminal or civil liability? If so, please describe.

Not applicable. All research is taking place in the United States.

Research Involving Prisoners

Not applicable. All research is being done using subjects from the University of Maryland population and will not include prisoners.

A-2. Informed Consent Document

The Effects of Respiratory Protective Masks on Maximum Oxygen Deficit

I, ___________________________, state that I am 18 years of age or older, in good physical health, and wish to participate in a research project being conducted by Arthur T. Johnson, Ph.D., William H. Scott Jr., M.A., and Stephanie J. Phelps, B.S., at the University of Maryland, College Park.

Purpose: This project is intended to determine oxygen values during exercise at several different exercise intensities (75, 85, 100, and 115% VO_{2max}). Exercise at each intensity will be completed for each respirator condition, namely with a military-style respiratory mask or a Hans-Rudolph breathing mask.

Methods and Procedures: All participants will be asked to report to the Human Performance Lab at the University of Maryland for an orientation session. During this visit, volunteers will be presented with a written informed consent document outlining test procedures and methods applicable to this investigation. Volunteers will be asked to read and sign this document before being allowed to take part in this study. An investigator will be present to review this document and to provide any answers to questions that an individual may have concerning this project. Next, the participant will be asked to complete three brief questionnaires, the first of which is a medical history form designed to provide investigators with information regarding an individual's present and past health status. The second questionnaire, Physical Activity Readiness Questionnaire, is constructed to determine whether vigorous physical activity is appropriate for the participant at this time. The Spielberger State-Trait Anxiety Inventory will be the final questionnaire administered to participants and will be used to provide investigators with information concerning the volunteer's general and present anxiety levels. Questions include: "I feel secure" and "I feel tense." This questionnaire is not intended to evaluate an individual's psychological state.

Fitness Test

A maximal fitness assessment test will be conducted during the orientation session using a motorized treadmill. A brief warm-up and stretching period will be performed prior to assessing fitness. The warm-up period will last approximately 5 minutes with the treadmill grade and speed set at a work rate corresponding to 50-60% of the participant's age-predicted maximal heart rate. The warm-up period will be immediately followed by a brief stretching period. Next, the volunteer will be fitted with a mask designed to collect expired air. The assessment phase begins with the treadmill speed and grade gradually adjusted to the warm-up work level, signifying the first stage in the fitness test and lasting for a duration of 3 minutes.

______________________ ______________________
Initials Date

The speed will be increased every third minute, while the grade is held constant, until the test is terminated due to several predetermined end-point factors: 1) the volunteer experiences fatigue; 2) the volunteer reaches the maximal heart rate; 3) the volunteer displays a response that suggests terminating the test; or 4) if the volunteer requests that the test be terminated.

Oxygen Deficit Sessions
Participants will be required to report to the lab on **8 separate days** (at approximately the same time of day) to exercise on a motorized treadmill at an exercise intensity ranging from 75-115% of maximal fitness capacity. Four of the sessions will require that a M40 military-style respiratory mask be worn during exercise, while the other four sessions will be completed with a breathing mask like that used in the fitness test. **Only one test will be performed each day.** The test session begins with a 15-20 minute rest period. Next, the participant will be fitted with the appropriate mask for the specified condition, and instructed to exercise at the determined exercise intensity until he or she is no longer able to tolerate the exercise conditions (work level or mask comfort). The speed and grade of the treadmill will be set to the appropriate level to elicit the specified work rate, and the treadmill will be turned on while the volunteer is straddling the belt. Once the participant steps onto the moving belt, the assessment period will begin. The test will be terminated if the volunteer displays responses that suggest ending the session or if they are no longer able to tolerate the condition. It is important to note that for all exercise tests, a short cool-down period will follow completion of the test to ensure subject safety. Each cool-down period will last approximately 5 minutes. These procedures will be followed for all 8 sessions (75, 85, 100, and 115% VO_{2max} in both mask conditions).

A heart rate monitor will be used to provide investigators with heart rate values. This device is a commercially available product worn by joggers to track heart rate during workouts. Also, perceived exertion and breathing mask comfort scales will be administered to participants during the exercise session to determine the subject's exertion and comfort of the respiratory mask or breathing mask.

At the 75 and 85% VO_{2max} exercise intensities, it is anticipated that exercise will last approximately 15-20 minutes; at the higher intensities (100 and 115% VO_{2max}) it is expected that exercise will last only 30 seconds–3 minutes. A single test condition will last up to approximately 30-45 minutes; therefore, this project will necessitate that individuals commit 6-7 hours to fulfill the requirements (1 orientation session with a maximal aerobic capacity test and 8 test conditions) outlined in this study.

Please note that there is no financial compensation for completion of any of the exercise tests performed as part of this study.

Benefits and Risks: Subjects will be entitled to receive test results after completing the project. This study has not been undertaken to benefit volunteers directly, but it is intended to provide investigators with information on oxygen values and performance time.

Initials ____________________ Date ____________________

Vigorous physical exercise may produce a potential life-threatening risk for individuals with cardiovascular problems (e.g. heart disease). This risk is very minimal in young individuals (18-40 years old) who are less likely to display symptoms associated with cardiovascular disease. The medical history and physical activity questionnaires will be administered to all participants to determine whether vigorous physical exercise creates a potential risk. Cool-down periods will be performed after each session to minimize the stress to the body normally associated with vigorous activities.

There is a risk of muscle injury occurring from beginning exercise without a proper warm-up period. As exercise will be completed in this study without warm-up periods, muscle injury is possible, though subjects will be continually monitored in an effort to maintain subject safety throughout the duration of this study.

Informed Consent and Confidentiality: An investigator will provide the participant with an informed consent document to read and sign prior to the individual taking part in this research project. Volunteers will be provided with a copy of the informed consent document containing important contact information should any study-related questions or inquiries arise.

All participants will be assigned an identification number and will be referred to by this descriptor in any publication or presentation of this data. All files will be maintained in the assistant investigator's office and will be accessible only to individuals directly responsible for the collection and analysis of this data.

Rights: Participants are free to withdraw from this investigation at any time without incurring a penalty. This desire may be expressed to an investigator through written or verbal communication. Individuals will be entitled to receive any benefits accrued at the time of termination.

Medical Care: The University of Maryland does not provide any medical or hospitalization insurance for participants in this research study nor will the University of Maryland provide any compensation for any injury sustained as a result of participation in this research study, except as required by law.

____________________ ____________________

Initials Date

Contact Information:

Arthur T. Johnson, Ph.D.
William H. Scott, Jr., M.A.
Stephanie J. Phelps, B.S.
Biological Resources Engineering (Bldg. #142)
Phone numbers: 301-405-1186 or 301-405-1199
Email: sjphelps@wam.umd.edu or ws77@umail.umd.edu or aj16@umail.umd.edu

If you have any questions about your rights as a research subject or wish to report a research-related injury, please contact: Institutional Review Board Office, University of Maryland, College Park, 20742; email: IRB@deans.umd.edu; telephone: 301-405-4212

____________________________________ _________________
Volunteer Signature Date

____________________________________ _________________
Investigator Signature Date

___________________ ___________________
Initials Date

A-3. Medical History Questionnaire

Medical History Questionnaire

Name ______________________________ **Date** ___________

Address ____

____

Phone # (Day) ____________________ **(Night)** ______________

Age _______ **Date of Birth (DOB)** __________ **Gender** ____

Height __________ **Weight** __________

Family History

List all *deceased* immediate family members (parents, grandparents, and brothers/sisters) as well as cause of death and age at death.

____

____

____

____

Medications

List any current medications or dietary supplements you may be taking and the reason:

____

____

____

____

Allergies (include allergies to medications as well):

____

____

____

Personal Health Conditions:

Have you had any of the following? Please circle the appropriate response:

High blood pressure	yes	no
Heart murmur	yes	no
Heart attack	yes	no
Stroke	yes	no
Diseases of the arteries	yes	no
Angina	yes	no
Rheumatic fever, scarlet fever	yes	no
Thyroid Disease	yes	no
Emphysema	yes	no
Diabetes	yes	no
Bronchitis, pneumonia	yes	no
Yellow jaundice	yes	no
Hepatitis	yes	no
Kidney Disease	yes	no
Depression	yes	no
Arthritis	yes	no
Tuberculosis	yes	no
Epilepsy	yes	no
Asthma	yes	no
Leukemia	yes	no
Cancer	yes	no
Glaucoma	yes	no
Elevated Cholesterol	yes	no
Polio	yes	no
Diphtheria	yes	no

Have you ever experienced any of the following? Please circle the appropriate response:

Frequent headaches	yes	no
Frequent colds	yes	no

Nose-bleeds	yes	no
Recurrent sore throats	yes	no
Wheezing spells	yes	no
Coughed up blood	yes	no
Coughed up phlegm	yes	no
Heart palpitations	yes	no
Chest pain w/exercise	yes	no
Dizzy spells	yes	no
Shortness of breath	yes	no
Swollen feet/ankles	yes	no
Heartburn or intestinal problems	yes	no
Pain or cramps in legs	yes	no
Painful joints	yes	no
Ulcers	yes	no
Recurrent constipation	yes	no
Recurrent diarrhea	yes	no
Prostrate trouble	yes	no
Kidney problems	yes	no
Phlebitis	yes	no
Varicose veins	yes	no
Osteoporosis	yes	no
Reynaud's syndrome	yes	no

Smoking Check the appropriate response below:

Never smoked ______ Stopped smoking more than 10 years ago _________

Smoke up to 1 pack/day _____ Smoke 1-2 pack/day ______________

3 + pack/day ______________

What type of smoking? (circle all that apply)

cigarette cigar pipe

Alcohol

How many alcoholic beverages per week do you consume? (circle one)

None up to 2/week 3-7/week 7-10/week 10+/week

What type of alcohol do you drink? ___________________________

Exercise

If you participate in a regular aerobic exercise program such as jogging or soccer, please indicate the frequency and type of exercise below. Regular means 3 or more times/week.

Circle one of the following (if yes):

1-3 times/week (circle one) yes no
type: ___________________________

4-5 times/week (circle one) yes no
type: ___________________________

6-7 times/week (circle one) yes no
type:____________________________

Date of Last Complete Physical Exam:______________________

Normal:____________ Abnormal ________________

Date of Last Chest X-ray: ____________________

Normal: _________________ Abnormal: _______________

Date of Last Electrocardiogram: __________________________

Normal: _________________ Abnormal: _______________

Date of Most Recent Blood Lipid Analysis: _______________________

Report values below if known:

Total Blood Cholesterol __________ Triglycerides _____________

HDL Cholesterol __________ LDL Cholesterol __________

Most Recent Hospitalization and Reason: _______________________________

____

Date and amount of Last Blood Donation: ______________________________

____

<u>For Women Only</u> (Circle appropriate responses)

Are you currently pregnant? yes no

Are you currently menstruating yes no

If yes, are your menstrual cycles regular (once per month)? yes no

<u>Health Insurance</u>

I do have health insurance (circle one) yes no

If yes, my insurance organization is: _____________________________________

I do have dental coverage (circle one) yes no

Do Not Write Below This Line:
Total Number of Cardiovascular Risk Factors:___________

A-4. Physical Activity Readiness Questionnaire

Physical Activity Readiness
Questionnaire-PAR-Q
(revised 1994)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly:
Check YES or NO.

YES	NO		
☐	☐	1.	Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
☐	☐	2.	Do you feel pain in your chest when you do physical activity?
☐	☐	3.	In the past month, have you had chest pain when you were not doing physical activity?
☐	☐	4.	Do you lose your balance because of dizziness or do you ever lose consciousness?
☐	☐	5.	Do you have a bone or joint problem that could be made worse by a change in your physical activity?
☐	☐	6.	Is you doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart?
☐	☐	7.	Do you know of any other reason why you should not do physical activity?

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want—as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those that are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- Start becoming much more physically active—begin slowly and build up gradually. This is the safest and easiest way to go.
- Take part in a fitness appraisal—this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively.

DELAY BECOMING MUCH MORE ACTIVE:

- If you are not feeling well because of temporary illness such as a cold or a fever—wait until you feel better; or
- If you are or may be pregnant—talk to your doctor before you start becoming more active.

Please note: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

You are encouraged to copy the PAR-Q but only if you use the entire form

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction.

NAME ________________________________

SIGNATURE ____________________________ DATE ____________________________

SIGNATURE OF PARENT ____________________ WITNESS ____________________________
or GUARDIAN (for participants under the age of majority)

Supported by: Health Canada Sante Canada

A-5. Maximal Oxygen Consumption Test Data Sheet

Maximal Oxygen Consumption

Subject # __________ **Date __________**

Age __________ **Weight __________**

Height __________

Work Rate (mph/ % grade)	**Time**	**Heart Rate**	**Oxygen Consumption**	**Minute Volume**	**RPE**
	0:00				
	0:30				
	1:00				
	1:30				
	2:00				
	2:30				
	3:00				
	0:00				
	0:30				
	1:00				
	1:30				
	2:00				
	2:30				
	3:00				
	0:00				
	0:30				
	1:00				
	1:30				
	2:00				
	2:30				
	3:00				

Work Rate (mph/ % grade)	**Time**	**Heart Rate**	**Oxygen Consumption**	**Minute Volume**	**RPE**
	0:00				
	0:30				
	1:00				
	1:30				
	2:00				
	2:30				
	3:00				
	0:00				
	0:30				
	1:00				
	1:30				
	2:00				
	2:30				
	3:00				

Performance Time ___________

Maximal Oxygen Consumption __________

A-6. Extrapolative Equations for Test Intensity

Note that the intensity range defined after each equation is the subject-specific intensity range for which the generally linear relationship between $\%\dot{V}O_{2\,max}$ and metabolic cost (kJ/min) was observed.

Subject #001: $\%\dot{V}O_{2\,max}$ = 25.657*metabolic cost – 14.966 (44% to 100% $\dot{V}O_{2\,max}$)

Subject #145: $\%\dot{V}O_{2\,max}$ = 27.204*metabolic cost – 21.025 (33% to 100% $\dot{V}O_{2\,max}$)

Subject #358: $\%\dot{V}O_{2\,max}$ = 55.838*metabolic cost – 21.8 (54% to 100% $\dot{V}O_{2\,max}$)

Subject #359: $\%\dot{V}O_{2\,max}$ = 25.707*metabolic cost – 5.6997 (40% to 100% $\dot{V}O_{2\,max}$)

Subject #379: $\%\dot{V}O_{2\,max}$ = 61.149*metabolic cost – 31.459 (58% to 100% $\dot{V}O_{2\,max}$)

Subject #401: $\%\dot{V}O_{2\,max}$ = 50.918*metabolic cost – 21.568 (35% to 100% $\dot{V}O_{2\,max}$)

Subject #414: $\%\dot{V}O_{2\,max}$ = 26.633*metabolic cost – 12.655 (50% to 100% $\dot{V}O_{2\,max}$)

Subject #419: $\%\dot{V}O_{2\,max}$ = 28.004*metabolic cost + 14.637 (53% to 100% $\dot{V}O_{2\,max}$)

Subject #420: $\%\dot{V}O_{2\,max}$ = 30.795*metabolic cost – 3.5485 (44% to 100% $\dot{V}O_{2\,max}$)

Subject #422: $\%\dot{V}O_{2\,max}$ = 43.517*metabolic cost – 43.515 (39% to 100% $\dot{V}O_{2\,max}$)

A-7. Pre-Test Food and Activity Log

FOOD AND ACTIVITY LOG

** NOTE TO SUBJECTS: Please be as thorough and honest as possible when filling out this log. Also, please try to replicate your activity and diet for the 24 hours prior to each test (*as best as possible*).**

Subject # _______________ Date: ______________

Record Start Time: ___________________
Record End Time: ____________________

Current Level of Daily Physical Activity (circle one):

Inactive (no regular physical activity)
Relatively Inactive (no regular organized activity)
Light Physical Activity (sporadic recreational activities)
Moderate Physical Activity (regular recreational/ fitness activities)
Very Vigorous Physical Activity (extensive physical activity at least four days/week)

Time	**Activity Completed**		**Food Consumed**		**Comments**
	Type	**Duration/ Intensity**	**Type**	**Amount**	

A-8. Oxygen Deficit Test Data Sheet

OD_{max} Exercise Test

Subject # ____________________ Test Date _______________

Intensity/ Speed _______________ Mask Condition M40 Hans Rudolph

Age ______________ Height _________________

Weight ____________ 1st Day of Last Period _____

Clothes Worn ____________________

Baseline:

Time	Heart Rate	VO_2
0:30		
1:00		
1:30		
2:00		

Time	Heart Rate	VO_2	RPE	BACS
0:30				
1:00				
1:30				
2:00				
2:30				
3:00				
3:30				
4:00				
4:30				
5:00				
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25:00				

B-1. Differences in Model VO_2 Values

Measured VO_2	Optimized VO_2	Error
0.44	0.50	0.06
0.42	0.38	-0.04
0.47	0.24	-0.23
0.43	0.46	0.03
0.43	0.59	0.16
0.48	0.38	-0.10
0.52	0.34	-0.18
0.45	0.13	-0.32
0.37	0.72	0.35
0.46	0.40	-0.06
0.21	0.20	-0.01
0.24	0.63	0.39
0.14	0.17	0.03
0.35	0.34	-0.01
0.33	0.35	0.02
0.60	0.32	-0.28
0.38	0.66	0.28
0.16	0.05	-0.11
0.38	0.67	0.29
0.33	0.34	0.01
0.27	0.36	0.09
0.31	0.34	0.03
0.23	1.07	0.84
0.29	0.29	0.00
0.15	0.15	0.00
0.24	0.25	0.01
0.26	0.16	-0.10
0.08	0.03	-0.05
0.11	0.24	0.13
0.44	0.21	-0.23
0.37	0.29	-0.08
0.39	0.38	-0.01
0.42	0.42	0.00
0.46	0.48	0.02
0.41	0.60	0.19
0.31	0.30	-0.01
0.24	0.29	0.05
0.31	0.28	-0.03
0.35	0.18	-0.17
0.40	0.41	0.01
0.43	0.74	0.31
0.40	0.40	0.00
0.37	0.03	-0.34
0.37	0.42	0.05
0.35	0.38	0.03
0.41	0.40	-0.01
0.37	0.12	-0.25
0.41	0.30	-0.11
0.42	0.36	-0.06

Average Error = 0.01 **Standard Deviation of Error** = 0.20

The preceding table defines the measured baseline $\dot{V}O_2$ values as compared to the $\dot{V}O_2$ values optimized by a second version of the model used in the study analysis. Comparison was completed to assess whether optimization of the baseline $\dot{V}O_2$ was preferable for fitting the data with the nonlinear model, as opposed to using those values measured prior to exercise commencement. The error between the $\dot{V}O_2$ values was calculated to determine the average error and standard deviation of the errors between the two model versions. As previously noted, the results indicated an unbiased model when the measured baseline $\dot{V}O_2$ is used. In addition, the level of precision of the measured baseline model is adequate for the purposes of this work. Therefore, the model in which baseline $\dot{V}O_2$ was set by the user, as opposed to optimized by the model itself, was used in the interest of using actual data as measured from the subjects.

B-2. Model Results – Coefficients and Fit Statistics

	001						
	C1	**C2**	**C3**	**VO2**	**Se/Sy**	**R**	**C2/C3**
75% M40	0.2100	0.6453	0.0032	0.44	0.5506	0.8370	201.6563
85% M40	0.0088	1.7022	0.0197	0.42	0.4406	0.9007	86.3185
100% M40	0.0008	2.7500	0.0489	0.43	0.4941	0.8746	56.2372
115% M40	0.0108	1.7400	0.0213	0.43	0.2841	0.9599	81.6901
85% M40	0.0088	1.7022	0.0197	0.42	0.4406	0.9007	86.3185
85% Hans	0.0620	0.8905	0.0028	0.47	0.5823	0.8141	318.0357

	145						
	C1	**C2**	**C3**	**VO2**	**Se/Sy**	**R**	**C2/C3**
75% M40	0.5375	0.4400	0.0013	0.48	0.7481	0.6650	338.4615
85% M40	0.1285	0.8397	0.0039	0.52	0.4775	0.8804	215.3077
100% M40	0.0046	1.9494	0.0219	0.37	0.5416	0.8435	89.0137
115% M40	0.1831	0.8884	0.0091	0.46	0.4256	0.9071	97.6264
85% M40	0.1285	0.8397	0.0039	0.52	0.4775	0.8804	215.3077
85% Hans	0.2933	0.5490	0.0015	0.45	0.8548	0.5215	366.0000

	358						
	C1	**C2**	**C3**	**VO2**	**Se/Sy**	**R**	**C2/C3**
75% M40	0.3996	0.2000	0.0004	0.21	0.9223	0.3896	500.0000
85% M40	0.6184	0.1014	-0.0001	0.24	0.8117	0.5867	-1126.6667
100% M40	0.0634	0.8200	0.0059	0.35	0.6403	0.7705	138.9831
115% M40	0.6258	0.2378	-0.0013	0.33	0.6430	0.7717	-182.9231
85% M40	0.6184	0.1014	-0.0001	0.24	0.8117	0.5867	-1126.6667
85% Hans	0.6513	0.1477	0.0002	0.14	0.8773	0.4835	738.5000

	359						
	C1	**C2**	**C3**	**VO2**	**Se/Sy**	**R**	**C2/C3**
75% M40	0.1630	0.4400	0.0006	0.60	0.8030	0.5985	733.3333
85% M40	0.0164	0.9871	0.0030	0.38	0.6337	0.7760	329.0333
100% M40	n/a	n/a	n/a	n/a	n/a	n/a	n/a
115% M40	0.2937	0.7273	0.0057	0.38	0.4432	0.9014	127.5965
85% M40	0.0164	0.9871	0.0030	0.38	0.6337	0.7760	329.0333
85% Hans	0.2320	0.5890	0.0011	0.16	0.5288	0.8506	535.4545

	379						
	C1	**C2**	**C3**	**VO2**	**Se/Sy**	**R**	**C2/C3**
75% M40	0.9649	0.0975	0.0001	0.33	0.9721	0.2428	975.0000
85% M40	0.0043	1.5418	0.0135	0.27	0.7080	0.7256	114.2074
100% M40	0.2700	0.5867	0.0053	0.23	0.7707	0.6541	110.6981
115% M40	0.1381	0.6642	0.0027	0.29	0.6945	0.7352	246.0000
85% M40	0.0043	1.5418	0.0135	0.27	0.7080	0.7256	114.2074
85% Hans	0.0437	0.8000	0.0027	0.31	0.7709	0.6410	296.2963

	401						
	C1	**C2**	**C3**	**VO2**	**Se/Sy**	**R**	**C2/C3**
75% M40	0.6171	0.2009	0.0007	0.15	0.8983	0.4442	287.0000
85% M40	0.4573	0.2460	0.0004	0.24	0.8260	0.5656	615.0000
100% M40	0.3645	0.3600	0.0170	0.08	0.6298	0.7809	21.1765
115% M40	0.0336	1.3000	0.0235	0.11	0.4049	0.9181	55.3191
85% M40	0.4573	0.2460	0.0004	0.24	0.8260	0.5656	615.0000
85% Hans	0.8805	0.1492	0.0001	0.26	0.9172	0.4003	1492.0000

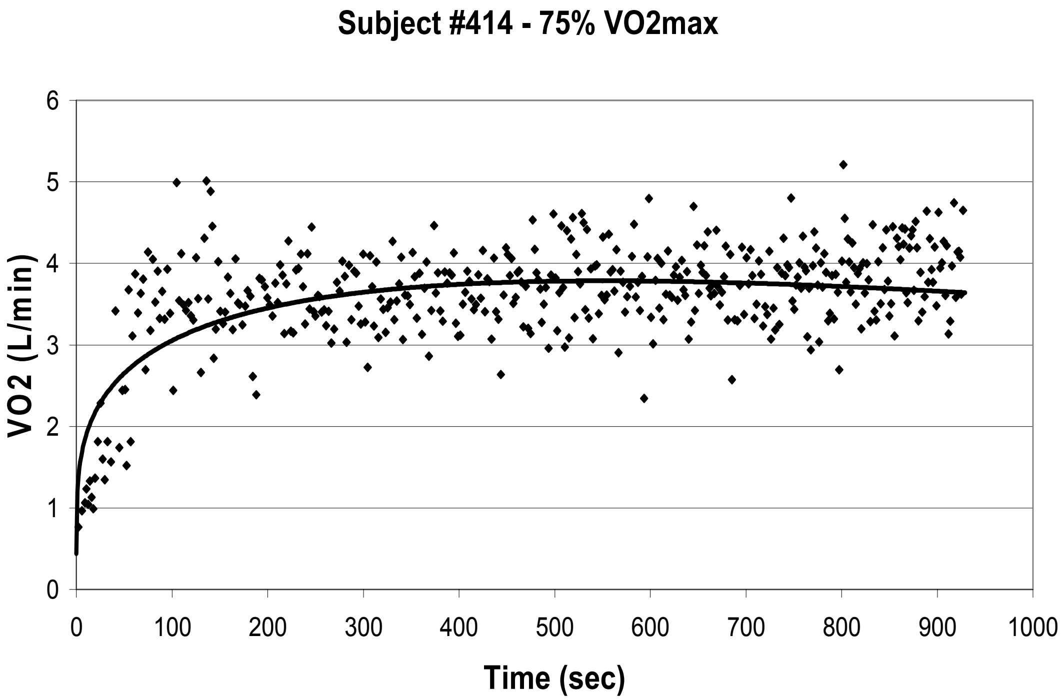
	414						
	C1	**C2**	**C3**	**VO2**	**Se/Sy**	**R**	**C2/C3**
75% M40	0.7672	0.2770	0.0005	0.44	0.7733	0.6362	554.0000
85% M40	0.3720	0.4084	0.0007	0.37	0.7099	0.7060	583.4286
100% M40	0.1555	0.6800	0.0023	0.42	0.5655	0.8267	295.6522
115% M40	0.0967	0.9914	0.0086	0.46	0.3533	0.9369	115.2791
85% M40	0.3720	0.4084	0.0007	0.37	0.7099	0.7060	583.4286
85% Hans	1.6770	0.1197	0.00001	0.39	0.8254	0.5667	11970.0000

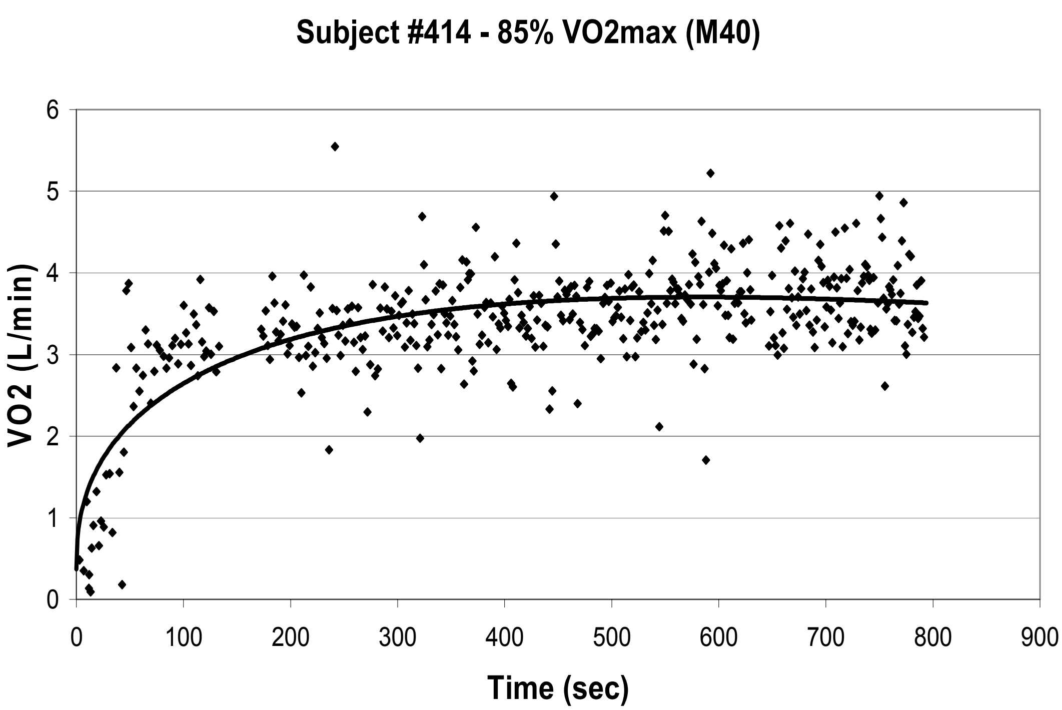
	419						
	C1	**C2**	**C3**	**VO2**	**Se/Sy**	**R**	**C2/C3**
75% M40	0.5561	0.2761	0.0004	0.41	0.7883	0.6171	690.2500
85% M40	0.4898	0.3000	0.0003	0.31	0.7773	0.6314	1000.0000
100% M40	0.1391	0.6500	0.0020	0.31	0.4576	0.8904	325.0000
115% M40	0.0688	0.8937	0.0046	0.35	0.4200	0.9096	194.2826
85% M40	0.4898	0.3000	0.0003	0.31	0.7773	0.6314	1000.0000
85% Hans	0.4796	0.3147	0.00040	0.24	0.7326	0.6817	786.7500

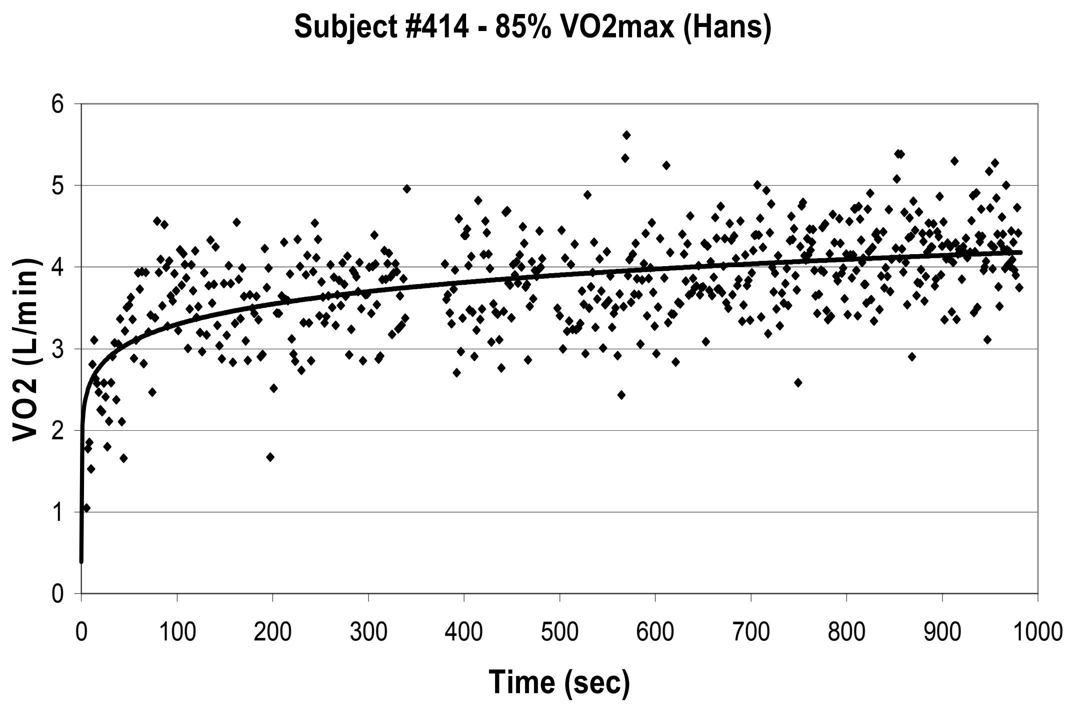
	420						
	C1	**C2**	**C3**	**VO2**	**Se/Sy**	**R**	**C2/C3**
75% M40	0.6539	0.2699	0.0004	0.40	0.8106	0.5875	674.7500
85% M40	0.1915	0.6575	0.0025	0.43	0.7020	0.7167	263.0000
100% M40	0.3955	0.4200	0.0010	0.37	0.6315	0.7781	420.0000
115% M40	0.0840	1.0000	0.0094	0.37	0.5161	0.8584	106.3830
85% M40	0.1915	0.6575	0.0025	0.43	0.7020	0.7167	263.0000
85% Hans	1.0486	0.1899	0.0001	0.40	0.7329	0.6820	1899.0000

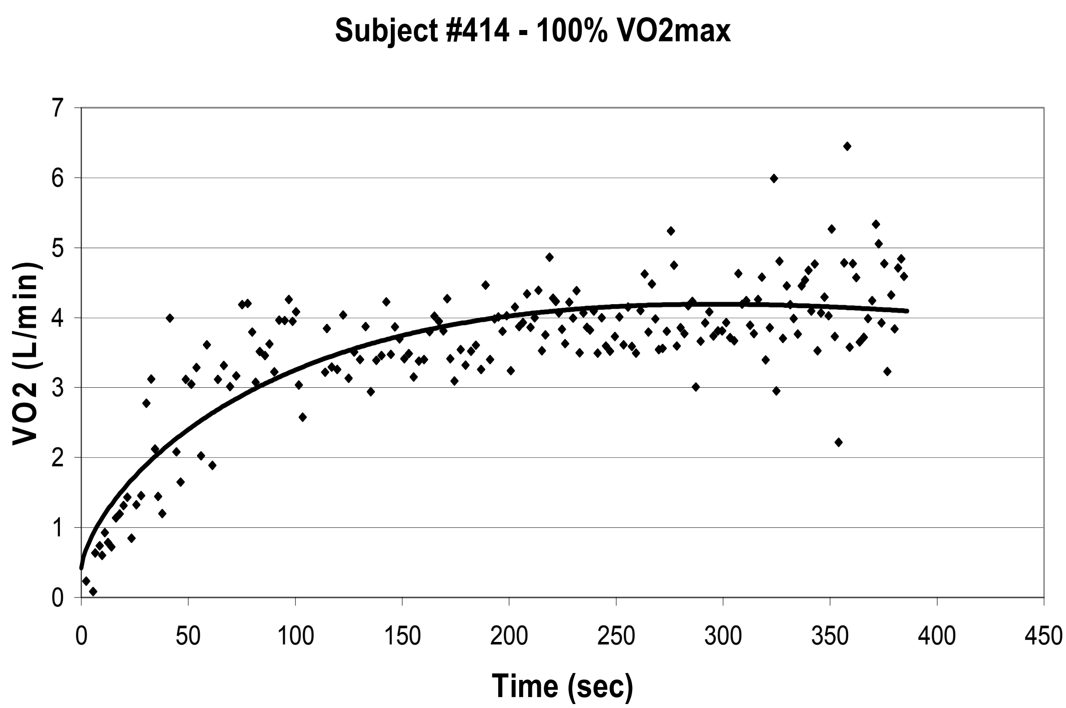
	422						
	C1	**C2**	**C3**	**VO2**	**Se/Sy**	**R**	**C2/C3**
75% M40	1.7918	0.0925	0.0001	0.35	0.9865	0.1727	925.0000
85% M40	0.7986	0.2500	0.0003	0.41	0.6467	0.7638	833.3333
100% M40	0.2523	0.5500	0.0018	0.41	0.4485	0.8948	305.5556
115% M40	0.0039	1.7177	0.0150	0.42	0.4176	0.9106	114.5133
85% M40	0.7986	0.2500	0.0003	0.41	0.6467	0.7638	833.3333
85% Hans	0.3836	0.4000	0.0006	0.37	0.6209	0.7846	666.6667

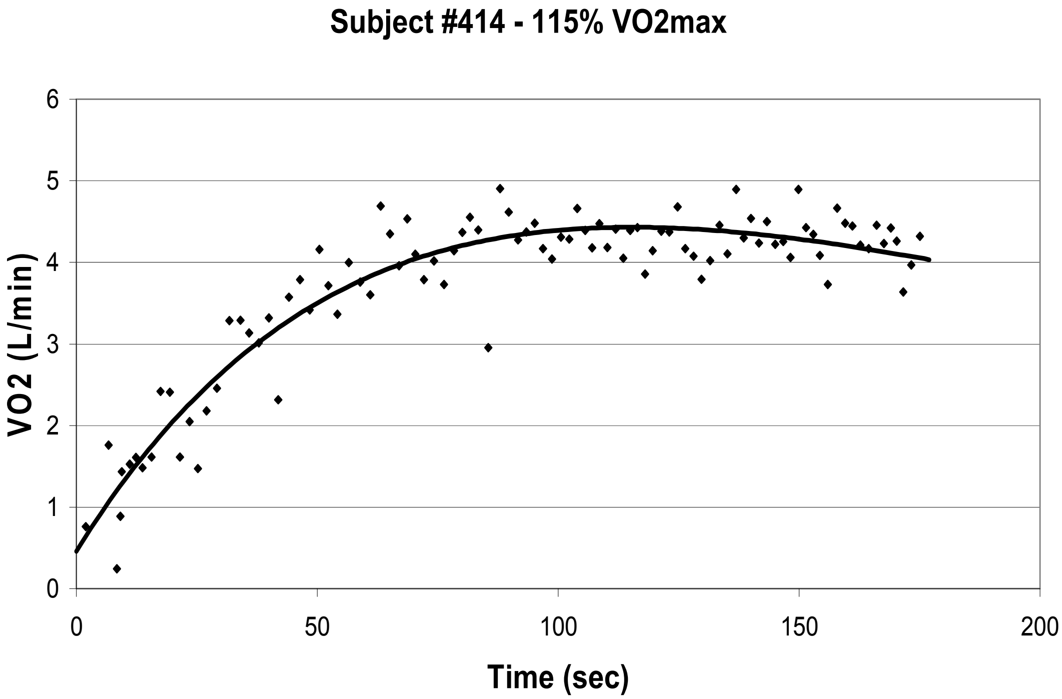
B-3. Raw Data vs. Model Results - Examples



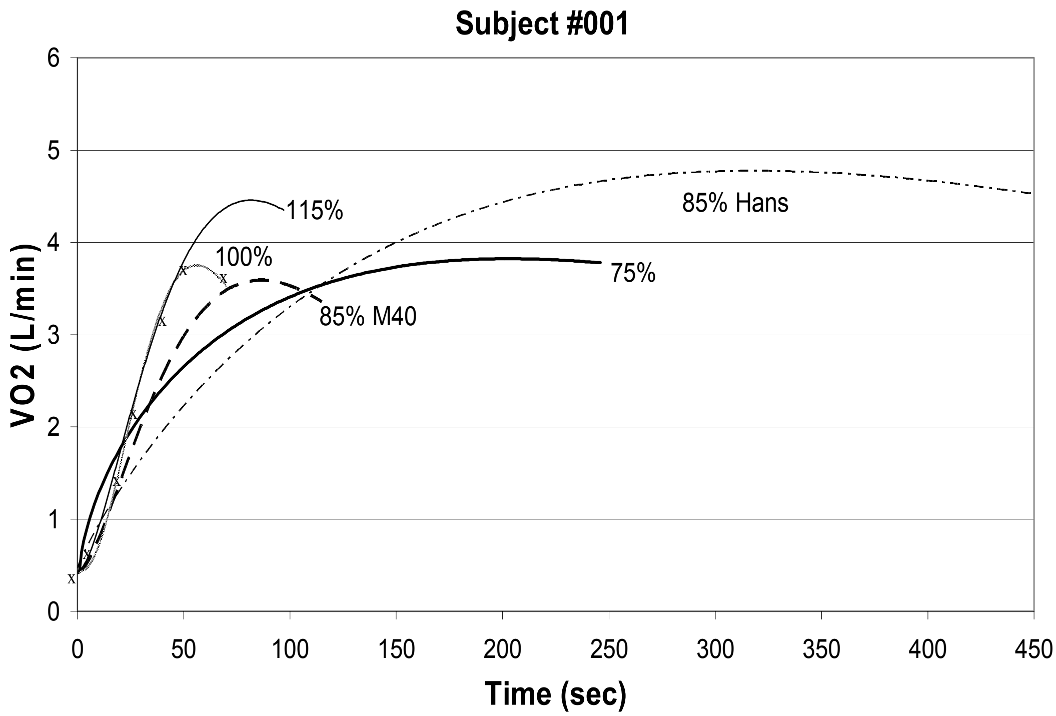


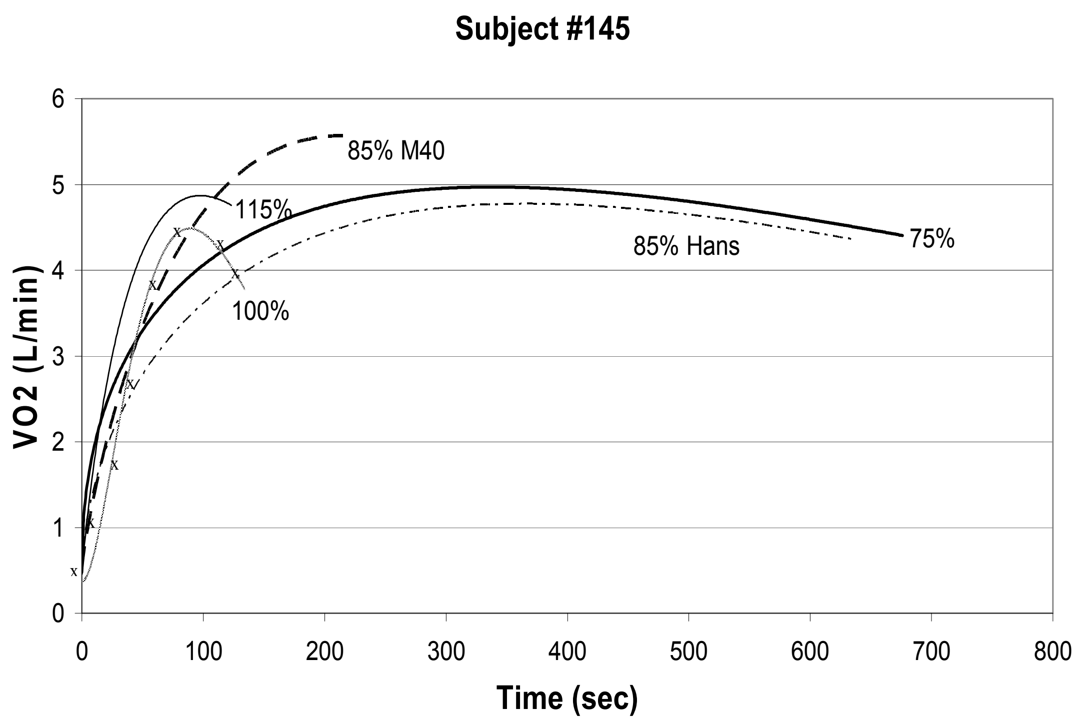

Subject #414 - 85% VO2max (Hans)
VO2 (L/min)
Time (sec)
0
1
2
3
4
5
6
0
100
200
300
400
500
600
700
800
900
1000


Subject #414 - 100% VO2max
VO2 (L/min)
Time (sec)
0
1
2
3
4
5
6
7
0
50
100
150
200
250
300
350
400
450

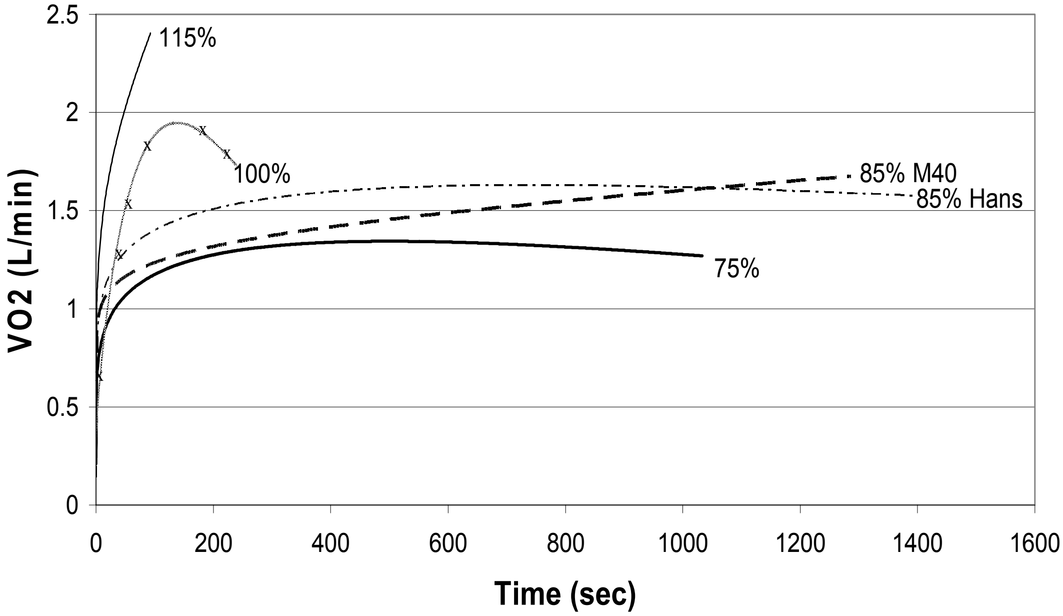

Subject #414 - 115% VO2max
VO2 (L/min)
Time (sec)
0
1
2
3
4
5
6
0
50
100
150
200

B-4. Subject Results – Model Graphs

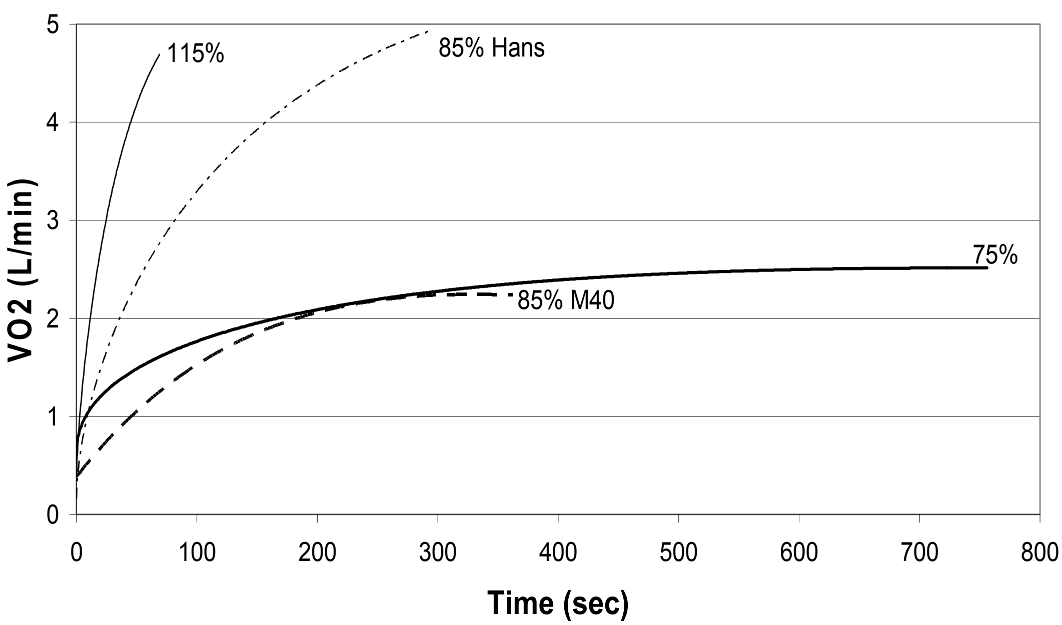


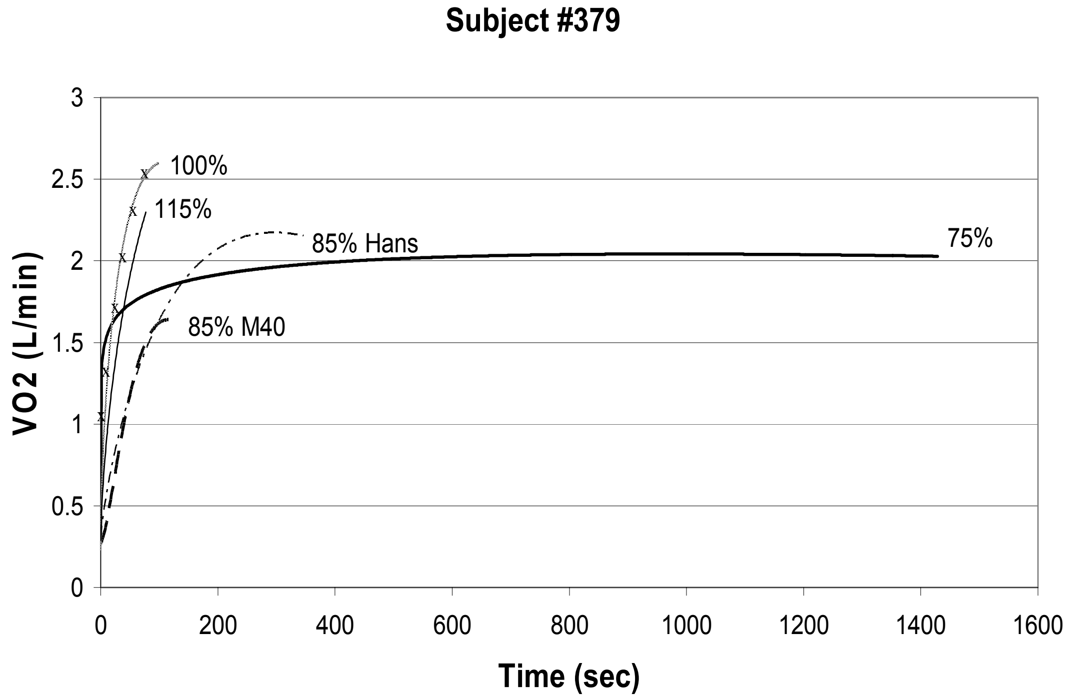


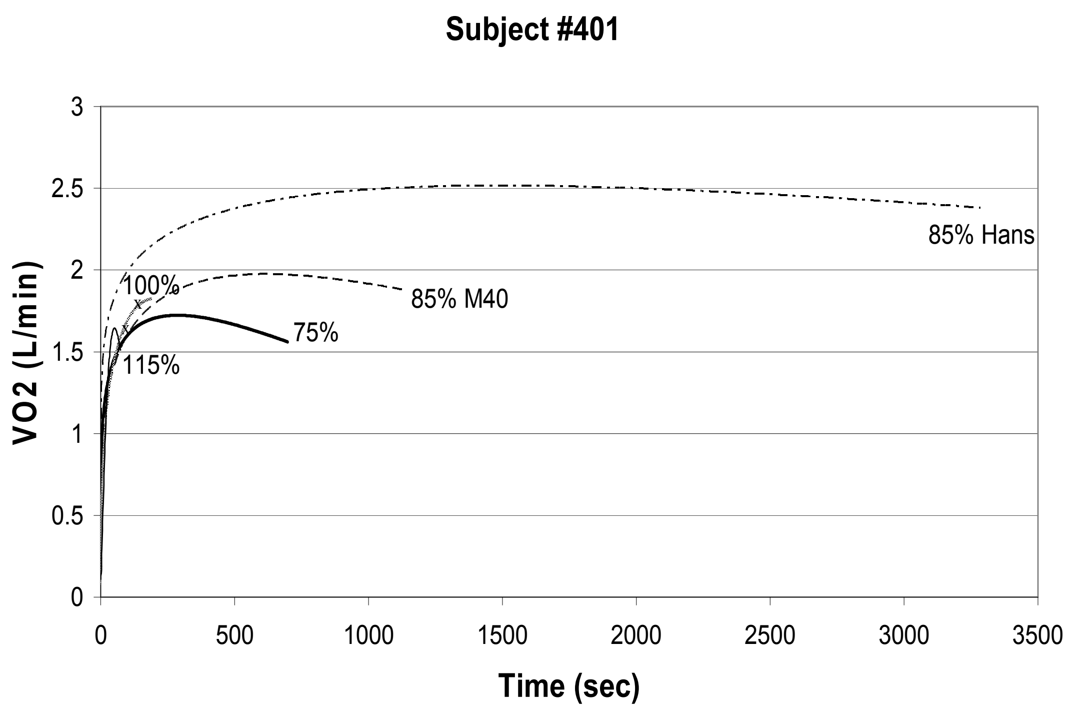
Subject #358

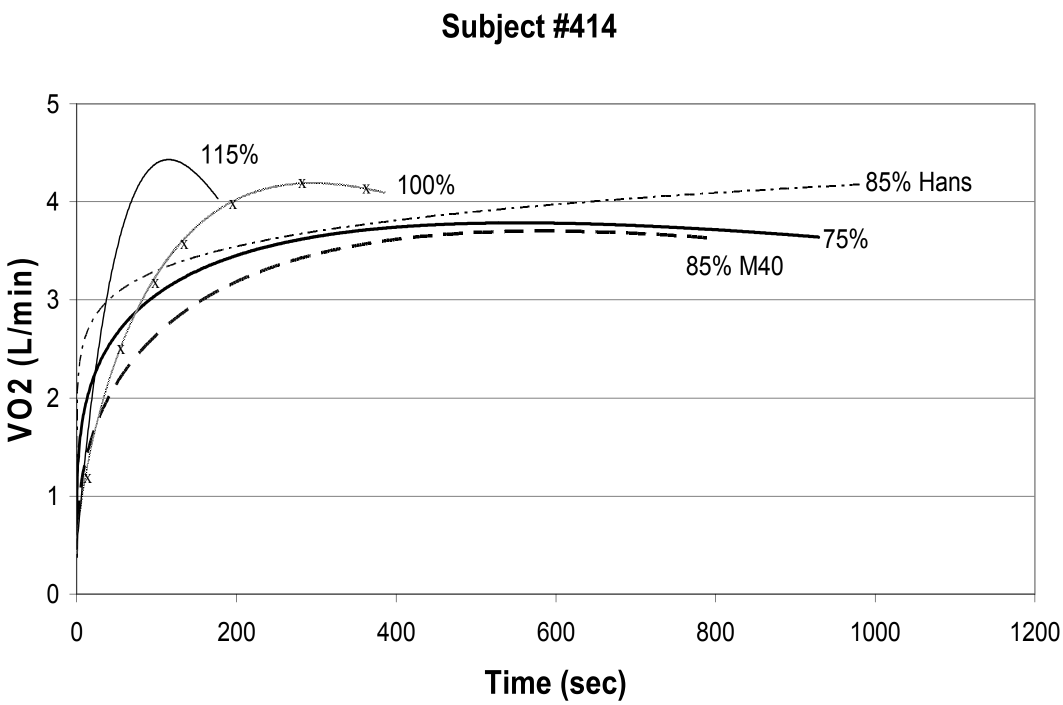


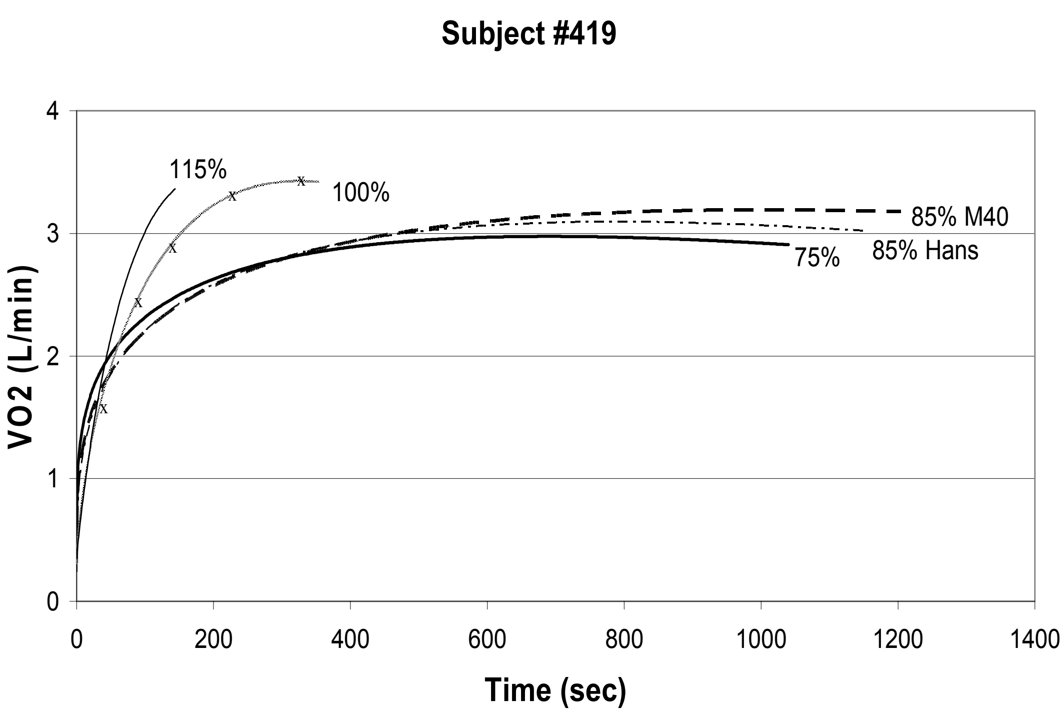
Subject #359



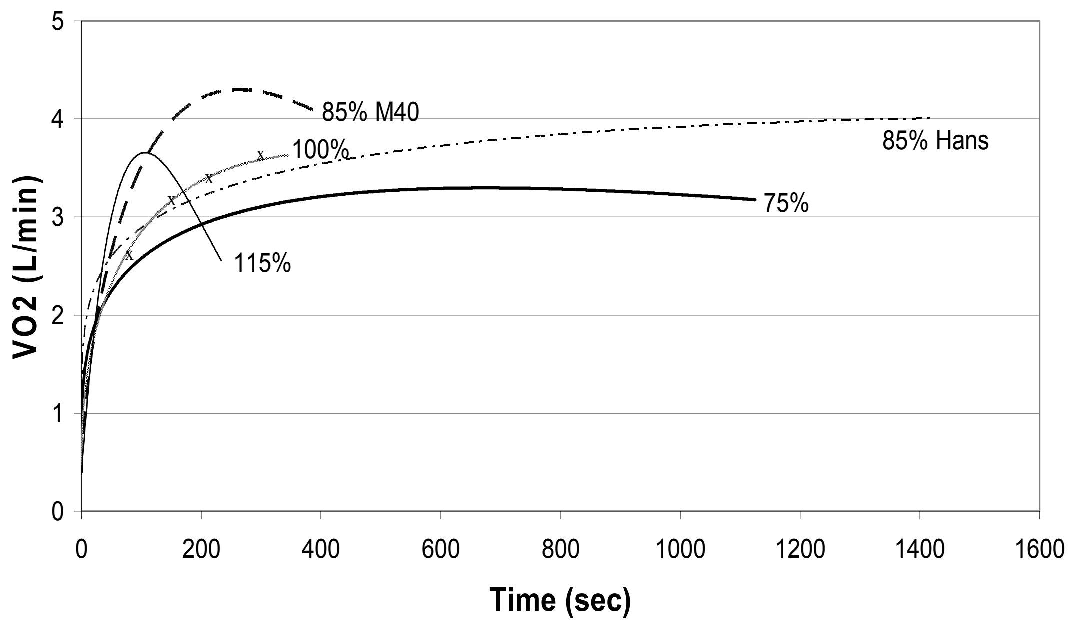

Subject #379
VO2 (L/min)
0
0.5
1
1.5
2
2.5
3
0
200
400
600
800
1000
1200
1400
1600
Time (sec)
100%
115%
85% Hans
75%
85% M40


Subject #401
VO2 (L/min)
0
0.5
1
1.5
2
2.5
3
0
500
1000
1500
2000
2500
3000
3500
Time (sec)
85% Hans
100%
85% M40
75%
115%

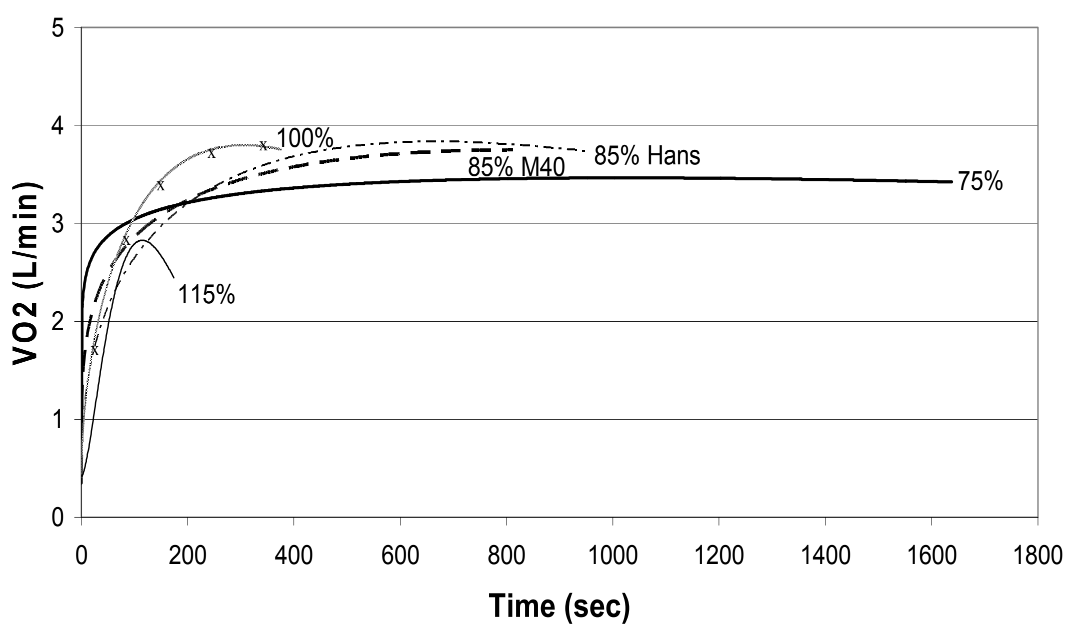

Subject #414
VO2 (L/min)
Time (sec)
115%
100%
85% Hans
75%
85% M40
0
1
2
3
4
5
0
200
400
600
800
1000
1200


Subject #419
VO2 (L/min)
Time (sec)
115%
100%
85% M40
75%
85% Hans
0
1
2
3
4
0
200
400
600
800
1000
1200
1400

Subject #420



Subject #422



B-5. Model Results - Reruns

** indicates rerun data set results

	001							
	C1	C2	C3	VO2	Se/Sy	R	C2/C3	
75%	0.2100	0.6453	0.0032	0.44	0.5506	0.8370	201.6563	
85%	0.0088	1.7022	0.0197	0.42	0.4406	0.9007	86.3185	
100%	0.0008	2.7500	0.0489	0.43	0.4941	0.8746	56.2372	
115%	0.0108	1.7400	0.0213	0.43	0.2841	0.9599	81.6901	
85% M40	0.0088	1.7022	0.0197	0.42	0.4406	0.9007	86.3185	
85% Hans	0.0620	0.8905	0.0028	0.47	0.5823	0.8141	318.0357	

	145							
	C1	C2	C3	VO2	Se/Sy	R	C2/C3	
75%	0.5375	0.4400	0.0013	0.48	0.7481	0.6650	338.4615	
85%	0.1285	0.8397	0.0039	0.52	0.4775	0.8804	215.3077	
100%	0.0046	1.9494	0.0219	0.37	0.5416	0.8435	89.0137	
115%	0.1477	1.0000	0.0125	0.50	0.4566	0.8922	80.0000	**
85% M40	0.1285	0.8397	0.0039	0.52	0.4775	0.8804	215.3077	
85% Hans	0.2933	0.5490	0.0015	0.45	0.8548	0.5215	366.0000	

	358							
	C1	C2	C3	VO2	Se/Sy	R	C2/C3	
75%	0.3996	0.2000	0.0004	0.21	0.9223	0.3896	500.0000	
85%	0.3600	0.2185	0.0002	0.24	0.8397	0.5460	1092.5000	**
100%	0.0634	0.8200	0.0059	0.35	0.6403	0.7705	138.9831	
115%	0.5596	0.2882	0.0002	0.33	0.6456	0.7696	1441.0000	**
85% M40	0.3600	0.2185	0.0002	0.24	0.8397	0.5460	1092.5000	**
85% Hans	0.6513	0.1477	0.0002	0.14	0.8773	0.4835	738.5	

	359						
	C1	C2	C3	VO2	Se/Sy	R	C2/C3
75%	0.1630	0.4400	0.0006	0.60	0.8030	0.5985	733.3333
85%	0.0164	0.9871	0.0030	0.38	0.6337	0.7760	329.0333
100%	n/a	n/a	n/a	n/a	n/a	n/a	
115%	0.2937	0.7273	0.0057	0.38	0.4432	0.9014	127.5965
85% M40	0.0164	0.9871	0.0030	0.38	0.6337	0.7760	329.0333
85% Hans	0.2320	0.5890	0.0011	0.16	0.5288	0.8506	535.4545

	379							
	C1	C2	C3	VO2	Se/Sy	R	C2/C3	
75%	0.6301	0.1800	0.0003	0.40	0.9808	0.2054	600.0000	**
85%	0.0952	0.6000	0.0020	0.30	0.8204	0.6305	300.0000	**
100%	0.2700	0.5867	0.0053	0.23	0.7707	0.6541	110.6981	
115%	0.1150	0.8100	0.0090	0.20	0.6999	0.7304	90.0000	**
85% M40	0.0952	0.6000	0.0020	0.30	0.8204	0.6305	300.0000	**
85% Hans	0.0437	0.8000	0.0027	0.31	0.7709	0.6410	296.2963	

	401							
	C1	C2	C3	VO2	Se/Sy	R	C2/C3	
75%	0.6171	0.2009	0.0007	0.15	0.8983	0.4442	287.0000	
85%	0.4573	0.2460	0.0004	0.24	0.8260	0.5656	615.0000	
100%	0.2632	0.4500	0.0040	0.33	0.7064	0.7136	112.5000	**
115%	0.0336	1.3000	0.0235	0.11	0.4049	0.9181	55.3191	
85% M40	0.4573	0.2460	0.0004	0.24	0.8260	0.5656	615.0000	
85% Hans	0.8805	0.1492	0.0001	0.26	0.9172	0.4003	1492.0000	

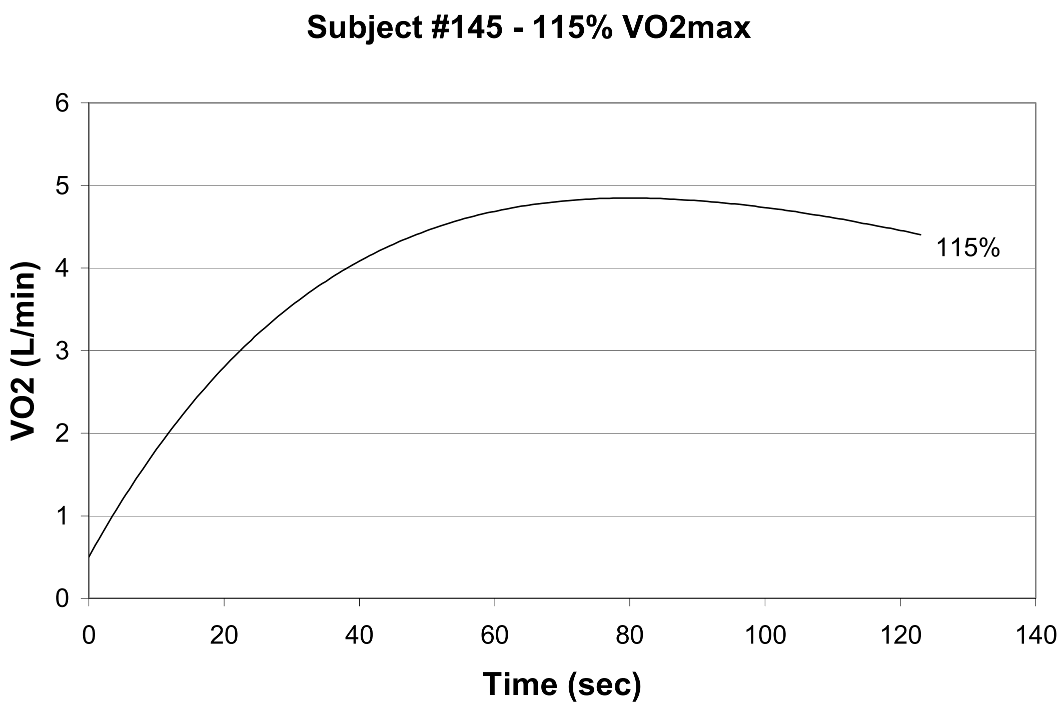
	414							
	C1	C2	C3	VO2	Se/Sy	R	C2/C3	
75%	1.0652	0.2100	0.0003	0.41	0.7782	0.6303	700.0000	**
85%	0.3720	0.4084	0.0007	0.37	0.7099	0.7060	583.4286	
100%	0.1555	0.6800	0.0023	0.42	0.5655	0.8267	295.6522	
115%	0.0967	0.9914	0.0086	0.46	0.3533	0.9369	115.2791	
85% M40	0.3720	0.4084	0.0007	0.37	0.7099	0.7060	583.4286	
85% Hans	1.6770	0.1197	0.00001	0.39	0.8254	0.5667	1970.0000	

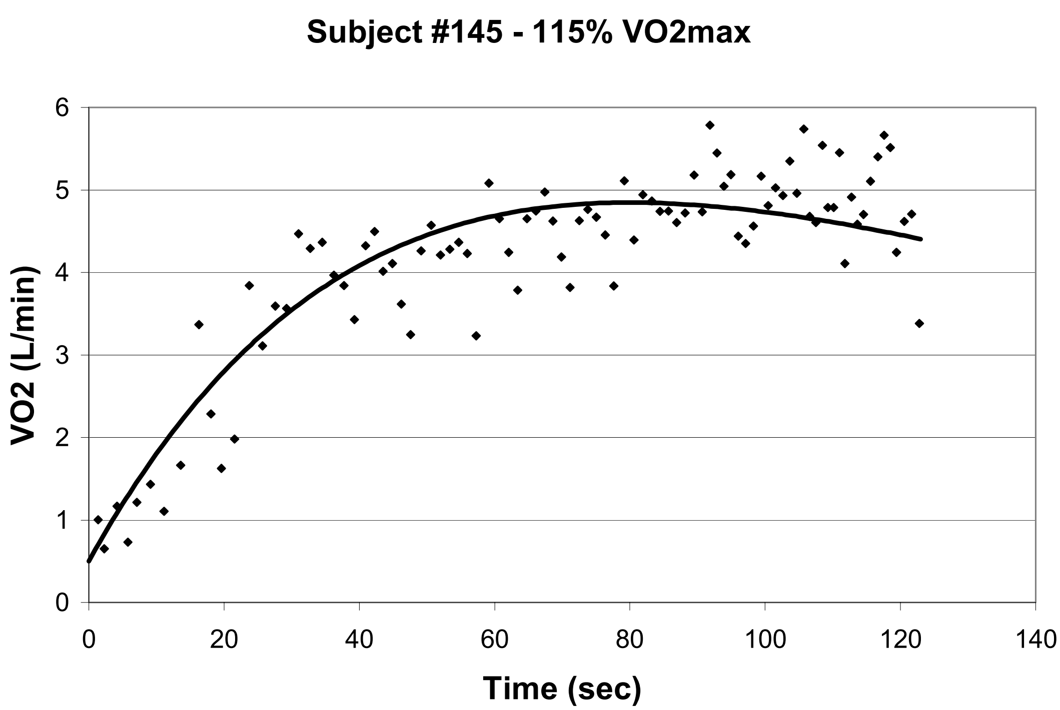
	419						
	C1	C2	C3	VO2	Se/Sy	R	C2/C3
75%	0.5561	0.2761	0.0004	0.41	0.7883	0.6171	690.2500
85%	0.5497	0.3150	0.0007	0.40	0.9018	0.4369	450.0000 **
100%	0.1391	0.6500	0.0020	0.31	0.4576	0.8904	325.0000
115%	0.0688	0.8937	0.0046	0.35	0.4200	0.9096	194.2826
85% M40	0.5497	0.3150	0.0007	0.40	0.9018	0.4369	450.0000 **
85% Hans	0.4796	0.3147	0.00040	0.24	0.7326	0.6817	786.7500

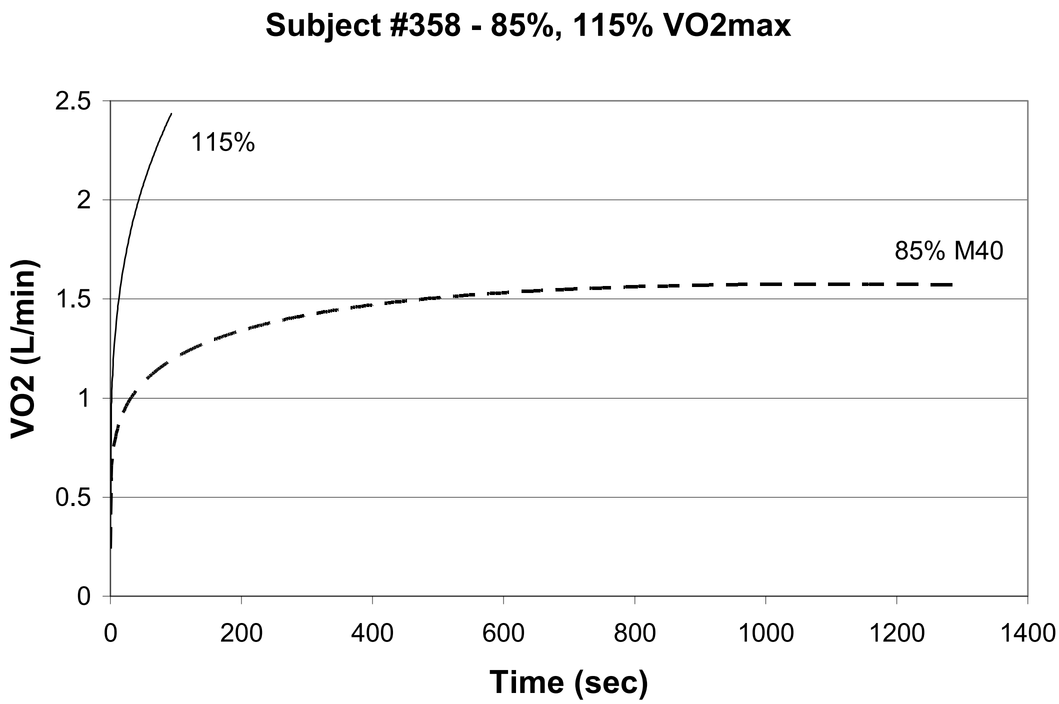
	420						
	C1	C2	C3	VO2	Se/Sy	R	C2/C3
75%	0.6539	0.2699	0.0004	0.40	0.8106	0.5875	674.7500
85%	0.1915	0.6575	0.0025	0.43	0.7020	0.7167	263.0000
100%	0.1718	0.7000	0.0040	0.42	0.7524	0.6655	175.0000 **
115%	0.0840	1.0000	0.0094	0.37	0.5161	0.8584	106.3830
85% M40	0.1915	0.6575	0.0025	0.43	0.7020	0.7167	263.0000
85% Hans	1.0486	0.1899	0.0001	0.40	0.7329	0.6820	1899.0000

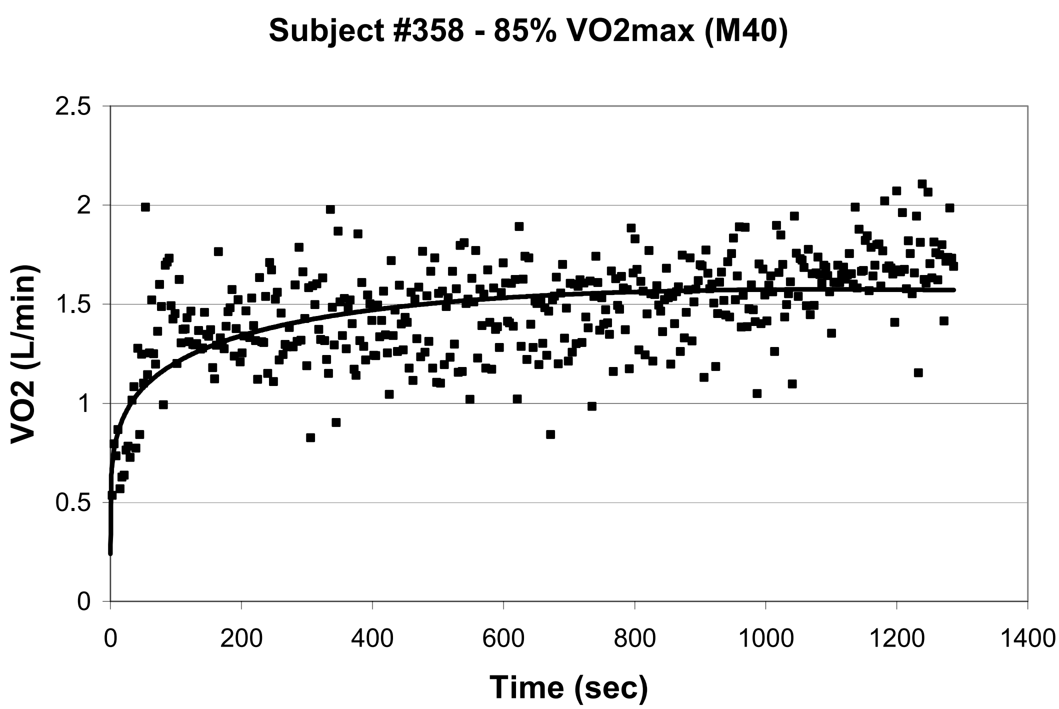
	422						
	C1	C2	C3	VO2	Se/Sy	R	C2/C3
75%	1.7918	0.0925	0.0001	0.35	0.9865	0.1727	925.0000
85%	0.4047	0.4000	0.0008	0.41	0.6943	0.7209	500.0000 **
100%	0.2523	0.5500	0.0018	0.41	0.4485	0.8948	305.5556
115%	0.0039	1.7177	0.0150	0.42	0.4176	0.9106	114.5133
85% M40	0.4047	0.4000	0.0008	0.41	0.6943	0.7209	500.0000 **
85% Hans	0.3836	0.4000	0.0006	0.37	0.6209	0.7846	666.6667

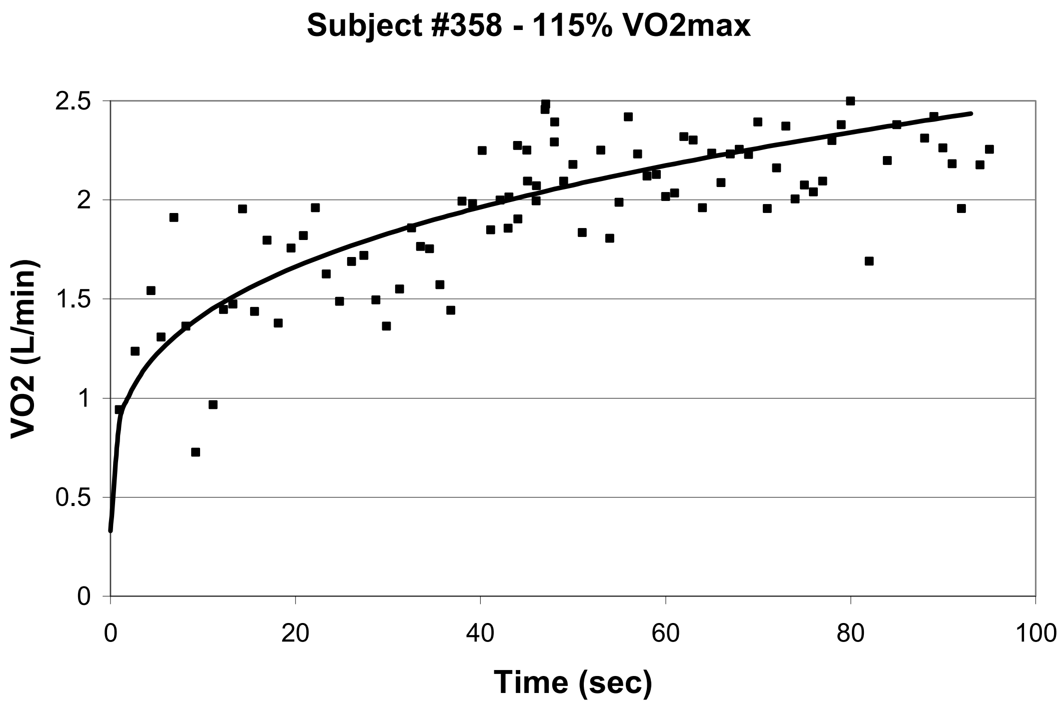
B-6. Model Result Graphs - Reruns



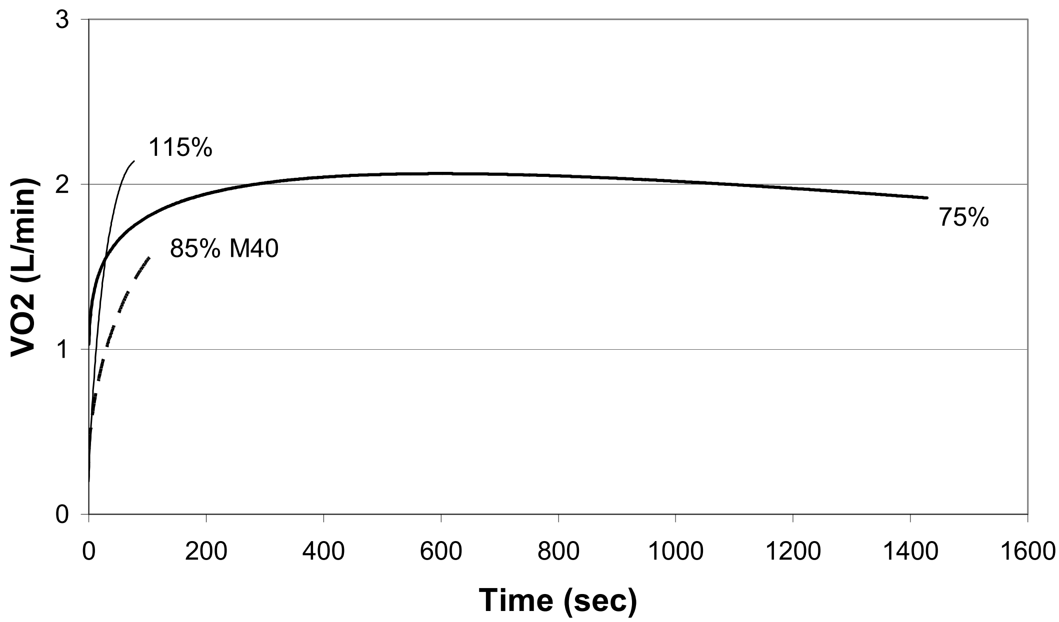



Subject #358 - 85%, 115% VO2max
115%
85% M40
VO2 (L/min)
Time (sec)
0
0.5
1
1.5
2
2.5
0
200
400
600
800
1000
1200
1400

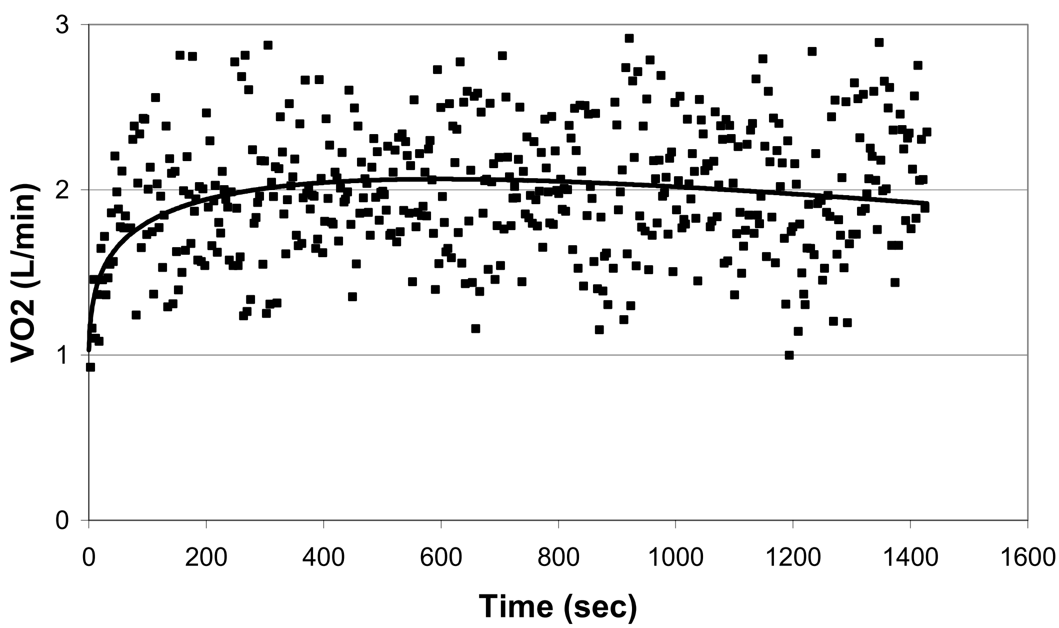

Subject #358 - 85% VO2max (M40)
VO2 (L/min)
Time (sec)
0
0.5
1
1.5
2
2.5
0
200
400
600
800
1000
1200
1400

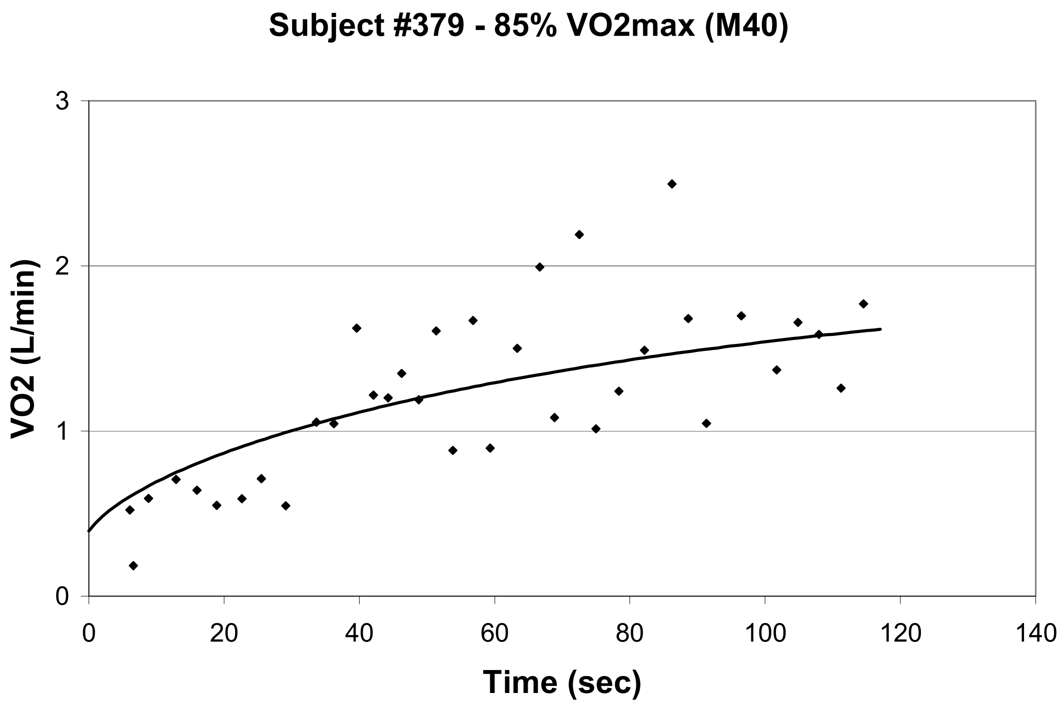

Subject #358 - 115% VO2max
2.5
2
1.5
1
0.5
0
VO2 (L/min)
0
20
40
60
80
100
Time (sec)

Subject #379 - 75%, 85%, 115% VO2max

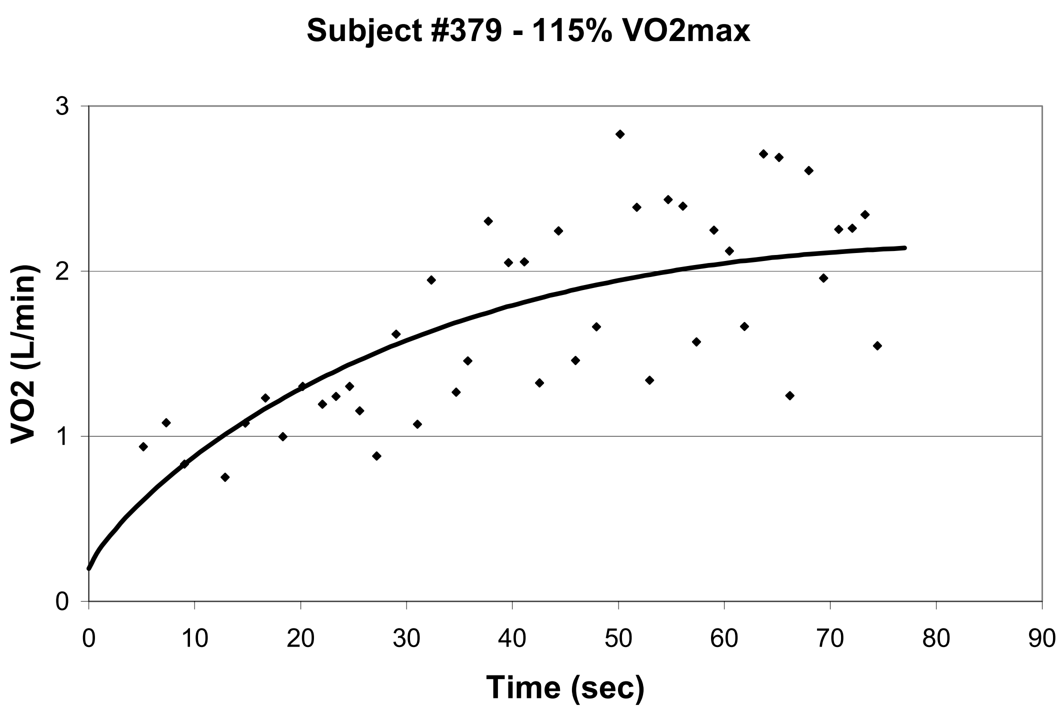


Subject #379 - 75% VO2max

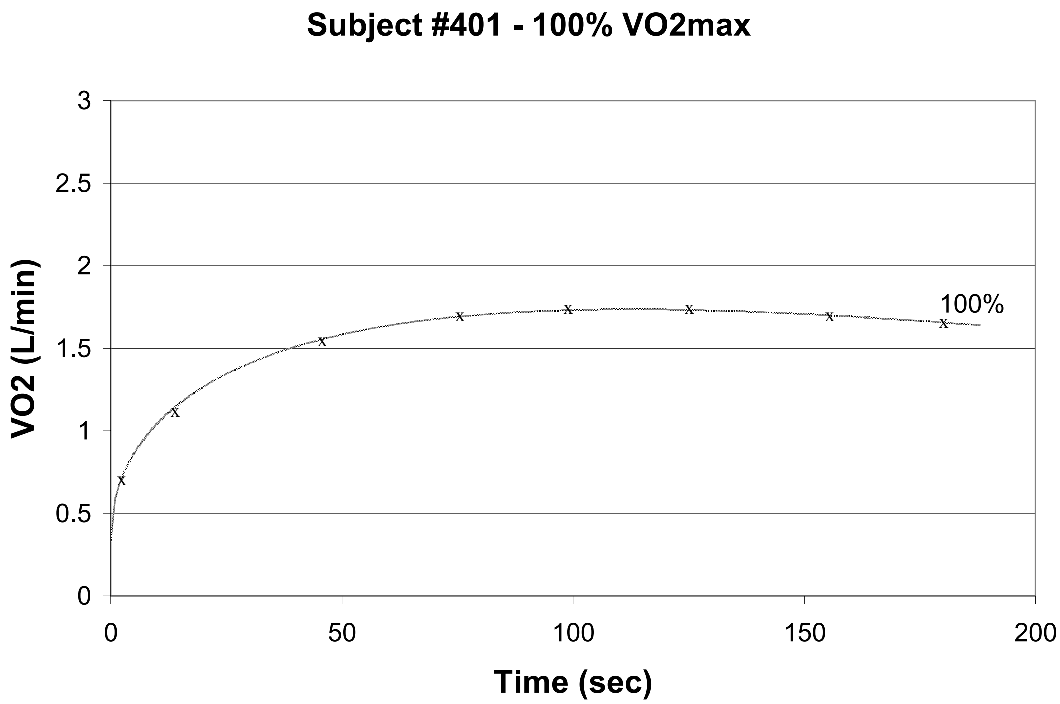




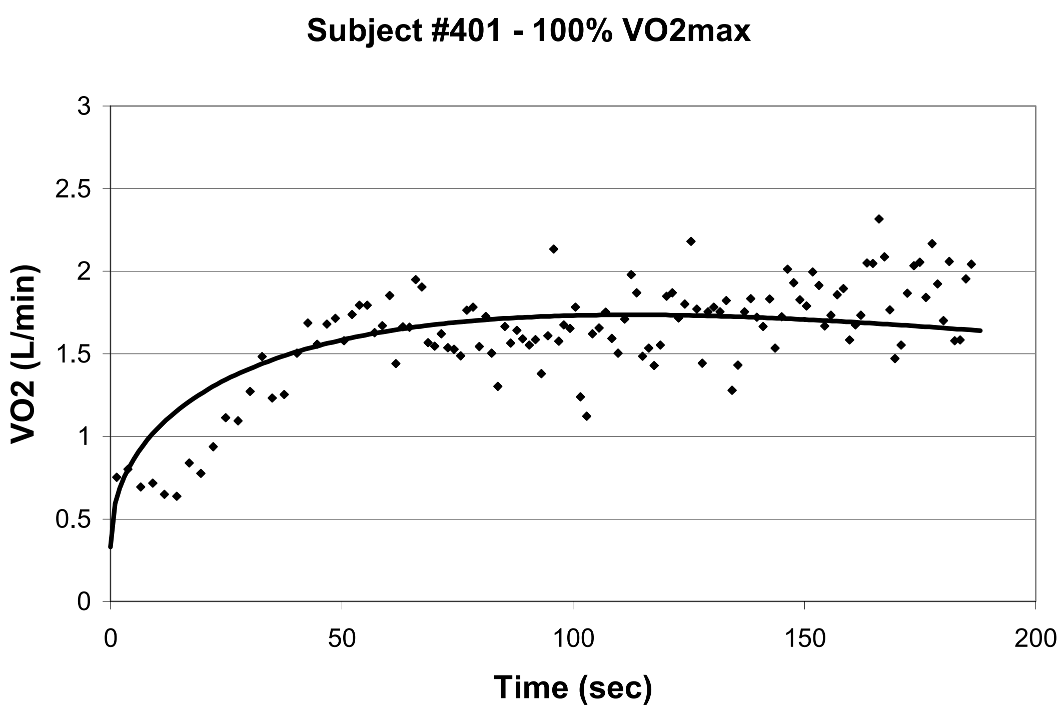
Subject #379 - 85% VO2max (M40)
VO2 (L/min)
0
1
2
3
0
20
40
60
80
100
120
140
Time (sec)



Subject #379 - 115% VO2max
VO2 (L/min)
0
1
2
3
0
10
20
30
40
50
60
70
80
90
Time (sec)

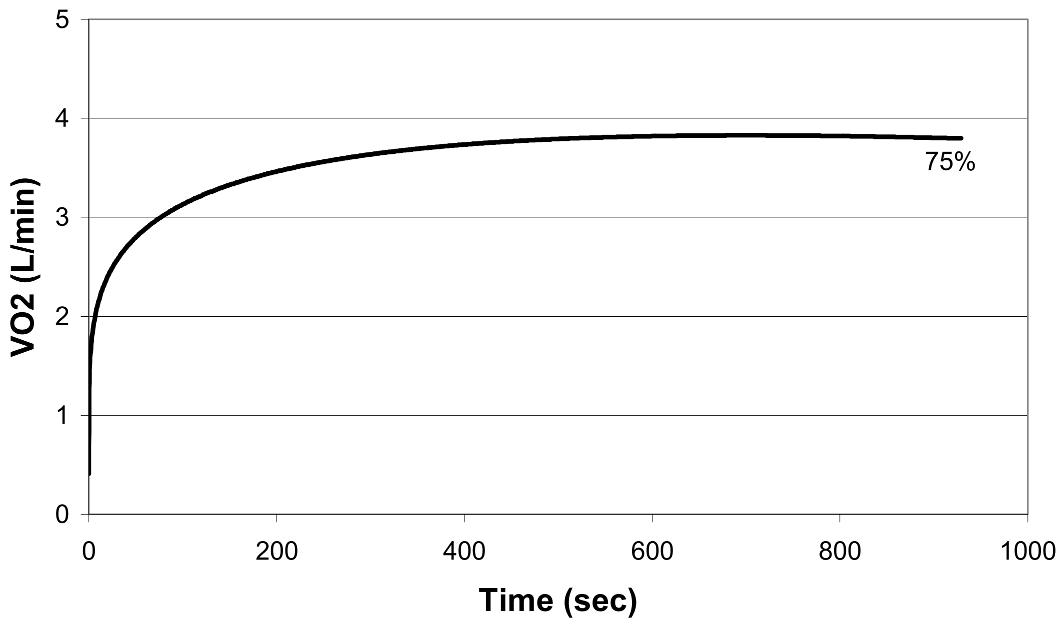


Subject #401 - 100% VO2max
3
2.5
2
1.5
1
0.5
0
0
50
100
150
200
VO2 (L/min)
Time (sec)
100%

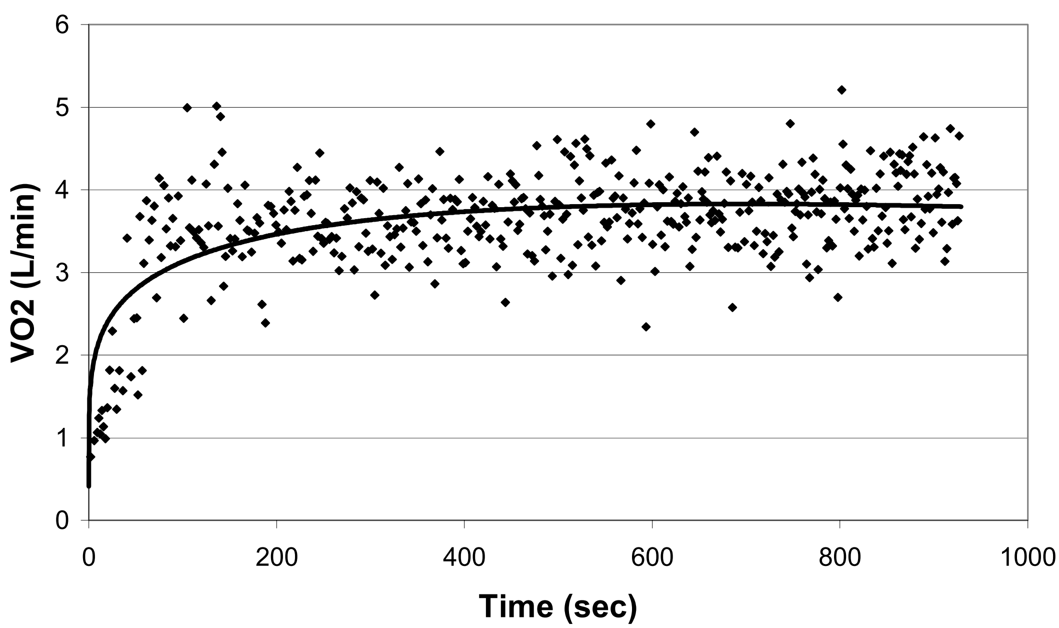


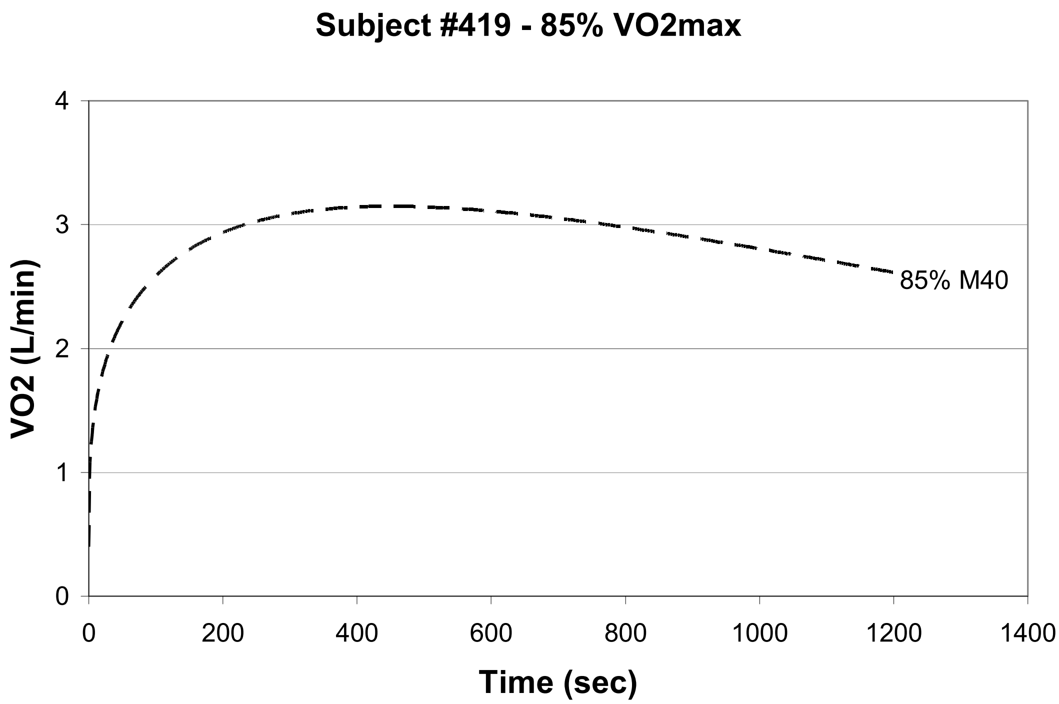
Subject #401 - 100% VO2max
3
2.5
2
1.5
1
0.5
0
0
50
100
150
200
VO2 (L/min)
Time (sec)

Subject #414 - 75% VO2max

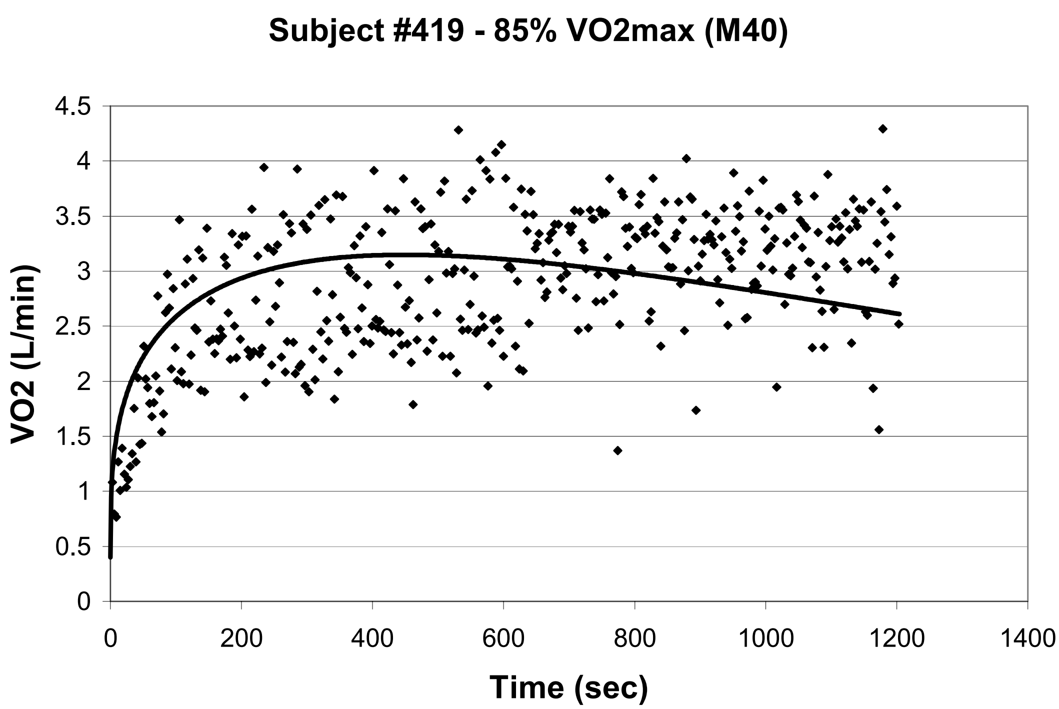


Subject #414 - 75% VO2max

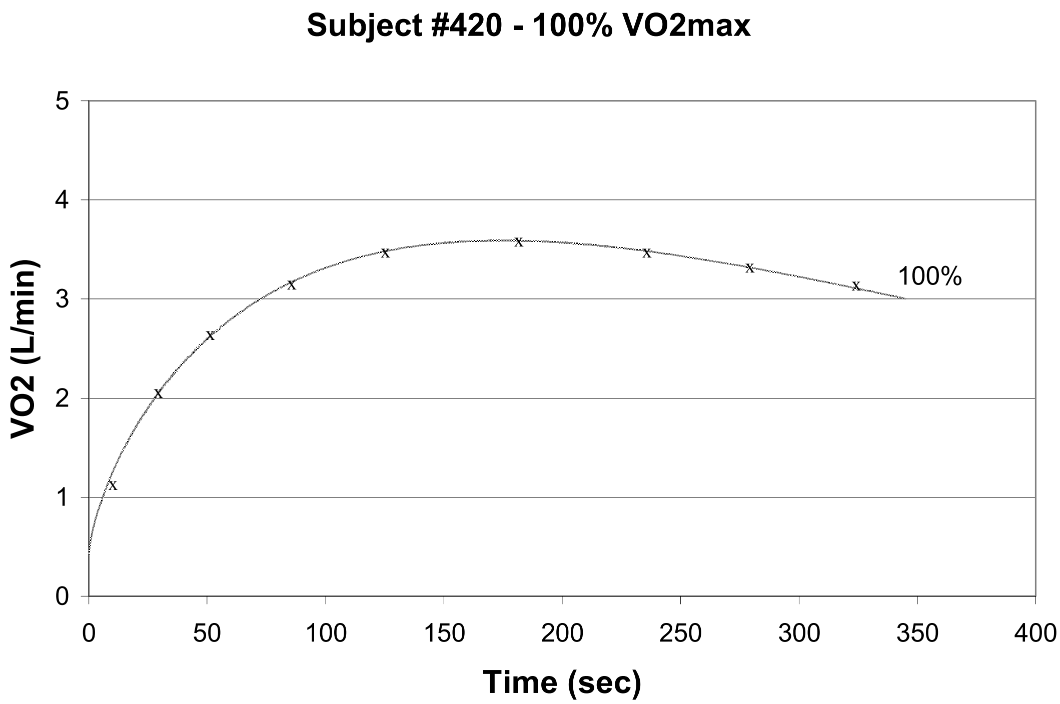


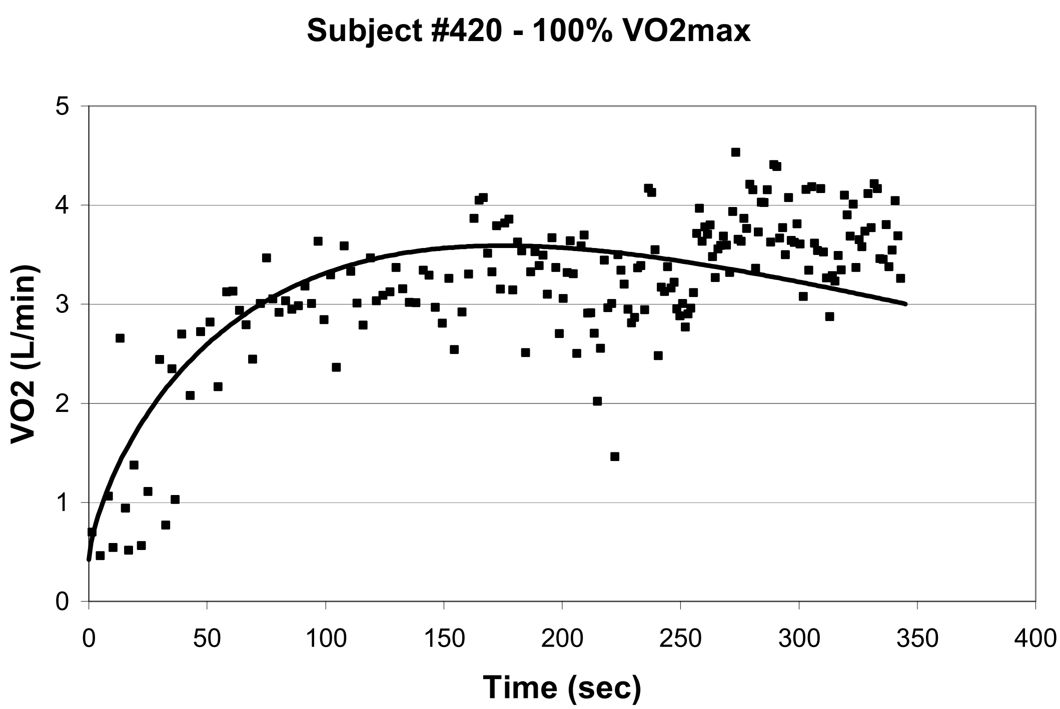


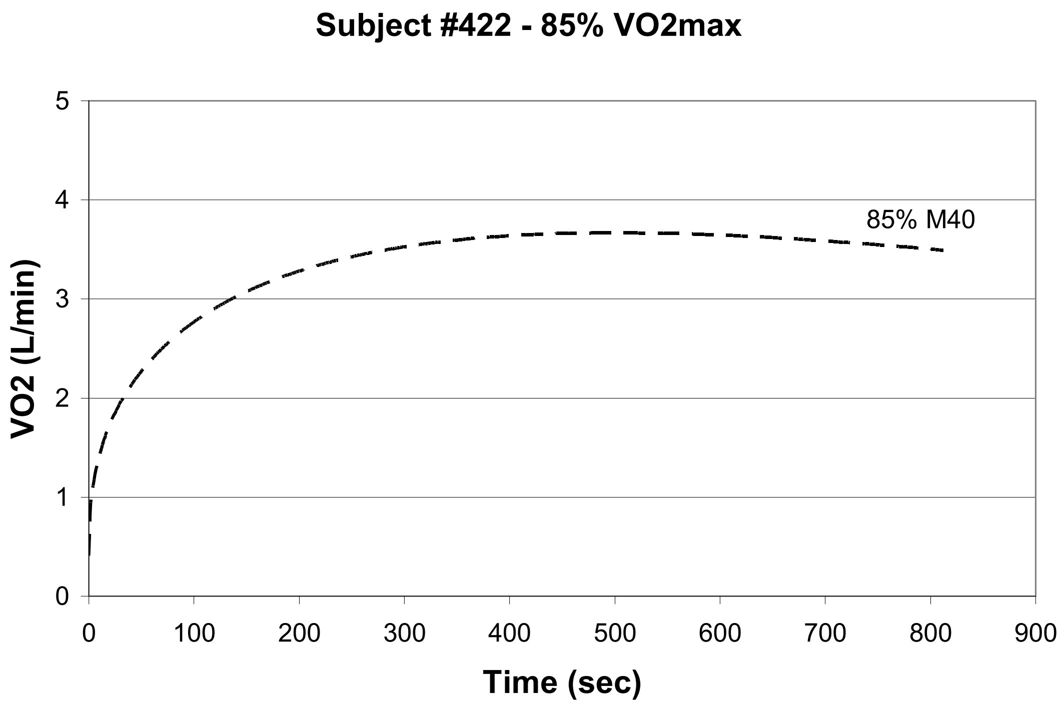
Subject #419 - 85% VO2max
VO2 (L/min)
Time (sec)
85% M40
0
1
2
3
4
0
200
400
600
800
1000
1200
1400

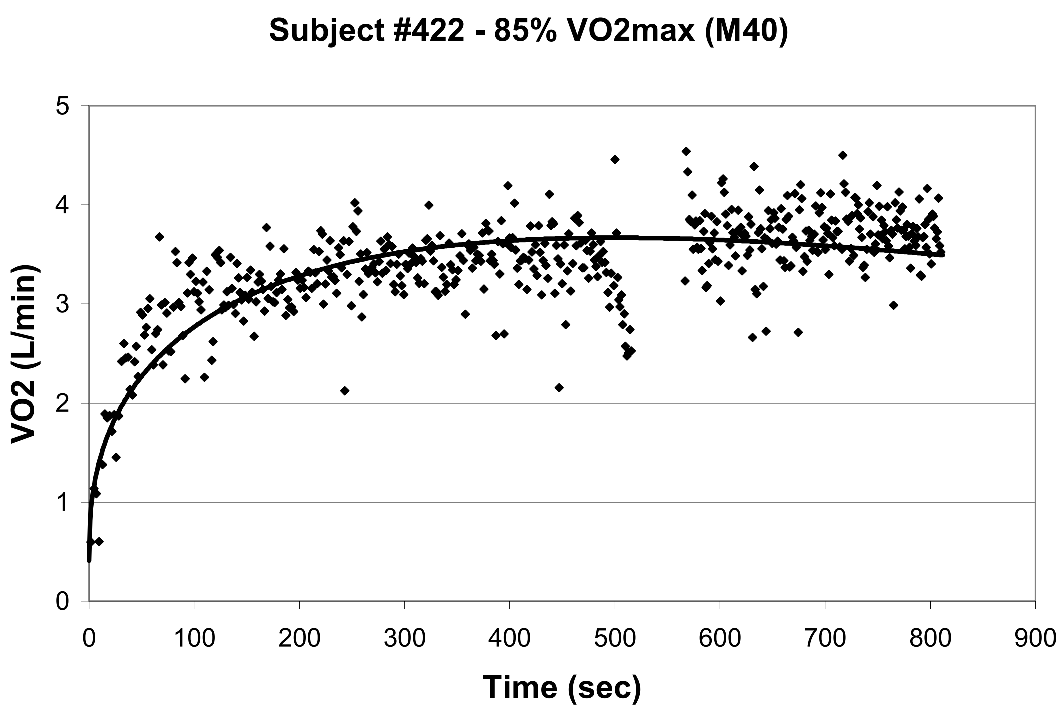


Subject #419 - 85% VO2max (M40)
VO2 (L/min)
Time (sec)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
200
400
600
800
1000
1200
1400


Subject #420 - 100% VO2max
VO2 (L/min)
Time (sec)
100%
0
1
2
3
4
5
0
50
100
150
200
250
300
350
400


Subject #420 - 100% VO2max
VO2 (L/min)
Time (sec)
0
1
2
3
4
5
0
50
100
150
200
250
300
350
400


Subject #422 - 85% VO2max
5
4
3
2
1
0
VO2 (L/min)
85% M40
0
100
200
300
400
500
600
700
800
900
Time (sec)


Subject #422 - 85% VO2max (M40)
5
4
3
2
1
0
VO2 (L/min)
0
100
200
300
400
500
600
700
800
900
Time (sec)

B-7. Oxygen Deficit Values – Beginning to Steady-State Only

	M40			
	75%	**85%**	**100%**	**115%**
001	33	34	36	43
145	40	52	44	46
358	9	12	23	24
359	19	22	N/A	49
379	13	19	34	29
401	17	22	23	30
414	21	28	37	41
419	25	28	42	42
420	26	48	39	43
422	14	34	40	32

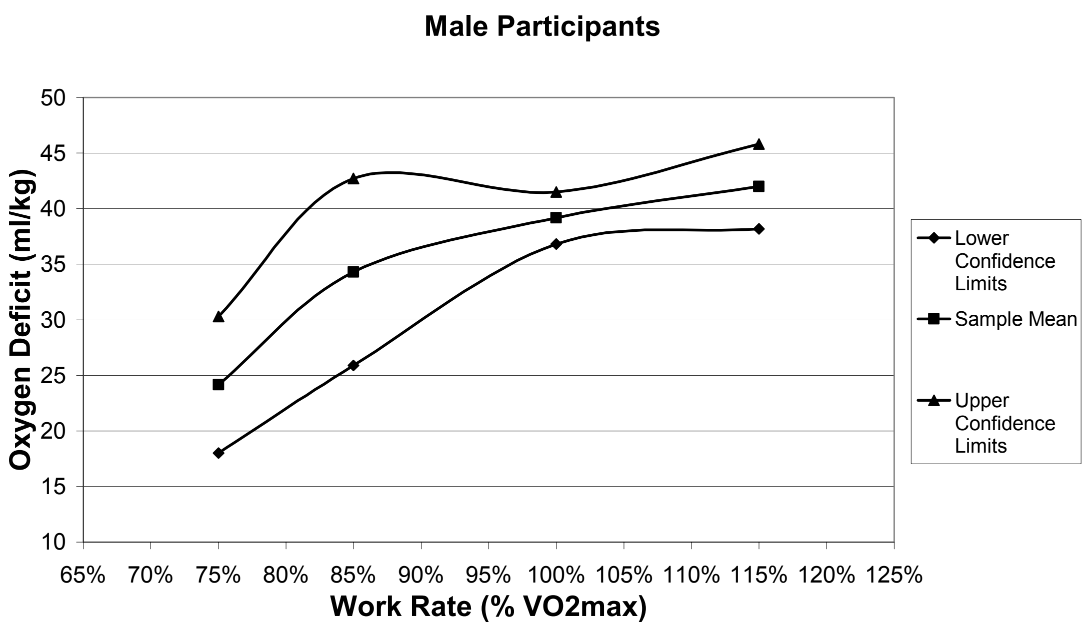
85%	
M40	**Hans**
34	45
52	41
12	10
22	53
19	28
22	20
28	18
28	30
48	27
34	37

B-8. Initial RPE Values Identified

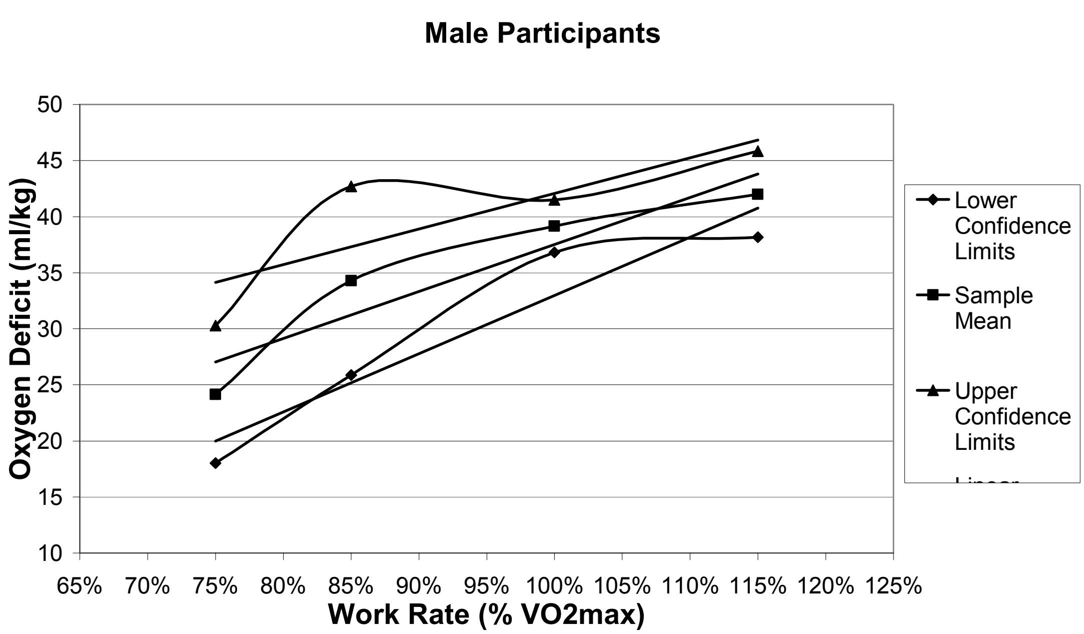
	M40					85%	
	75%	85%	100%	115%		M40	Hans
001	13	12	6	13		12	13
145	11	12	13	15		12	11
358	9	11	14	20		11	7
359	10	12	N/A	6		12	12
379	9	11	15	16		11	13
401	13	15	19	20		15	13
414	12	12	12	15		12	11
419	9	8	11	16		8	7
420	9	11	12	14		11	9
422	9	12	12	15		12	9

B-9. Male and Female Transfer Functions

Work Rate vs. OD – male participants:



Work Rate vs. OD – male participants; trendlines added:



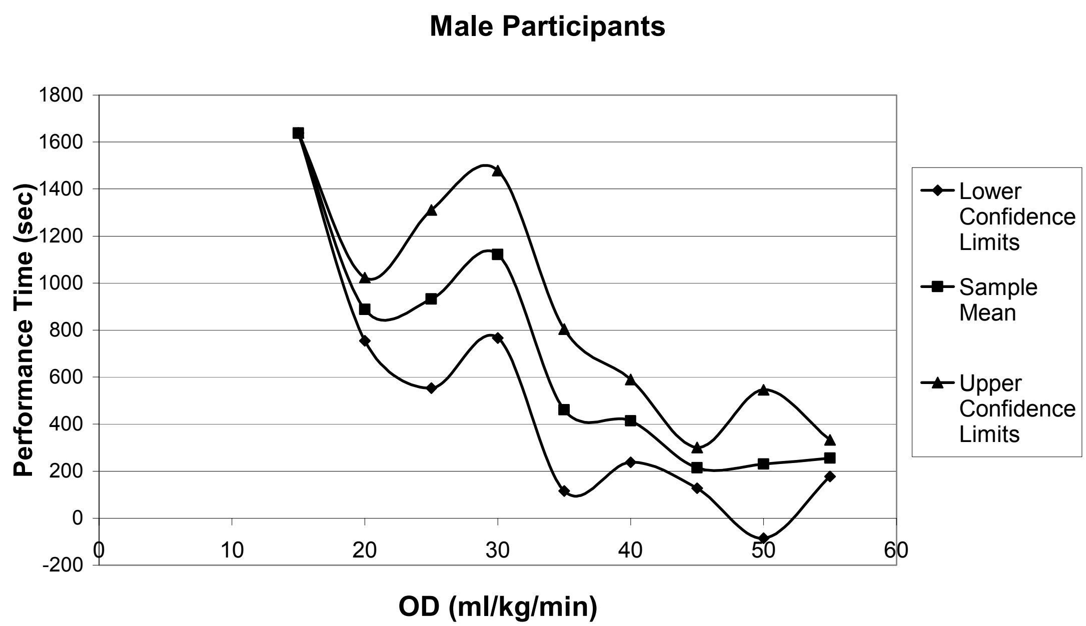
The linear functions defining the male oxygen deficit response for exercise completed across multiple intensities while wearing an M40 respirator mask were as follows:

a) Upper confidence limit: OD = 31.753($\dot{V}O_2/\dot{V}O_{2\,\max}$) + 10.312 ($R^2$ = 0.6723);

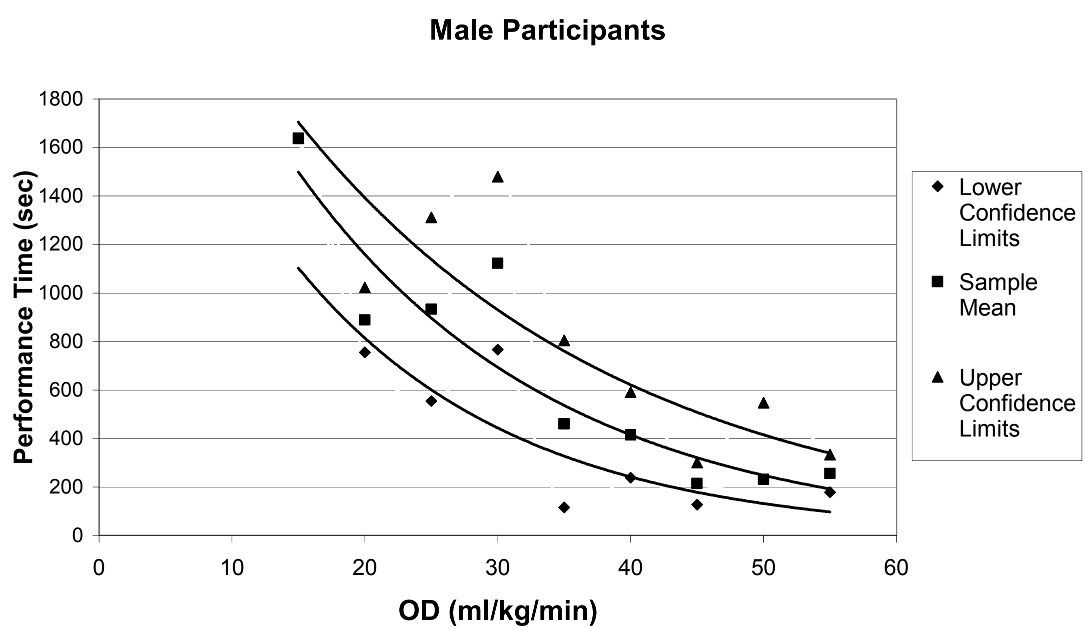
b) Sample mean: OD = 41.863($\dot{V}O_2/\dot{V}O_{2\,\max}$) – 4.3474 ($R^2$ = 0.8717); and

c) Lower confidence limit: OD = 51.973($\dot{V}O_2/\dot{V}O_{2\,\max}$) – 19.007 ($R^2$ = 0.9052).

OD vs. Performance Time – male participants:



OD vs. Performance Time – male participants; trendlines added:



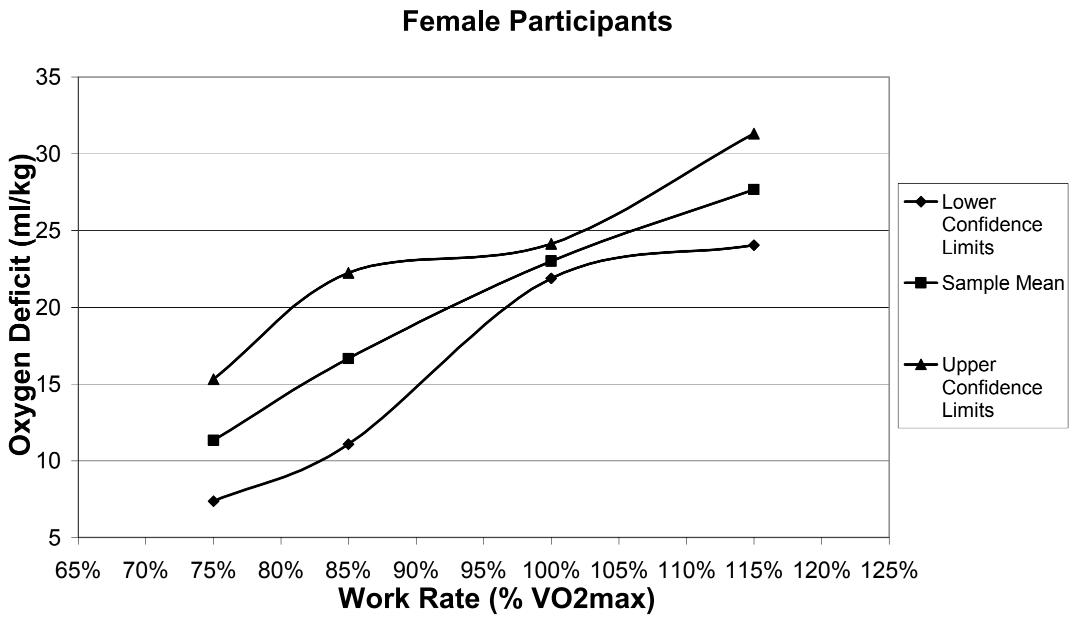
The exponential functions defining the expected performance time for males based on the oxygen deficit developed during exercise while wearing an M40 respirator mask were identified as follows:

a) Upper confidence limit: Perf. Time = $3121.9e^{-0.0404*OD}$ ($R^2 = 0.7807$);

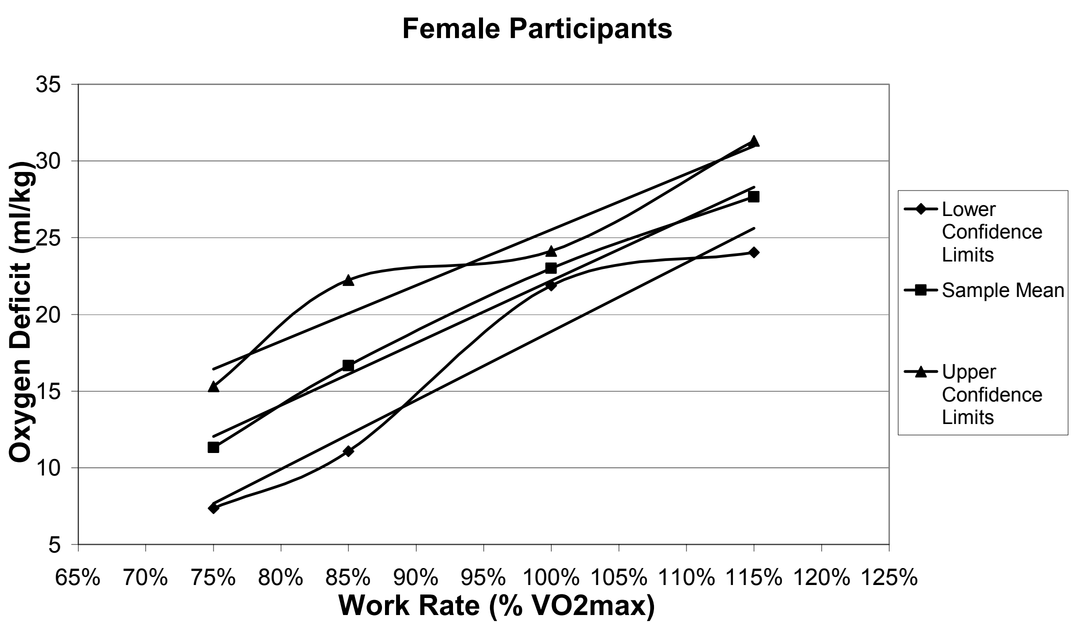
b) Sample mean: Perf. Time = $3240.4e^{-0.0514*OD}$ ($R^2 = 0.8712$); and

c) Lower confidence limit: Perf. Time = $2744.5e^{-0.0608*OD}$ ($R^2 = 0.6940$).

Work Rate vs. OD – female participants:



Work Rate vs. OD – female participants; trendlines added:



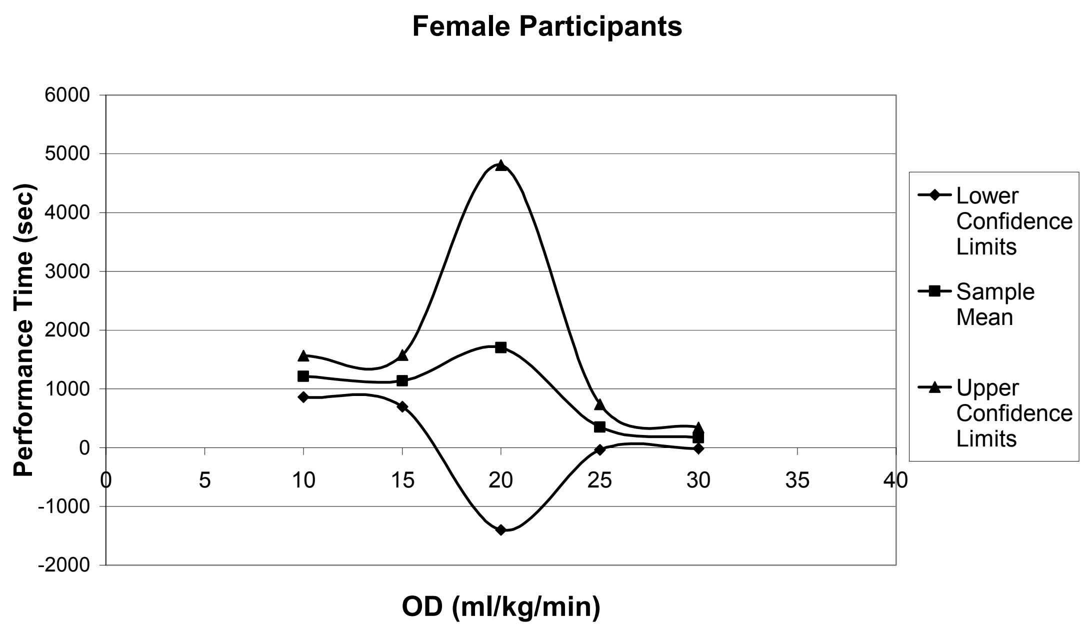
The linear functions defining the female oxygen deficit response for exercise completed across multiple intensities while wearing an M40 respirator mask were as follows:

a) Upper confidence limit: OD = 36.392($\dot{V}O_2/\dot{V}O_{2\,\max}$) – 10.869 ($R^2$ = 0.9379);

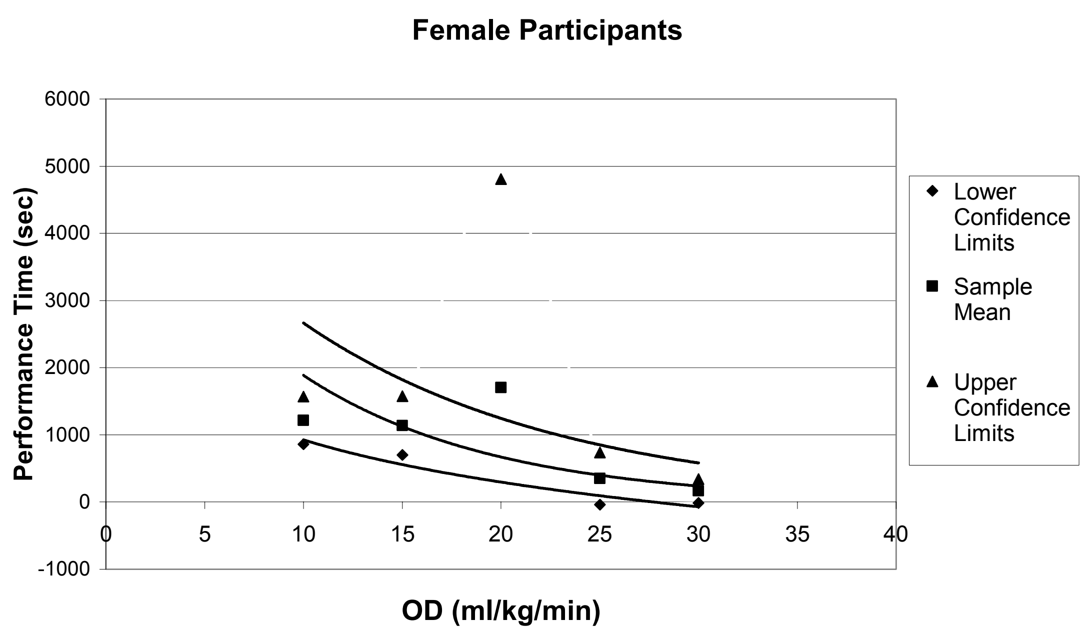
b) Sample mean: OD = 40.635($\dot{V}O_2/\dot{V}O_{2\,\max}$) – 18.429 ($R^2$ = 0.9879); and

c) Lower confidence limit: OD = 44.878($\dot{V}O_2/\dot{V}O_{2\,\max}$) – 25.988 ($R^2$ = 0.936).

OD vs. Performance Time – female participants:



OD vs. Performance Time – female participants; trendlines added:



The defining the expected performance time for females based on the oxygen deficit developed during exercise while wearing an M40 respirator mask were identified as follows:

a) Upper confidence limit: Perf. Time = $5704.4e^{-0.0761*OD}$ ($R^2 = 0.3735$);

b) Sample mean: Perf. Time = $5305.6e^{-0.1034*OD}$ ($R^2 = 0.6877$); and

c) Lower confidence limit: Perf. Time = $-907.55\ln(OD) + 3015.8$ ($R^2 = 0.9315$).

Bibliography

Aoyagi, Y., McLellan, T.M., and Shephard, R.J. 1995. Determination of body heat storage in clothing: calorimetry versus thermometry. *European Journal of Applied Physiology* 71: 197-206.

Bangsbo, J., Gollnick, P.D., Graham, T.E., Juel, C., Kiens, B., Mizuno, M., and Saltin, B. 1990. Anaerobic energy production and O_2 deficit-debt relationship during exhaustive exercise in humans. *Journal of Physiology* 422: 539-559.

Bangsbo, J., Peterson, A., and Michalsik, L. 1993. Accumulated O_2 deficit during intense exercise and muscle characteristics of elite athletes. *International Journal of Sports Medicine* 14: 207-213.

Bangsbo, J. 1996. Oxygen deficit: A measure of the anaerobic energy production during intense exercise? *Canadian Journal of Applied Physiology* 21(5): 350-363.

Bangsbo, J. 1998. Quantification of anaerobic energy production during intense exercise. *Medicine and Science in Sports and Exercise* 30: 47-52.

Barstow, T.J. 1994. Characterization of VO_2 kinetics during heavy exercise. *Medicine and Science in Sports and Exercise* 26(11): 1327-1334.

Bearden, S.E., and Moffatt, R.J. 2000. VO_2 kinetics and the O_2 deficit in heavy exercise. *Journal of Applied Physiology* 88: 1407-1412.

Benchetrit, G. 2000. Breathing pattern in humans: diversity and individuality. *Respiration Physiology* 122: 123-129.

Carter, H., Jones, A.M., Barstow, T.J., Burnley, M., Williams, C.A., and Doust, J.H. 2000. Oxygen uptake kinetics in treadmill running and cycle ergometry: a comparison. *Journal of Applied Physiology* 89: 899-907.

Chiou, Y. 2004. Model of exercise performance while wearing a respiratory protective mask. M.S. thesis. University of Maryland, College Park.

Convertino, V.A., Goldwater, D.J., and Sandler, H. 1984. Oxygen uptake kinetics of constant-load work: upright vs. supine exercise. *Aviation, Space, and Environmental Medicine* 55(6): 501-506.

Coyne, M. K. 2001. Modeling the pulmonary effects of respiratory protective masks during physical activity. Ph.D. diss. Univ. of Maryland, College Park.

Demarle, A.P., Slawinski, J.L., Laffite, L.P., Bocquet, V.G., Koralszstein, J.P., and Billat, V.L. 2001. Decrease of O_2 deficit is a potential factor in increased time to exhaustion after specific endurance training. *Journal of Applied Physiology* 90: 947-953.

Doherty, M., Smith, P.M., and Schroder, K. 2000. Reproducibility of the maximum accumulated oxygen deficit and run time to exhaustion during short-distance running. *Journal of Sports Sciences* 18: 331-338.

Ellis, R. and Gulick, D. 1994. *Calculus with Analytic Geometry*. Fort Worth: Harcourt Brace and Company.

Ericksson, B.O., Gollnick, P.D., and Saltin, B. 1973. Muscle metabolism and enzyme activities after training in boys 11-13 years old. *Acta Physiologica Scandinavica*. 87: 485-497.

Gagge, A.P., and Nishi, Y. 1983. Heat exchange between human skin surface and thermal environment. In: Lee, D.H.K. (Ed)., *Handbook of Physiology: Reactions to Environmental Agents.* American Physiological Society, Bethesda, MD. pp. 69-92.

Gardner, A., Osborne, M., D'Auria, S., and Jenkins, D. 2003. A comparison of two methods for the calculation of accumulated oxygen deficit. *Journal of Sports Sciences* 21: 155-162.

Gastin, P.B., Costill, D.L., Lawson, D.L., Krzeminski, K., and McConell, G.K. 1995. Accumulated oxygen deficit during supramaximal all-out and constant intensity exercise. *Medicine and Science in Sports and Exercise* 27: 255-263.

Graham, T.E. 1996. Oxygen deficit: Introduction to the assumptions and the skepticism. *Canadian Journal of Applied Physiology* 21(5): 347-349.

Green, S. and Dawson, B. 1993. Measurement of anaerobic capacities in humans: Definitions, limitations, and unsolved problems. *Sports Medicine* 15(5): 312-327.

Hermansen, L. 1969. Anaerobic energy release. *Medicine and Science in Sports* 1:32-38.

Hill, D.W. 1996. Determination of accumulated O_2 deficit in exhaustive short-duration exercise. *Canadian Journal of Applied Physiology* 21(1): 63-74.

Hill, D.W., Davey, K.M., and Stevens, E.C. 2002. Maximal accumulated O_2 deficit in running and cycling. *Canadian Journal of Applied Physiology* 27(5): 463-478.

Hill, D.W., Halcomb, J.N., and Stevens, E.C. 2003. Oxygen uptake kinetics during severe intensity running and cycling. *European Journal of Applied Physiology* 89: 612-618.

Hoogeveen, A.R. and Keizer, H.A. 2003. The VO_2 overshoot at the onset of constant-load exercise in elite cyclists: an undescribed phenomenon. *Journal of Exercise Physiology Online* 6(4): 34-41.

Jacobsen, D.J., Coast, R., and Donnelly, J.E. 1998. The effect of exercise intensity on the slow component of VO_2 in persons of different fitness levels. *Journal of Sports Medicine and Physical Fitness* 38(2): 124-131.

Johnson, A.T. 1991. *Biomechanics and Exercise Physiology*. New York: John Wiley & Sons, Inc.

Johnson, A.T. 1999. *Biological Process Engineering: An Analogical Approach to Fluid Flow, Heat Transfer, and Mass Transfer Applied to Biological Systems*. New York: John Wiley & Sons, Inc.

Johnson, A.T., Benjamin, M.B., and Silverman, N. 2002. Oxygen consumption, heat production, and muscular efficiency during uphill and downhill walking. *Applied Ergonomics* 33: 485-491.

Johnson, AT., Scott, W.H., Phelps, S.J., Caretti, D.M., and Koh, F.C. 2005. How is respirator comfort affected by respiratory resistance? *Journal of the International Society for Respiratory Protection*. 22: 38: 38-46.

Jurkowski, J.E.H., Jones, N.L., Toews, C.J., and Sutton, J.R. 1981. Effects of menstrual cycle on blood lactate, O_2 delivery, and performance during exercise. *Journal of Applied Physiology* 51(6): 1493-1499.

Kamon, E., and Pandolf, K. 1972. Maximal aerobic power during laddermill climbing, uphill running and cycling. *Journal of Applied Physiology* 32: 467-73.

Karlsson, J. and Saltin, B. 1970. Lactate, ATP and CP in working muscles during exhausting exercise in man. *Journal of Applied Physiology* 29: 598-602.

Koh, F.C. 2005. *Instantaneous Oxygen Uptake Program*. University of Maryland, College Park. LabView Student Edition. Austin: National Instruments Corporation.

Krogh A. and Lindhard, J. 1920. The changes in respiration at the transition from work to rest. *Journal of Physiology (London)* 53: 431-437.

Lebrun, C.M. 1993. Effect of the different phases of the menstrual cycle and oral contraceptives on athletic performance. *Sports Medicine* 16(6): 400-430.

McArdle, W.D., Katch, F.I., and Katch, V.L. 2000. *Essentials of Exercise Physiology*. Baltimore: Lippincott Williams and Wilkins.

McCuen, R.H. 1985. *Statistical Methods for Engineers*. Upper Saddle River: Prentice-Hall Inc.

McCuen, R.H. 1993. *Microcomputer Applications in Statistical Hydrology.* Upper Saddle River: Prentice-Hall Inc.

McCuen, R.H. 2003. *Modeling Hydrologic Change: Statistical Methods.* Boca Raton: Lewis Publishers, CRC Press.

McCuen, R.H. 2006. *Breath-by-Breath Optimization Model Program*. University of Maryland, College Park. FORTRAN.

Medbo, J.I., Mohn, A.C., Tabata, I., Bahr, R., Vaage, O., and Sejersted, O.M. 1988. Anaerobic capacity determined by maximal accumulated O_2 deficit. *Journal of Applied Physiology* 64: 50-60.

Medbo, J.I. and Burgers, S. 1990. Effect of training on the anaerobic capacity. *Medicine and Science in Sports Exercise* 23: 618-624.

Medbo, J.I. and Tabata, I. 1993. Anaerobic energy release in working muscle during 30s to 3 min of exhausting exercise. *Journal of Applied Physiology* 75: 1654-1660.

Moore, A. and Murphy, A. 2003. Development of an anaerobic capacity test for field sport athletes. *Journal of Science and Medicine in Sport* 6(3): 275-284.

Myers, J., Walsh, D., Sullivan, M., and Froelicher, V. 1990. Effect of sampling on variability and plateau in oxygen uptake. *Journal of Applied Physiology* 68(1): 404-410.

Ocel, J.V., Miller, L.E., Pierson, L.M., Wootten, D.F., Hawkins, B.J., Myers, J., and Herbert, W.G. 2003. Adaptation of pulmonary oxygen consumption slow component following 6 weeks of exercise training above and below the lactate threshold in untrained men. *Chest*. 124(6): 2377-2383.

Ott, R.L., and Longnecker, M. 2001. *An Introduction to Statistical Methods and Data Analysis.* Pacific Grove: Duxbury.

Özyener, F., Rossiter, H.B., Ward, S.A., and Whipp, B.J. 2003. Negative accumulated oxygen deficit during heavy and very heavy intensity cycle ergometry in humans. *European Journal of Applied Physiology* 90: 185-190.

Ramsbottom, R., Nevill, A.M., Nevill, M.E., Newport, S., and Williams, C. 1994. Accumulated oxygen deficit and short-distance running performance. *Journal of Sports Sciences* 12: 447-453.

Ramsbottom, R., Nevill, A.M., Seager, R.D., and Hazeldine, R. 2001. Effect of training on accumulated oxygen deficit and shuttle run performance. *Journal of Sports Medicine and Physical Fitness* 41: 281-290.

Renoux, J.C., Petit, B., Billat, V., and Koralsztein, J.P. 1999. Oxygen deficit is related to the exercise time to exhaustion at maximal aerobic speed in middle distance runners. *Archives of Physiology and Biochemistry* 107(4): 280-285.

Robergs, R.A. and Burnett, A.F. 2003. Methods used to process data from indirect calorimetry and their application to VO_{2max}. *Journal of Exercise Physiology Online* 6(2): 44 – 57.

Roscoe, J.T. 1969. *Fundamental Research Statistics for the Behavioral Sciences*. New York: Holt Rinehart and Winston Inc.

Saatci, E., Miller, D.M., Stell, I.M., Lee, K.C., and Moxham, J. 2004. Dynamic dead space in face masks used with noninvasive ventilators: a lung model study. *European Respiratory Journal*. 23: 129-135.

Saltin, B. 1987. The physiological and biochemical basis of aerobic and anaerobic capacities in man: effect of training and range of adaptation. In: Maehlum, S., Nilsson, S., Renstrom, P. (Eds.) *An update on sports medicine: proceedings from the 2nd Scandinavian conference on sports medicine*. Syntex, Strommen, pp. 16-59.

Saltin, B. 1990. Anaerobic capacity: Past, present, and prospective. In: Taylor et al. (Eds.) *Biochemistry of Exercise VII*. pp. 387-412. Champaign: Human Kinetics.

Scott, C.B., Roby, F.B., Lohman, T.G., and Bunt, J.C. 1991. The maximally accumulated oxygen deficit as an indicator of anaerobic capacity. *Medicine and Science in Sports and Exercise* 23(5): 618-624.

Scott, C.B. 1999. Oxygen deficit and slow oxygen component relationships between intermittent and continuous exercise. *Journal of Sports Sciences* 17: 951-956.

Scott, C.B. 2000. Energy Expenditure of Heavy to Severe Exercise and Recovery. *Journal of Theoretical Biology* 207: 293-297.

Stirling, J.R., Zakynthinaki, M.S., and Saltin, B. 2005. A model of oxygen uptake kinetics in response to exercise: including a means of calculating oxygen demand/deficit/debt. *Bulletin of Mathematical Biology* 67: 989-1015.

Vandewalle, H., Peres, G., and Monod, H. 1987. Standard anaerobic exercise tests. *Sports Medicine* 4: 268-289.

Whaley, M.H., Brubaker, P.H., Otto, R.M., Armstrong, L.E. 2000. *ACSM's Guidelines for Exercise Testing and Exercise Prescription.* 6th Edition. Philadelphia: Lippincott Williams and Wilkins.

Whipp, B.J. and Ward, S.A. 1993. Pulmonary gas exchange kinetics during exercise: Physiological inferences of model order and parameters. *Journal of Thermal Biology* 18: 599-604.

Yano, T., Yunoki, T., and Ogata, H. 2003. Relationship in simulation between oxygen deficit and oxygen uptake in decrement-load exercise starting from low exercise intensity. *Journal of Physiological Anthropology and Applied Human Science* 22(1): 1-5.

Yano, T., Yunoki, T., Matsuura, R., and Ogata, H. 2004. Effect of exercise intensity on the slow component of oxygen uptake in decremental work load exercise. *Journal of Physiology and Pharmacology* 55(2): 315-24.