A MATHEMATICAL MODEL FOR PREDICTING MAXIMAL HEART RATE, MAXIMAL OXYGEN UPTAKE, AND OXYGEN UPTAKE KINETICS DURING WALKING AND RUNNING AT VARIED INTENSITIES

Andrew Maurice Borror

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Approved by:

Claudio L. Battaglini

Edgar Shields

Brian Mann

ABSTRACT

Andrew Maurice Borror: A mathematical model for predicting maximum heart rate, maximal oxygen uptake, and oxygen uptake kinetics during treadmill walking and running at varied intensities
(Under the direction of Claudio L. Battaglini)

Maximal oxygen uptake (VO_2 max) is difficult to measure and most predictions are inaccurate due to a variety of assumptions. The purpose of this study was to validate a dynamical system model (DSM) for predicting HR max and VO_2 max during walking and running. A secondary purpose was to predict VO_2 responses using a neural network. Twenty-six healthy males completed a maximal cardiopulmonary exercise test (CPET) and a submaximal protocol. The models were applied to the submaximal data to estimate the participants' HR/VO_2 responses and predict their HR max and VO_2 max. The model accurately tracked HR and VO_2 responses (R^2 = -.85-0.99). However, it did not accurately estimate max ($R^2 < 0$). Further refinement of the model is needed. This study elucidated some of the challenges of using a DSM and demonstrated that a neural network may be useful for easily predicting VO_2 responses.

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LIST OF ABBREVIATIONS

BP	Blood Pressure
CPET	Cardiopulmonary Exercise Test
CRF	Cardiorespiratory Fitness
DSM	Dynamical System Model
ECG	Electrocardiogram
GA	Genetic Algorithm
GXT	Graded Exercise Test
HR	Heart Rate
HR max	Maximum Heart Rate
kg	Kilogram
ANN	Neural Network
PFA	Perceived Functional Ability
PA-R	Physical Activity Rating
PAR-Q	Physical Activity Readiness Questionnaire
R	Coefficient of Correlation
RPE	Rate of Preceived Exertion
SD	Standard Deviation
SEE	Standard Error of the Estimate
VT	Ventilatory Threshold
VO_2 max	Maximal Oxygen Uptake
W	Watts

CHAPTER 1

INTRODUCTION

Cardiorespiratory fitness (CRF) is considered the single best measurement of fitness and overall health in people. Low CRF has been associated with the development of chronic conditions as well as all cause mortality[1–6]. In clinical populations and sedentary individuals, low CRF is associated with lower levels of functionality and overall quality of life[1,3–6]. In athletes, CRF is the best predictor of performance in endurance events. Knowing an individual's CRF makes it possible to accurately prescribe exercise and to evaluate how CRF changes over time, whether due to exercise training, ageing, or disease.

CRF is typically expressed as maximal oxygen uptake (VO_2 max), or the highest volume of oxygen an individual can consume during exercise[7]. A maximal cardiopulmonary exercise test (CPET) with indirect calorimetry is considered the gold standard procedure for the assessment of VO_2 max. Unfortunately, this is an elaborate procedure that requires expensive equipment, trained technicians, an all-out effort from individuals. In clinical populations, supervision from a physician during the test is recommended, adding another level of complexity.

Due to these limitations, submaximal exercise tests that do not require an all-out effort are popular for estimating VO_2 max. These tests are used instead of maximal tests when equipment and specialized personnel are not available or in situations where there are a large number of individuals to be tested in a short period of time. Additionally, submaximal exercise tests may be more appropriate than maximal tests depending on the population, setting, and desired applicability of the results.

While useful at times, current submaximal exercise tests have some disadvantages. These tests have a large degree of uncertainty and error due to many assumptions incorporated in linear mathematical models that are used to predict VO_2 max[8,9]. One major assumption is that heart rate (HR) and oxygen uptake (VO_2) have a linear relationship with exercise intensity, which is known not to be true[10]. Another source of error is the ubiquitous "220-age" equation used to estimate an individual's maximum heart rate (HR max). Although the "220-age" equation is a rough estimate that broadly fits a large population, it may not be accurate for a specific individual as it can produce errors of estimation larger than 12 bpm[8,11,12]. Errors like this can become magnified when incorporated into a mathematical model and extrapolated out to predict VO_2 max. Submaximal exercise tests also make the assumption that biomechanical efficiency is the same from person to person and that steady state is reached during each stage (Mazzoleni 17). In general, current submaximal estimations fail to take into account the person-specific nature of physiology and the non-linearity of HR and VO_2 responses.

Recently, studies have provided promising evidence of mathematical models that may be able to address these issues[8,13]. Mazzoleni et al. (2016) developed a mathematical model that is able to account for the inter-individual differences along the non-linearity of HR and VO_2 responses during cycling[8]. Using a dynamical system model (DSM) and genetic algorithm (GA), it is able to accurately predict HR max, VO_2 max, and VO_2 kinetics using power and cadence as indicators of exercise intensity[8]. This model offers more accuracy in predicting HR max and VO_2 max compared to current estimations that use linear mathematical models and age-based equations for HR max[8]. The prediction of HR max is useful for exercise prescription using HR training zones, a practice that is common in the general public. The prediction of VO_2 max has applications for both athletes and clinicians, including accurate exercise prescription, the evaluation of training progression, and the measurement of CRF as it changes over time. Validating Mazzoleni et al.'s model for walking and running would be useful as these are common modalities people are comfortable with. Treadmill tests also tend to produce higher VO_2 max values than cycling tests because running involves whole-body movement[7,14]. Since this model allows real-time predictions, VO_2 can be estimated without the need for a specific protocol or achievement of steady-state exercise[15]. This would be particularly useful for runners, as real-time estimations of VO_2 during exercise could be used during their training.

One limitation of this model is that it still requires the measurement of VO_2 data to predict VO_2 max. Once the model is validated, it could potentially be simplified if VO_2 measurement was no longer necessary. Beltrame et al. (2016) recently utilized an artificial neural network (ANN) technique to estimate VO_2 during exercise using only HR and other easy-to-obtain inputs[13]. Applying an ANN to the model used by Mazzoleni could allow VO_2 max to be accurately predicted without the need to measure VO_2 data[13,15]. This is exciting because it would make real-time VO_2 estimations and the accurate assessment of VO_2 max possible in a variety of settings such as a hospitals, clinics, or athletic facilities using only a heart rate monitor and a measure of exercise intensity (e.g. treadmill or running watch).

Purpose Statement

The purpose of this study will be to evaluate the accuracy of a DSM and GA for predicting HR max and VO_2 max, as well as VO_2 kinetics during walking and running at varied intensities. The secondary purpose of this study will be to predict VO_2 kinetics and VO_2 max using HR and exercise intensity data by incorporating an ANN into the model.

Research Questions

RQ_1. Can a DSM and GA accurately predict HR max by measuring HR data and exercise intensity during a submaximal treadmill walking test?

RQ_2. Can a DSM and GA accurately predict HR max by measuring HR data and exercise intensity during a submaximal treadmill running test?

RQ_3. Can a DSM and GA accurately predict VO_2 max by measuring VO_2 data and exercise intensity during a submaximal treadmill walking test?

RQ_4. Can a DSM and GA accurately predict VO_2 max by measuring VO_2 data and exercise intensity during a submaximal treadmill running test?

RQ_5. Can a DSM, ANN, and GA accurately predict VO_2 max by measuring HR data and exercise intensity during a submaximal treadmill walking test?

RQ_6. Can a DSM, ANN, and GA accurately predict VO_2 max by measuring HR data and exercise intensity during a submaximal treadmill running test?

Hypotheses

H_1. A DSM and GA can accurately predict HR max by measuring HR data and exercise intensity during a submaximal treadmill walking test.

H_2. A DSM and GA can accurately predict HR max by measuring HR data and exercise intensity during a submaximal treadmill running test.

H_3. A DSM and GA can accurately predict VO_2 max by measuring VO_2 data and exercise intensity during a submaximal treadmill walking test.

H_4. A DSM and GA can accurately predict VO_2 max by measuring VO_2 data and exercise intensity during a submaximal treadmill running test.

H_5. A DSM, ANN, and GA can accurately predict VO_2 max by measuring HR data and exercise intensity during a submaximal treadmill walking test.

H_6. A DSM, ANN, and GA can accurately predict VO_2 max by measuring HR data and exercise intensity during a submaximal treadmill running test.

Operational Definitions

- *Regularly Active:* Classified as participating in regular physical activity at least 3 days per week for 30 minutes.
- *Familiarization:* Session that occurs two days prior to the testing session in order to familiarize the subjects with protocols being implemented and equipment being used.
- *Learning Effect:* Phenomenon that occurs after the initial testing session; i.e., subjects know what to expect the second time and greater changes are observed.
- *Submaximal*: Describes an exercise intensity where VO_2 remains below VO_2 max.
- *VO_2:* Volume of oxygen consumed.
- *VO_2 max:* Maximal volume of oxygen consumed.
- *VO_2 max determination criteria*: A subject's maximum rate of oxygen uptake during a graded exercise test that meets 3 of the 5 following criteria: (1) plateau of $\leq 0.15\ L \cdot min^{-1}$; (2) respiratory exchange ratio (RER) > 1.10 (3) blood lactate concentration $\geq 8\ mmol \cdot L^{-1}$; (4) RPE ≥ 18; (5) HR within 10bpm of predicted HR max.

- *VO_2 peak:* A subject's highest volume of oxygen consumption attained during a graded CPET.
- Dynamical System Model: A mathematical model used to predict physical occurrences that change over time. For current applications, the dynamical system is predictive, meaning it can predict future observations by examining past and present states of the system.
- Artificial Neural Network: A computational model designed to mimic neurons in the human brain, where inputs interact with one another along with hidden neurons to provide outputs. ANNs need to be trained using inputs with known outputs to establish connections that allow future outputs to be generated from inputs alone.
- Genetic Algorithm: A mathematical procedure designed to explore a search space and find near-optimal solutions using natural selection-inspired operations such as mutation, crossover, and selection.

Delimitations

- All subjects were regularly-active males between 18-35 years of age who exercise for at least 30 minutes, 3 days per week.
- All subjects were familiarized with facilities, exercises, and testing protocols being used prior to taking baseline measurements in order to reduce the learning effect.
- All subjects were recruited from the central North Carolina area via email and face to face contact.
- All subjects were cleared by a physician for exercise participation prior to participating in the study.

- All subjects followed appropriate pre-testing guidelines prior to each testing session (see appendix A).

Assumptions

- All subjects strictly followed the pre-assessment guidelines prior to testing sessions.
- All subjects gave their maximal effort during VO_2 max testing sessions.
- All subjects avoided intentional alterations in breathing during VO_2 measurements.
- All subjects honestly reported medical history, activity levels, RPE, and any discomfort that occurs throughout the study.

Limitations

- The results of this study may only apply to healthy subjects with a normal heart rate response during exercise.
- The generalizability of this study may only apply to healthy, regularly active males between the ages of 18-35.
- It is possible that subjects did not adhere to pre-assessment guidelines entirely as researchers were not with them during the hours prior to testing.
- Subjectivity to the smoothing coefficients, parameter estimation bounds, initial guesses, mutation coefficients, and convergence criteria.

Significance of the Study

This study was designed to validate a novel method for predicting HR max and VO_2 max based on submaximal treadmill tests. Prior studies have relied on a variety of assumptions that fail to take into account the non-linearity of HR and VO_2 dynamics, along with the person-specific nature of physiological responses during exercise testing for the prediction of HR max and VO_2 max. The model used in this study accounted for these factors and was also based on time series rather than steady-state measurements. This allows real-time estimates of VO_2 without requiring steady state exercise or a specific protocol. As long as the inputs include exercise intensity and heart rate, VO_2 can be predicted during any arbitrary protocol of varied exercise intensities. Potentially, accurate predictions of VO_2 max can also be made using data from a submaximal exercise effort.

The ability to accurately predict HR max and VO_2 max without directly measuring VO_2 data has numerous implications for both athletes and clinical populations. Accurately assessing an individual's CRF may be possible without the equipment, expense, and effort of a traditional CPET. This would allow more frequent evaluations of an athlete's physical fitness to see how their body is adapting over time due to exercise training. Real-time VO_2 predictions could be incorporated into fitness watches, improving exercise prescription and providing feedback during training. This model would also be helpful for clinicians to see how their patients are progressing due to pathologies or exercise interventions without a maximal CPET. VO_2 max is a critical measurement that has been given a lot of attention in the field of exercise physiology. An accurate method of estimating VO_2 max without measuring VO_2 data would make it highly accessible, benefitting athletes and the assessment of health in all people.

CHAPTER II

REVIEW OF LITERATURE

For organizational purposes, Chapter II was divided into the following sections: SECTION I. Cardiorespiratory fitness and the oxygen cascade. SECTION II. Maximal oxygen uptake. SECTION III. Submaximal prediction tests. SECTION IV. Non-exercise equations. SECTION V. Dynamical system modeling.

Cardiorespiratory fitness and the oxygen cascade

Cardiorespiratory fitness (CRF) is the single greatest predictor of all-cause mortality and the development of chronic diseases[1–6]. Specifically, CRF refers to the ability of the cardiovascular and respiratory systems to supply oxygen to the skeletal muscles during exercise[16]. Another term used to describe this pathway is the oxygen cascade.

Oxygen Cascade

The oxygen cascade describes a pathway that includes the pulmonary system, the cardiovascular system (e.g. heart and blood vessels), and muscle tissue. It includes oxygen intake, oxygen delivery to the muscles, and oxygen uptake into active tissues. When oxygen is taken up into the muscles, it is converted into energy in the electron transport chain. Assuming all of the oxygen is converted into energy, it is possible to measure an individual's CRF by measuring the amount of oxygen utilized during a maximal CPET. This measure of CRF is commonly called maximal oxygen uptake (VO_2 max).

Maximal Oxygen Uptake

VO_2 max is defined as the volume of oxygen consumed during maximal exercise[7]. An individual's VO_2 max is determined by the functional capacity of the oxygen cascade to utilize oxygen and remove metabolic waste. It has become the standard measure of CRF and the functional limit of an individual's aerobic capacity[17]. VO_2 max was originally conceptualized by Hill et al. and Herbst et al. in the 1920's, who observed that there was a limit to the body's ability to consume oxygen[7]. Today, this is widely accepted and VO_2 max is commonly reported as a physiological characteristic like height, weight, or age[17].

Measurement of VO_2 max

The gold standard measurement of VO_2 max is done via indirectly calorimetry by measuring gas exchange with a metabolic cart during a maximal graded exercise test (GXT)[18–20]. One of the most widely used protocols for measuring VO_2 max is the Bruce treadmill protocol, which takes subjects through increasingly difficult stages until volitional exertion. Although VO_2 max is a critical marker of functional ability and cardiovascular health, it is rarely assessed in the general public. VO_2 max assessment requires expensive equipment, trained technicians, and an all-out effort from participants.

Since it is an indirect measurement, there is inherent error in the assessment of VO_2 max. The six variables directly measured are minute ventilation, O2 faction, CO_2 fraction, barometric pressure, temperature, and water vapor pressure[17]. Error rates around 3% are common, even for repeated measurements on a subject exercising at a steady state[7,17,21]. Additionally, there is controversy surrounding the criteria for determining an individual's true VO_2 max value.

Criteria for Determining VO_2 max

Originally, a plateau in VO_2 was the criteria for determining whether or not an individual reached VO_2 max. Although a plateau in VO_2 is a good indicator, this plateau is not seen in all individuals[7,17]. Therefore, secondary criteria have been considered to determine whether or not max is reached. Typically, determination of whether an individual reached VO_2 max requires 3 of the 5 following criteria: (1) plateau of $\leq 0.15\ L\cdot min^{-1}$; (2) respiratory exchange ratio (RER) > 1.15 (3) blood lactate concentration $\geq 8\ mmol\cdot L^{-1}$; (4) RPE > 18; (5) HR within 10bpm of predicted HR max. Significant debate over all of these criteria exists[14,17]. An RER > 1.15 and blood lactate concentration $\geq 8\ mmol\cdot L^{-1}$ both indicate than a subject is relying heavily on anaerobic metabolism and may have reached VO_2 max. However, these criteria are not universally met, even in individuals who reach a plateau in VO_2[17]. Reaching HR max may be a good indicator of a maximal test, but the "220-Age" equation is known to have an error of up to 12 bpm[11,11,12]. Finally, RPE is a highly subjective measure and it is important to note participant motivation can have a large impact on the VO_2 max value derived from a GXT[17,18].

Limiting Factors of VO_2 max

Since the oxygen cascade is a multi-step pathway, VO_2 max can be limited by whichever step is the rate-limiting factor. In healthy individuals exercising at sea level, pulmonary function does not appear to be the limiting factor for VO_2 max, as arterial O_2 saturation in the blood remains around 95%[7]. However, there is debate over whether the key limiting factor is oxygen delivery or oxygen extraction in the skeletal muscle[7]. Oxygen delivery includes cardiac output (HR x stroke volume) and oxygen carrying capacity and oxygen extraction is explained by arterial-venous oxygen difference (a-vO_2 difference)[7]. According to Basset and Howley, almost all of the oxygen in the blood extracted during maximal exercise, so it is unlikely that a-vO_2 difference the limiting factor in healthy individuals[7]. Thus, it is probable that an increase in blood flow (or oxygen delivery) is the limiting factor in healthy individuals[7]. It is known that stroke volume increases with training and that blood doping, a practice that increases the oxygen carrying capacity of the blood, both increase VO_2 max[7]. Therefore, it is likely that an increase in oxygen delivery is the main limiting factor of VO_2 max in healthy individuals[7,22]. It is important to mention brain regulation of motor unit recruitment may also play a role in maximal exercise capacity[14]. However, more research is needed in this area.

Submaximal Prediction Tests

As previously stated, the measurement of VO_2 max is expensive and impractical. There are field tests to estimate VO_2 max, but they still make numerous assumptions and require the participant to give an all-out effort[19]. Due to its relevance, a great deal of effort has been put into finding ways to accurately estimate VO_2 max without performing a maximal CPET. Generally, submaximal CPETs require participants to be at steady state during a certain stage[9]. Based on their heart rate at that level, predictions are made as to what that person's VO_2 would be at their HR max. The current submaximal methods of estimating VO_2 max can be broken up into three main categories: cycling tests, treadmill tests, and step tests.

Submaximal Cycling and Step Tests

Submaximal cycling and step tests are frequently used to estimate an individual's CRF level. For reference, Akalan at al. (2008) created a summary table of submaximal exercise tests[9]. Unfortunately, most of the predictions in the literature do not present cross-validation results and several have poor correlation coefficients (R) or high values of the standard error of the estimate (SEE)[23]. Additionally, many of them were developed using age/sex specific populations. A few of the most commonly used and widely validated include the YMCA bike test and the Astrand bike test. Commonly used step tests include the YCMA step test and the Queens College Step test.

Submaximal Treadmill Tests

It is known that cycle ergometers and treadmills produce different VO_2 max values, with treadmills producing higher values due to greater motor unit recruitment[24]. Therefore, submaximal treadmill tests have been created as an attempt to more accurately predict VO_2 max. For reference, Akalan at al. (2008) created a summary table of submaximal treadmill tests[9]. Unfortunately, few treadmill protocols have been widely validated[9]. One of the most accepted walking protocols is the single-stage treadmill test[25]. It has been validated for males and females from 20-59 years of age ($R = 0.86$, $SEE = 5.0$)[9]. While the correlation is strong, the SEE is rather high, likely due to assumptions used in the estimation equation.

Assumptions of Submaximal Exercise Tests

Submaximal exercise tests make a variety of assumptions to predict VO_2 max. One key assumption is that the VO_2 cost is the same for everyone at a given workload. This ignores factors like biomechanical efficiency, genetics, and training effects[9,21]. Submaximal tests typically assume that steady state HR is reached at each workload. Another assumption is that HR and VO_2 are linear, which is known not to be true[26]. It is true that HR and VO_2 are intrinsically related. However, tests that use only heart rate in their prediction model tend to underestimate VO_2 max due to the asymptotic rather than linear relationship between HR and VO_2[26].

Perhaps the most crucial assumption and source of error is the ubiquitous "220-age" equation for HR max. It is true that HR declines with age[11]. However, age-based regression equations like "220-age" typically have an SEE exceeding 10 bpm. While this equation represents a general trend for an entire population, it has poor accuracy for determining the HR max of an individual. HR is influenced by a variety of factors including genetics, and the response to given exercise intensities vary from person to person[26]. Additionally, these tests assume that there is a linear rise in VO_2 with an increase in workload, which is not to be untrue, especially above lactate threshold[27]. As a whole, submaximal exercise tests fail to take into account the non-linear nature of VO_2 dynamics and the inter-individual variation in physiology.

Non-exercise Equations

For practicality and ease of measurement, various groups have attempted to estimate VO_2 max without an exercise bout. These equations are useful in certain situations because they provide a rough estimate of VO_2 without any exercise bout. However, they do not provide sufficient accuracy for certain applications. Two of the most common non-exercise equations were developed by Jackson et al (1990) and George et al. (1997)[28,29]. The equation developed by Jackson et al. (1990) uses age, height, weight, gender, and a Physical Activity-Rating (PA-R) questionnaire to estimate VO_2 max[29]. George et al. improved this model by adding a Perceived Functional Ability (PFA) questionnaire[28]. While the non-exercise equation does surprisingly well for an entire population, its reliability for accurately predicting a specific individual's VO_2 max is questionable.

Like the submaximal tests, regression equations make a lot of assumptions about the linearity of the relationships between VO_2 max, heart rate, age, mass, etc. However, as previously stated, these relationships are known to be non-linear[10,30]. Both non-exercise equations and submaximal exercise tests fail to take into account the non-linearity of VO2, along with the person-specific nature of physiology. In an attempt to account for these factors, new attention has been given to DSMs for estimating VO_2 max.

Dynamical System Modeling

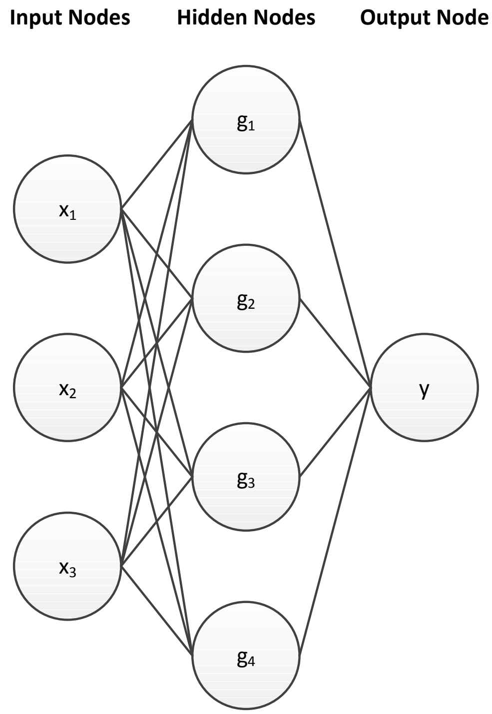
Prior studies have used dynamical system mathematical models to predict HR and VO_2 responses[8,13,31,32]. These models are able to capture the inter-individual differences in human physiology and account for with the non-linearity of HR and VO_2 responses during exercise[8]. Recently, Mazzoleni et al. developed a model that is able to accurately predict HR and VO_2 responses during a submaximal bout of cycling using power and cadence as indicators of exercise intensity[8]. Mazzzoleni developed this model based on the previous work by Sitrling et al[8,31,32]. Stirling et al.'s original model required steady state to predict the model parameters and did not include a term to account for the delay in HR and VO_2 changes in response to the demand[31,32]. Mazzoleni addressed these issues by adding a new state equation for demand[8]. Mazzoleni also added a genetic algorithm (GA) to the equation[8]. A GA is a heuristic parameter estimation method inspired by evolution[15]. It simulates a population of solutions over time utilizing the concepts of inheritance, selection, crossover, and mutation. Using a GA along with a DSM allows the estimation of HR max and VO_2 max.

This new model, which combines a DSM and a GA, offers more accuracy in predicting VO_2 max than current submaximal exercise tests that use linear mathematical models[8]. Validating this model for treadmill walking and running would be useful as treadmill tests tend to produce higher VO_2 max values than cycling tests[7,14]. Additionally, walking is a comfortable, widely accessible form of exercise. This model would also allow VO_2 to be estimated at any time point, without the need for a specific protocol or achievement of steady-state exercise[15]. The ability to have real-time estimations of VO_2 during exercise and the ability to accurately predict VO_2 max based on a submaximal effort both have numerous applications for exercise prescription and the evaluation of CRF. Accurate prediction of HR max would be useful for exercise prescription and HR training zones. One limitation of this model is that it still requires the measurement of VO_2 data using a metabolic cart. However, this limitation can be addressed with the application of an ANN.

Artificial Neural Networks

An ANN is an information processor inspired by how the brain interprets information[33]. It consists of a structure of elements ("neurons") that work in unison to solve problems through learning by example. ANNs can be trained to detect patterns that are too complex to be noticed by humans or other mathematical models. They establish relationships between neurons through multiple layers of interaction (hidden neurons), as demonstrated by **Figure 1**. Training an ANN requires inputs with known outputs. Once trained, an ANN is able to make predictions of unknown outputs based on the inputs.

Figure 1. Artificial Neural Network Diagram



Recently, Beltrame et al. (2016), utilized an ANN technique to estimate VO_2 during treadmill exercise using HR and other easy-to-obtain inputs like speed, grade, and body mass[13]. Applying an ANN to the DSM used by Mazzoleni would allow VO_2 max to be accurately predicted without the need to measure VO_2 data[13,15]. This model would make real-time VO_2 estimations and the assessment of VO_2 max possible in a variety of settings such as a hospitals, clinics, or athletic facilities using only a heart rate monitor and measure of exercise intensity (eg. Running watch or treadmill).

CHAPTER III

METHODOLOGY

Subjects

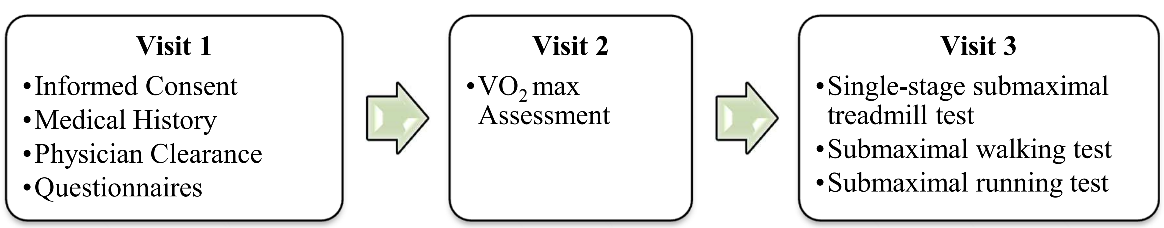
Twenty subjects were recruited to participate in this study. Recruitment for the study was completely voluntary; subjects were made aware of the project via flyers, emails, phone calls, and face-to-face interaction with research team members. Recruitment sites included areas that fall within that of central North Carolina. Approval from the Institutional Review Boards in Exercise and Sport Science and School of Medicine (Biomedical) at UNC-Chapel Hill was obtained before commencing with the recruitment of subjects.

All subjects participating in the study were regularly active males between the ages of 18 and 35. The regularly active nature of the subjects was determined by participation in exercise for at least 30 minutes 3 days per week. Subjects were considered healthy, classified as low-risk for maximal exercise testing based on guidelines set forth by the American College of Sports Medicine (ACSM)[34], and not taking any medications that could alter their HR or VO_2 responses. Interested subjects were enrolled in the study if they presented no cardiopulmonary or musculoskeletal disease that precluded their participation in any aspect of the study as determined by a physician physical evaluation.

Study Design

Below is a brief overview of each visit the subjects attended throughout the course of the study. Visit one included physical screening, medical history forms, and physical activity questionnaires. Visit two included the full Bruce protocol for assessment of VO_2 max. The third and final visit took place within one week of the second visit, following at least 48 hours of rest. The third visit consisted of three separate submaximal treadmill exercise tests that lasted approximately 10 minutes each. The first was the single-stage treadmill test developed by Ebbeling et al. (1991), the second was a submaximal walking protocol, and the third was a submaximal running protocol[25]. The second and third submaximal testing protocols consisted of stages varying intensities from 40- 85% of each subject's measured VO_2 max. Collectively, the three submaximal testing protocols lasted approximately 28 minutes (including warm up and cool down time). There were 5 minutes of rest between each test. Figure 1 provides a visual timeline of the visits described above.

Figure 2. Study Timeline



Instrumentation

Anthropometric / Screening

Height was measured to the nearest 0.1 cm via a Portable stadiometer (Perspective Enterprises, Portage, MI USA), and mass was measured to the nearest 0.1 kg via a mechanical scale (Detecto, Webb City, MO USA). A medical history questionnaire (Department of Exercise and Sports Science) was used to log the subjects' medical history, age, race, and relative physical activity level within the past year. This was utilized in conjunction with the physical examination, Physical Activity Readiness Questionnaire (PAR-Q), and resting ECG to determine the subject's ability to participate in the study. The resting ECG was accomplished with a GE CASE Cardiosoft V. 6.6 ECG diagnostic system (General Electric, Palatine, IL USA). Blood pressure was measured manually by auscultation via a Diagnostix 700 aneroid sphygmomanometer (American Diagnostics Corporation, Hauppauge, NY USA) and a Litmann stethoscope (3m, St. Paul, MN USA). Physical Activity Rating (PA-R) and Perceived Functional Ability (PFA) questionnaires were completed for use in the non-exercise equations to estimate VO_2 max [28,29].

Cardiopulmonary

VO_2 max and submaximal VO_2 data were measured with a Parvo Medics TrueMax 2400 Metabolic System (Parvo Medics, Salt Lake City, UT USA) on a GE CASE T-2100 Treadmill Exercise Testing System (General Electric, Palatine, IL USA). Rate of perceived exertion (RPE) was assessed via a Borg 6-20 Rate of Perceived Exertion (RPE) scale[35]. Heart rate was monitored via a Garmin heart rate monitor (Garmin International, Inc., Olathe, KS USA). Lactate was assessed using a Lactate Plus handheld analyzer (Sports Resource Group, Hawthrone, NY USA).

Procedures

All subjects reported to the Exercise Oncology Research Laboratory (EORL) on a total of three separate occasions for screening and testing purposes. All subjects within the study were required to undergo a physical screening by a physician in accordance with a 12-lead ECG, medical history questionnaire, and PAR-Q form. Before reporting for testing sessions, subjects were required to follow a set of pre-assessment guidelines. Prior to testing, all subjects gave verbal confirmation that the pre-assessment guidelines were followed. These guidelines included maintaining a proper hydration status as assessed by an American Optical, Hand Held TS Meter (Keene, New Hampshire, USA) refractometer, being at least two hours fasted, refraining from caffeine consumption for at least eight hours prior, refraining from exercise for at least 24 hours prior to testing, and refraining from alcohol consumption for at least twenty-four hours prior to any testing (Appendix A).

Visit One: Physical Screening & Questionnaires

The first visit to the laboratory included the signing of the informed consent form and completion of the medical history, PAR-Q, PA-R, and PFA questionnaires (Appendices B-E). All subjects within the study were required to undergo a physical screening by a physician in accordance with a 12-lead ECG, medical history questionnaire, and PAR-Q form. A 12-lead resting ECG was conducted as part of the physical examination by a physician member of the research team. Height and weight measurements were taken along with resting HR and blood pressure (BP).

Visit Two: Maximal CPET

Visit two consisted of a maximal CPET on the treadmill, following the procedures of the Bruce protocol (Appendix F). Each subject began by standing quietly on the treadmill for three minutes while the researchers collect resting metabolic and HR data. Once the test began, the subject walked/ran as the treadmill speed and incline increased every three minutes. HR and RPE (6-20) were continually monitored and recorded during the last 30 seconds of every stage (Appendix G). Termination of the test was determined by the subjects' reaching volitional exhaustion or a plateau or decrease in VO_2 with an increase in exercise intensity. At the end of the test, the subjects rested for 3 minutes; blood lactate was then analyzed. After the blood lactate collection, subject's vital measurements (HR, BP) were checked. If heart rate had dropped below 100 bpm and blood pressures returned to baseline values, subjects were cleared to leave the laboratory. In between visits two and three, subjects were asked to refrain from strenuous exercise.

VO_2 max was determined using the following criteria: (1) plateau of ≤ 0.15 L·min^{-1} with increase of exercise intensity in the last stages of the test; (2) respiratory exchange ratio (RER) > 1.15 (3) blood lactate concentration ≥ 8 mmol·L^{-1}; (4) RPE ≥ 18; (5) HR within 10 bpm of predicted HR max[34]. If three of these five criteria were not met, the measurement was considered a VO_2 peak and not a VO_2 max. An expanded discussion of the criteria for determining VO_2 max was included in the review of the literature. Determination of the VO_2 max value was done by averaging the three highest values obtained during the last minute of the test (after 8-breath average data smoothing).

Visit Three: Submaximal CPETs

After at least 48 hours of rest, but within one week of the maximal CPET, subjects returned to the EORL for submaximal testing. Each subject began by completing the 8-minute single-stage treadmill test, which consisted of a four-minute warmup and four-minutes at a 5% grade[25] (Appendix I). At the end of the protocol, subjects rested for five minutes before beginning the submaximal walking protocol. During this time, the VO_2 metabolic cart was set up to collect breath-by-breath measurements. Next, subjects completed the submaximal walking protocol (Appendix G), consisting of a one-minute warm up, three one-minute hard stages interspersed with two-minute easy stages, and a one-minute standing cooldown. Subjects then rested for three minutes before beginning the submaximal running protocol. The running protocol also consisted of a warm up, three difficult stages interspersed with easy stages, and a cool down (Appendix G). Subjects maintained a jog throughout the entire running protocol (ie. they will not be allowed to walk). HR, VO_2, and exercise intensity (eg. speed, grade) data were measured continuously throughout the test. RPE was recorded at the end of the hard stages.

Data Analysis

Data Processing

Data processing was conducted according to the methods outlined by Mazzoleni et al[8,36]. HR (bpm), speed (mph), and grade (%) were measured at 1Hz. The raw HR data was smoothed using cubic smoothing splines in order to obtain a time derivative. VO_2 data was sampled at breath by breath intervals and then linearly interpolated at 1 Hz to match the HR, speed, and grade data. After interpolation, the VO_2 data was smoothed using cubic smoothing splines to allow the calculation of a numerical derivative. Optimal smoothing criteria were based on mutual information techniques[37]. The original VO_2 data was also sampled using 8-breath averaging technique for plotting purposes[38].

Dynamical System Model

The following differential equation was used to model HR and VO_2 responses:

$$\dot{y} = A\left(y - y_0\right)^{\alpha}\left(y_x - y\right)^{\beta}\left(D - y\right)^{\gamma}$$

where A, α, β, and λ are constants related to an individual's physiology and fitness. Although the model form is the same, the corresponding parameter values differ depending on whether HR or VO_2 is being analyzed. D refers to the demand for HR or VO_2 as a function of time and exercise intensity: $\dot{D} = B\left(f\left(\vec{\psi}\right) - D\right)^{\kappa}$

where B is a constant and $f(\vec{\psi})$ is the exercise intensity function: $f(\vec{\psi}) = f(p, \omega)$. Without knowing anything about the exercise intensity function, it is possible to obtain an approximation using a second order Taylor series expansion,

$$f(p, \omega) \approx c_0 + c_1 p + c_2 \omega + c_3 p^2 + c_4 \omega^2 + c_5 p \omega,$$

where C_0 – C_5 are constants related to an individual's physiology and fitness.

The original model derived by Stirling et al. did not account for the physiological delay in HR and VO_2 responses to changes in exercise intensity, for which it was highly criticized[31,32,39].

Mazzoleni et al. addressed this concern by adding a delay term and two state-equations that do not require the subject to be at steady state[8].

Genetic Algorithm

A GA was used in conjunction with the DSM to estimate HR max and VO_2 max, along with all of the other model parameters (A, α, C_o, etc.). During this process, time series predictions for HR and VO_2 were also produced. In other words, VO_2 was estimated at every given point in time based on the exercise intensity and person-specific parameters. The GA used a population size of 120 and generation limit of 1,000. It was run 20 times to reduce the risk of obtaining a false result. It also employed a tournament selection scheme, a BLX-α crossover scheme, and a Gaussian mutation scheme. The demand function was solved numerically and constraints were placed on the parameters to prevent solutions from becoming imaginary or physiologically invalid.

Neural Network

After initial data processing, an ANN was trained using five inputs (HR, the time derivative of HR, speed, grade, and mass) and one target variable (VO_2). Prior to initializing, the training, testing, and validation parameters were set to 70%, 15%, and 15%, respectively. The Levenberg-Marquardt generalization algorithm was chosen and the number of hidden neurons was set to 20. There parameters were then run, allowing the ANN to form a generalization algorithm capable of predicting VO_2 responses based on the five inputs.

Statistical Analysis

Collected data for this current study were analyzed with SPSS Statistics version 20.0 (SPSS Inc., Chicago, IL USA) and MATLAB version R2017b (MathWorks, Natick, MA USA). The alpha level was set *a priori* for all statistical analyses at 0.05.

Descriptive Statistics

Descriptive statistics were calculated in order to exhibit the study population characteristics (age, height, body mass, etc.). Descriptive statistics were also calculated for the HR max and VO_2 max estimations from the DSM, as well as for the VO_2 max predictions from the ANN, non-exercise equations (Appendix I), single-stage treadmill test, and Bruce protocol estimation equation.

Line of Identity Analyses

The accuracy of model predictions was evaluated against the true values obtained from the CPET by calculating the coefficient of determination (R^2) and standard error of the estimate (SEE). All of the R^2 and SEE values were calculated from line of identity analyses. This is because the purpose at hand is prediction of physiological metrics. Rather than looking at the relationship between two variables (standard linear regression), we want to see the predictive power of the models. Therefore, it is possible for the R^2 to be negative, indicating that a fixed line at the mean of the data would be a better fit than the model being evaluated.

All of the following tests were conducted for both walking and running: The accuracy of the time series predictions versus the experimental measurements were evaluated for each participant by calculating the R^2 value and SEE for: (1) the DSM-GA estimate of HR; (2) the DSM-GA estimate of VO_2; and (3) the ANN prediction of VO_2. The accuracy of the maximal predictions versus the experimental measurements were evaluated for each participant by calculating the R^2 value and SEE for: (1) the DSM-GA estimate of HR max; (2) the DSM-GA estimate of VO_2 max; and (3) the ANN prediction of VO_2 max. The accuracy of the trained ANN was evaluated by calculating the R^2 value and SEE. The accuracy of the single-stage treadmill test, Jackson non-exercise equation, George non-exercise equation, 220 – age equation, and 208 – (0.7 x age) were evaluated by calculating the R^2 value and SEE. The DSM-GA estimates of HR max were compared to measured values of HR max using a dependent samples t-test. The DSM-GA estimates of VO_2 max were compared to measured values of VO_2 max using a dependent samples t-test. Finally, dependent samples t-tests were used to assess the accuracy of the model for walking compared to running for: (1) the DSM estimate of HR max; (2) the DSM estimate of VO_2 max; and (3) the ANN prediction of VO_2 max.

CHAPTER IV

RESULTS

Subjects

Twenty-six subjects were recruited to participate in the study. Twenty-four of the subjects met the previously mentioned criteria for determination of VO_2 max. One subject was significantly less fit than the rest, making the running test nearly maximal and therefore, this subject was excluded and analyses were performed on the remaining 23 subjects. Subjects characteristics are depicted as means and standard deviations in **Table 1**.

Table 1. Subject Characteristics

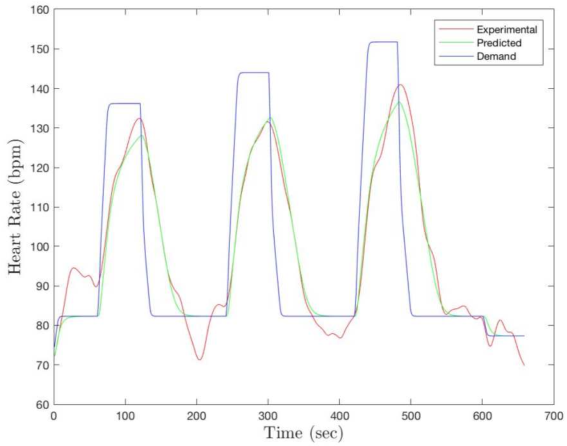
Characteristics	Mean	SD
Age (years)	21.61	3.49
Weight (kg)	74.89	11.69
Height (cm)	174.76	7.31
Composite PA-R (0-17)	12.17	3.43
Composite PFA (2-26)	21.69	3.63
Resting Heart Rate (bpm)	56	9
Maximum Heart Rate (bpm)	194	8
VO_2 Max (ml/kg/min)	62.17	8.70

Heart Rate & Oxygen Uptake Kinetics

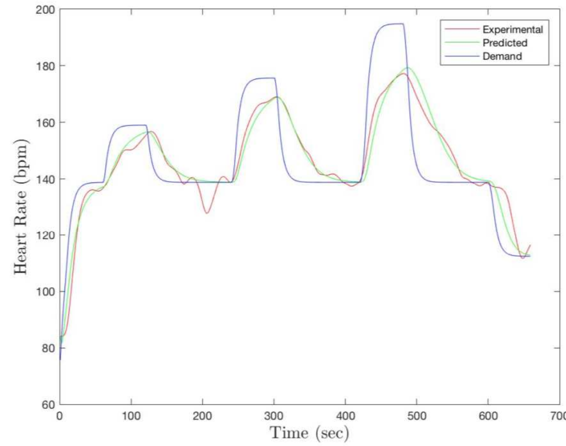
To assess the accuracy of the model for predicting HR and VO_2 kinetics, R^2 and SEE were calculated. The time series predictions were highly correlated with the experimental values for HR and VO_2 for both walking (**Table 2**). **Figure 3** provides an example time series plot of the predictions for (a) walking HR (b) walking VO_2, (c) running HR, and (d) running VO_2.

Table 2. HR and VO_2 time series prediction accuracy for walking and running

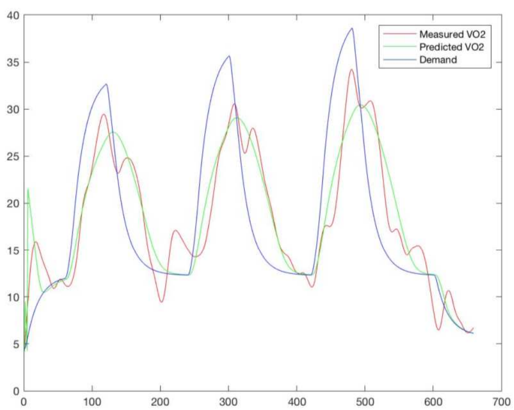
	Heart Rate		**Oxygen Uptake**	
	R^2	**SEE** (bpm)	**R^2**	**SEE** (ml/kg/min)
DSM-GA Walk	0.97	3.1	0.92	1.9
DSM-GA Run	0.96	3.7	0.88	2.7



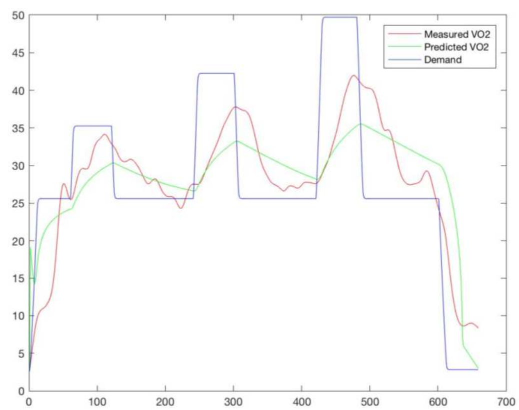
a.



b.



c.



d.

Figure 3. Example time series plot for (a) walking HR (b) running HR, (c) walking VO_2, and (d) running VO_2.

Maximum Heart Rate Estimations

The model was used to estimate HR max from submaximal data for the walk test and run test separately. The accuracy of the model was compared to traditional equations used to estimate HR max. The results can be seen in **Table 3**.

Table 3. Comparison of HR max estimations

	R^2	SEE (bpm)
220 - Age	-0.12	9.7
208 – 0.7*Age	0.14	8.5
DSM-GA: Walk	-3.68	19.9
DSM-GA: Run	-4.38	21.4

Dependent samples t-tests were used to determine if each HR max estimation significantly differed from the measured value. The mean from the model estimation was significantly different from the mean of the true HR values for walking ($p = 0.02$) and running ($p < 0.01$). The mean of the 220 – age equation was significantly different than the mean for the true HR max values ($p = 0.01$). The mean of the 208 – 0.7 * age was not significantly different than the mean for the true HR max values ($p = 0.64$). Line of identity plots for the model and the non-exercise equations can be seen in **Figure 4**.

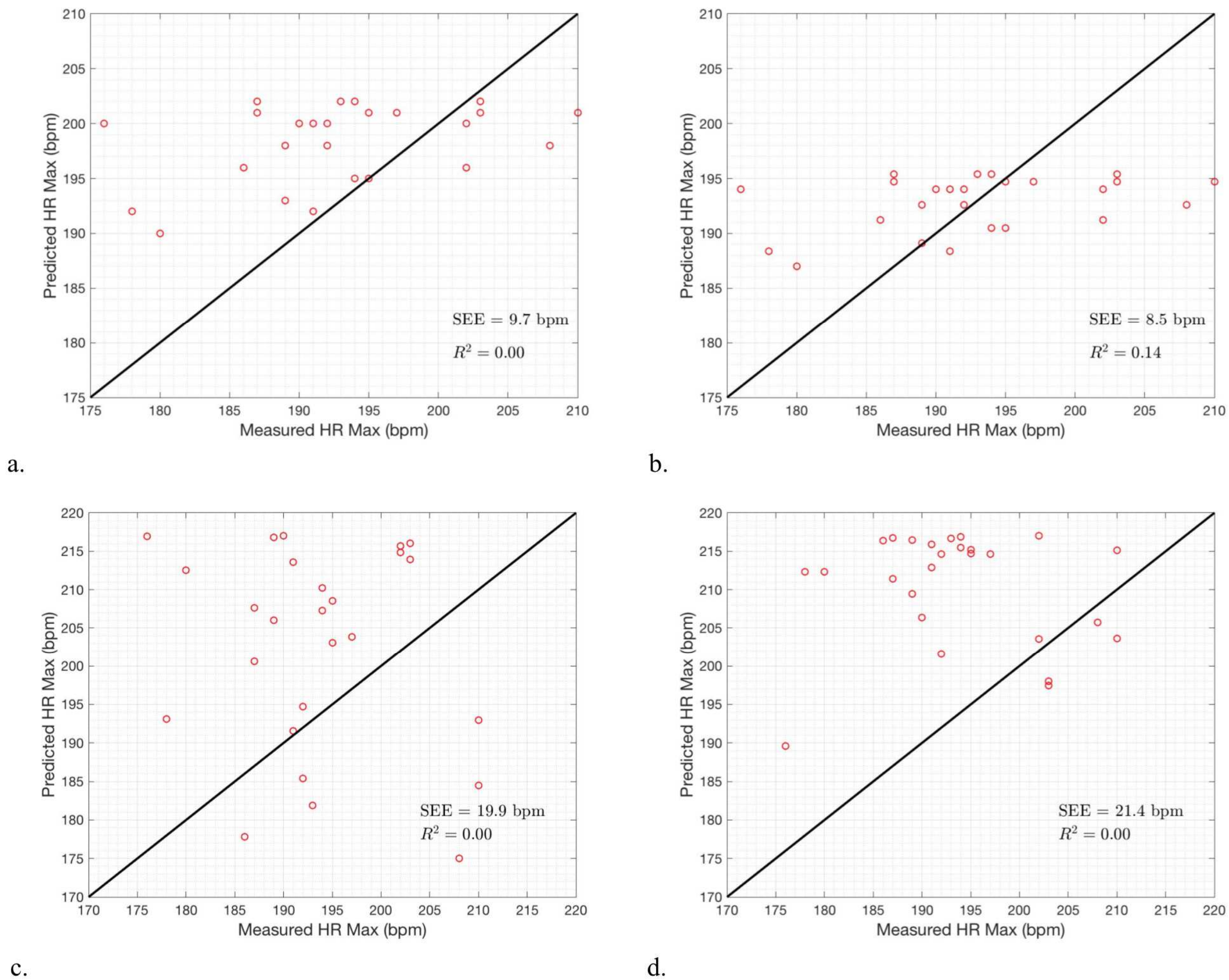


Figure 4. HR max predictions from the (a) 220 – Age equation, (b) 208 – .7*age equation, (c) walking model, and (d) running model.

VO_2 Max Estimations

The model was used to estimate VO_2 max from submaximal VO_2 data for the walk test and run test separately. The accuracy of the model was compared to the Ebbeling single-stage treadmill test, the Jackson and George non-exercise equations, and the maximal Bruce protocol equation. The results can be seen in **Table 4**.

Table 4. Comparison of VO_2 max estimations

	R^2	SEE (ml/kg/min)
DSM-GA: Walk	-2.62	18.67
DSM-GA: Run	-2.20	17.54
Ebbeling Single-stage	0.17	8.94
Jackson Non-exercise	-0.30	11.21
George Non-exercise	0.10	9.32
Bruce (maximal)	-0.17	10.61

Dependent samples t-tests were used to determine if each VO_2 max estimation significantly differed from the measured value. The model estimates were significantly different from the experimental measures for both walking ($p < 0.001$) and running ($p < 0.001$). The VO_2 max estimations were significantly different than the true VO_2 max values for the Jackson ($p < 0.001$) and George ($p < 0.001$) equation. The Bruce equation was also significantly different than the measured value ($p < 0.001$). The Ebbeling single-stage treadmill test was not significantly different than the measured VO_2 max mean ($p = 0.41$). Line of identity plots for each of the prediction methods can be seen in **Figure 5**.

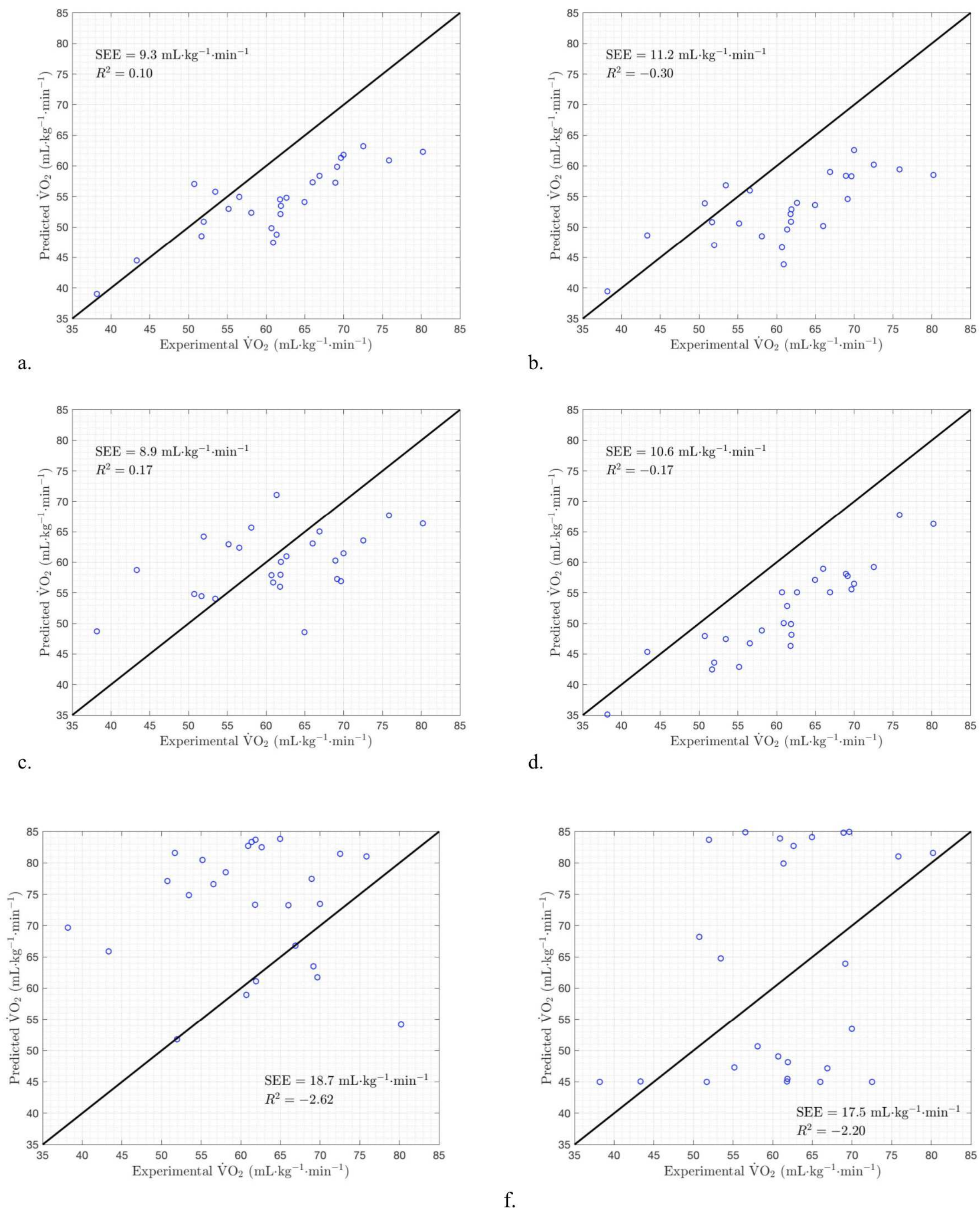


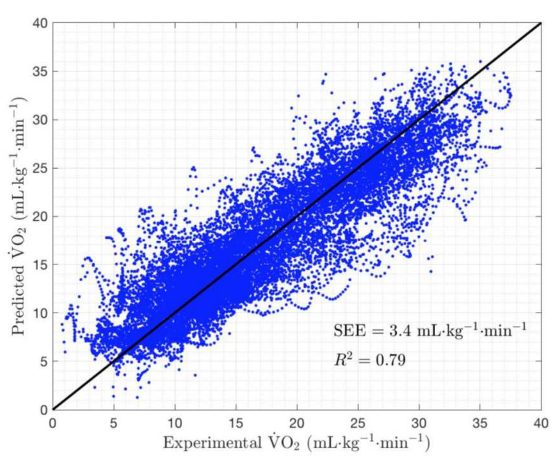
Figure 5. Line of identity plots comparing the VO_2 max predictions to the experimental values for the (a) George equation, (b) Jackson equation, (c) Ebbeling single-stage test, (d) Bruce equation, (e) DSM-GA: Walk estimation, and (f) DSM-GA: Run estimation.

ARTIFICIAL NEURAL NETWORK

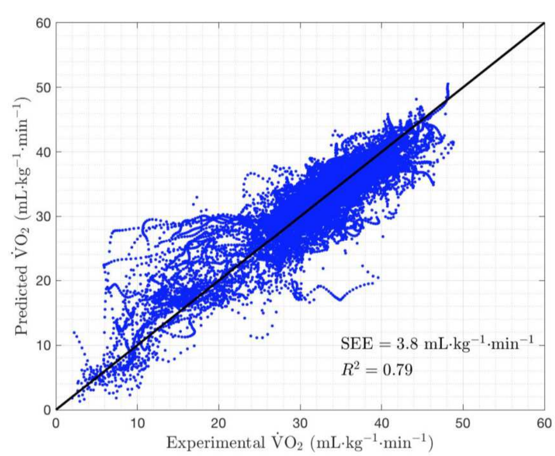
The accuracy of an ANN is influenced by the number of hidden neurons. Increasing the number of hidden neurons improves the accuracy of the model, but can lead to overfitting the data, consequently reducing its generalizability. Previous studies by Mazzoleni et al. observed diminished returns in accuracy beyond 20 hidden neurons for HR/VO_2 applications[8,36]. Therefore, this was selected for the final ANN.

Time Series Predictions

The time series predictions from the ANN were highly correlated with the experimental VO_2 for both walking (R^2 = 0.79, SEE = 3.4 ml/kg/min) and running (R^2 = 0.79, SEE = 3.8 ml/kg/min). The line of identity plots for (a) walking and (b) running can be seen in **Figure 6**. **Figure 7** provides an example time series plot for one subject's VO_2 prediction for (a) walking and (b) running.

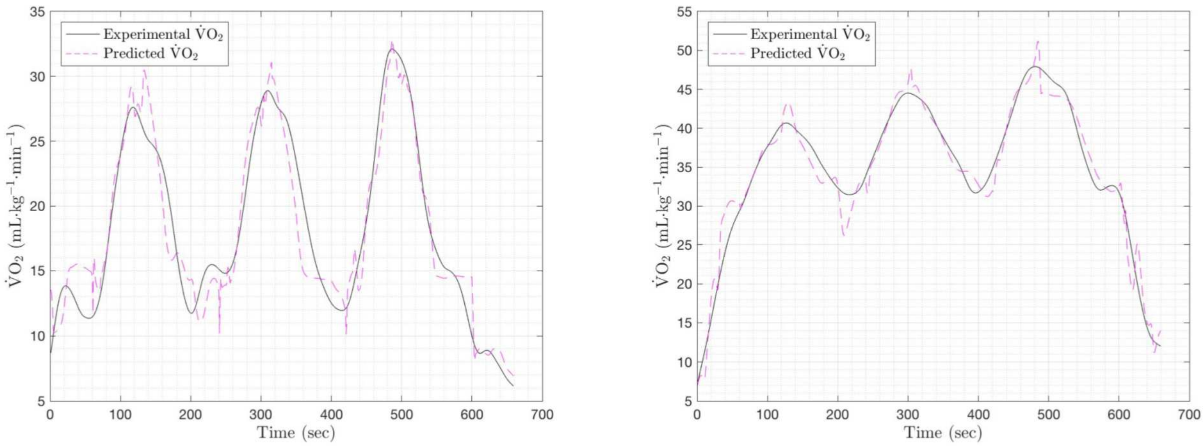


a.



b.

Figure 6. Line of identity plot comparing the ANN VO_2 prediction to the experimental values for (a) walking and (b) running

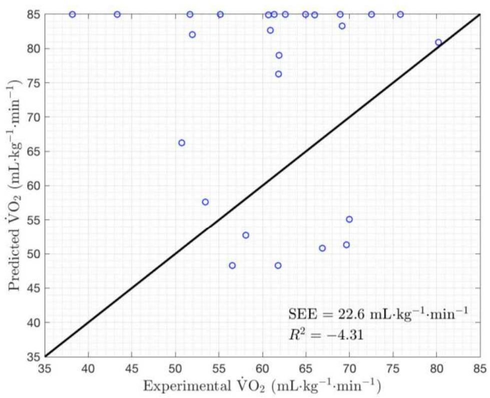


a. b.

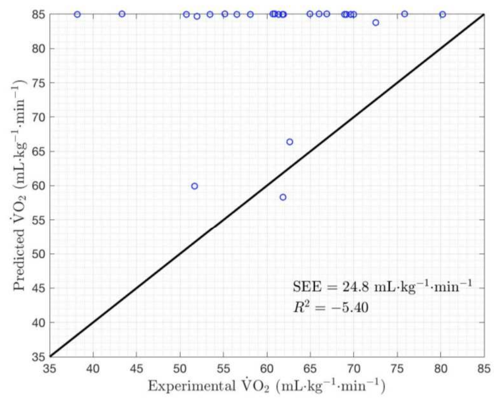
Figure 7. Example time series plot of the ANN's VO_2 prediction for (a) walking and (b) running.

VO_2 Max Predictions

The time series predictions from the ANN were used as VO_2 inputs for the DSM-GA, yielded estimations of VO_2 max with only the measurement of HR data and exercise intensity. The VO_2 max estimates were poorly correlated with the experimental data from the CPET for both walking (R^2 = -4.31, SEE = 22.6 ml/kg/min) and running (R^2 = 5.40, SEE = 24.8 ml/kg/min). **Figure 8** depicts the line of identity analysis for the VO_2 max estimations from the ANN used in conjunction with the DSM-GA for (a) walking and (b) running.



e.



f.

Figure 8. Line of identity plots comparing the VO_2 max predictions using data from the ANN to the experimental values for (a) walking and (b) running.

CHAPTER V

DISCUSSION

Traditional methods for VO_2 max prediction based on submaximal exercise bouts were dependent on linear systems and physiological assumptions[9,11,21,26,27]. Early studies by Akalan et al. and Jamnick et al. began to address these issues by eliminating age-based equations or assumptions of linearity[9,40]. Mazzoleni et al. continued this progression, developing a cycling model to eliminate both of these assumptions[8,36]. By using a dynamical demand function, it had the adaptability necessary for precise evaluation of cardiopulmonary function. This type of model performs best when given a dynamic protocol involving both on and off oxygen kinetics (ie. periods of increased workload and periods of decreased workload or rest). The present study built upon the work of Mazzoleni et al., attempting to develop a model for treadmill walking and running. The purpose of this study was to evaluate the accuracy of a DSM and GA for predicting HR max and VO_2 max, as well as VO_2 kinetics during walking and running at varied intensities. The secondary purpose of this study was to predict VO_2 kinetics and VO_2 max using HR and exercise intensity data by incorporating an ANN into the model.

VO_2 Max

The presence of a plateau in VO_2 is a highly debated topic in exercise physiology[17]. Only six of the 26 subjects exhibited a plateau in oxygen uptake. While it is a good indicator that someone has reached their maximum, a plateau is not seen in all individuals[7,17]. Therefore, determination of whether an individual reached VO_2 max requires 3 of the 5 following criteria: (1) plateau of ≤ 0.15 $L \cdot min^{-1}$; (2) respiratory exchange ratio (RER) > 1.15 (3) blood lactate concentration ≥ 8 $mmol \cdot L^{-1}$; (4) RPE > 18; (5) HR within 10bpm of predicted HR max. Significant debate over all of these criteria exists[14,17]. In the present study, only seven of the 26 subjects exhibited an RER > 1.15. These seven subjects had low VO_2 max values (M = 51.43, SD = 6.91) compared to the overall subject pool (M = 61.32, SD = 9.61). This makes sense, as someone who is less aerobically trained and/or less fit would be forced to rely more heavily on anaerobic metabolism in order to meet the metabolic demand. Every subject had lactate concentrations in excess of the criteria (≥ 8 $mmol \cdot L^{-1}$ [M = 13.79, SD = 2.35]). Twenty-two out of 26 subjects came within 10 bpm of their predicted maximum heart rate, as determined by the "220-Age" equation. It is worth noting that 10 bpm is a rather arbitrary number, and points out the inaccuracy of such equations. Twenty-four out of the 26 subjects had an RPE of 18 or higher, while two had an RPE of 17 (M = 18.73, SD = 0.72). However, RPE is a highly subjective measure and it can be difficult to assess RPE right at the end of a maximal effort[17,18].

The current study utilized the Bruce protocol because it is one of the most widely accepted treadmill protocols for VO_2 max assessment and it is known to elicit increased muscle mass activation due to large increases in grade[41,42]. While widely accepted, it is not without limitations. Particularly, it is characterized by a large increase in gradient relative to speed. This can cause runners to experience muscular fatigue and decreased efficiency if they are not used to running uphill[43]. Additionally, it is generally accepted that maximal CPETs lasting 8-12 minutes will elicit the highest VO_2 max values[43]. The test length in the present study was longer than this interval (M = 14.29 min, SD = 1.88 min).

Another issue related to the determination of VO_2 max is the data averaging technique utilized[38,44]. VO_2 data has a lot of noise because it is an indirect measurement with great variability from breath to breath. The goal of data averaging is to minimize noise and differentiate high VO_2 values due to inherent variability from those due to physiological increases in VO_2. However, over-smoothing can lead to underestimation of VO_2 responses and VO_2 max. Meyers et al. found that averages from single-breath to 60-second averaging can impact VO_2 measures by 20%[45]. Regardless of technique and rationale, exercise physiologists need to begin stating their methodology to allow comparison. Based on prior evidence from Robergs et al. and Astorino et al., the following method was used in the present study for the determination of VO_2 max. VO_2 data was exported in the 8-breath average format from the metabolic cart. VO_2 max was calculated by taking the average of the three highest measures obtained during the last minute of the test.

Time Series Predictions (HR & VO_2 kinetics)

Dynamical System Model & Genetic Algorithm

In terms of fitting the data, the model tracked HR and VO_2 responses quite well. As anticipated, the predictions were more accurate for walking (HR: $R^2 = 0.97 \pm 0.03$, SEE = 3.1 ± 0.3 bpm; VO_2: $R^2 = .92 \pm 0.07$, SEE = 1.9 ± 1.2 ml/kg/min) than for running (HR: $R^2 = 0.96 \pm 0.03$, SEE = 3.7 ± 0.5 bpm ; VO_2: $R^2 = .88 \pm 0.10$, SEE = 2.7 ± 1.8 ml/kg/min). One potential reason for this is that walking allows more diverse inputs. By switching between a slow walk on flat ground and a brisk walk with a large incline, the intensity can change rather dramatically, providing the model with inputs across a wide range of intensities. On the contrary, running has a narrow window. In order to maintain a run, the speed must be kept above ~4.5 mph. In order for the test to be submaximal, the speed needs to be kept at a reasonably slow pace. This means the intensity will not fluctuate as drastically, as the minimum energy cost for running is still somewhat high. As evidenced by the time series plots in **Figure 3**, the walk test had nice transient peaks and valleys, whereas the running data had more noise and less variation.

Overall, the model was not as accurate as the previously tested cycling model developed by our team, which was based on power and cadence[8,36]. One potential reason for this is the biomechanical differences from person to person[21,36]. Another hindrance for the model in the present study is that there were instances in multiple subjects where HR and VO_2 increased without an increase in exercise intensity. One potential reason for this that may not be accounted for in the model is the braking phenomenon on a treadmill that is decelerating. Going from the higher to lower intensites during the protocol, the subjects were forced to expend energy in order to slow down with the treadmill, potentially altering the physiological response during the transition phase. Running on a treadmill is biomechanically different than running on the ground, which could affect the applicability of the model[46–48]. Interestingly, in many of the data files, the subjects' HR increased around 200 seconds, which is one minute into the recovery stage. Whether this is physiological or circumstantial is unclear. For instance, perhaps there is a physiological overcompensation to the recovery workload due to an imbalance between venous return and contractility. Or perhaps circumstances such as drying off with a towel or anticipating the next stage had an impact on HR. This could be due to, among other things, psychological factors and sympathetic stimulation.

One important strength of the model is that it is able to account for inter-individual differences in physiology and fitness without being given the information a priori. These differences are captured in the model parameters, which are estimated with the GA. However, perhaps the model at hand was not able to fully account for differences in biomechanics with the given parameters and parameter bounds. There is subjectivity related to where the parameter bounds are placed and the amount to which the GA is allowed to mutate.

It is crucial to mention that although the time series predictions are impressive, they may not represent real-world solutions. Currently, the genetic algorithm is not converging on proper values for resting HR/VO_2 and HR/VO_2 max, yet it is able to give alternative values for the other parameters and still come up with a solution that has low residual error. This solution, though it has low error, represents an "artificial" solution that does not authentically depict physiological reality. Potential reasons for this will be discussed later.

Another weakness of using this method to predict VO_2 responses is that it still requires the measurement of VO_2 data. This concern was addressed by the secondary purpose of this study—to predict VO_2 responses with HR and exercise intensity data using an ANN.

Artificial Neural Network

The ANN was able to accurately predict VO_2 responses throughout both the walking (R^2 = 0.79, SEE = 3.4 ml/kg/min) and running tests (R^2 = 0.79, SEE = 3.8 ml/kg/min). The running predictions were less accurate at lower intensities, where the model tended to overestimate VO_2 responses. This could be due to voluntary ventilation or other factors occurring during the recovery stages (eg. wiping sweat with a towel, changing the spit tube, etc.). One significant concern for the ANN is that the current methods are overfitting the data. Additionally, the narrow demographics of the subject pool limit the generalizability of the results. Further analyses, testing, and validation are necessary to generalize these findings. However, these preliminary findings suggest that ANNs may be useful for estimation of VO_2 using only heart rate and exercise intensity as inputs.

HR Max Estimations

The typical equations for predicting HR max performed horrendously. As seen in **Table 3**, the ubiquitous "220 – age" equation would have been outperformed by a horizontal line at the mean of the data. The "208 – .7*age" performed slightly better, explaining 14% of the variance in HR max. Both of these equations had SEEs of ~9 bpm. Although non-exercise equations are simple and work well for populations as a whole, they make assumptions based on age that diminish their ability to accurately estimate a specific individual's HR max. Non-linear mathematical models can potentially provide greater accuracy by reducing these assumptions.

Unfortunately, the current model yielded inconsistent results for both walking (R^2 = -3.68, SEE = 19.9 bpm) and running (R^2 = -4.38, SEE = 21.4 bpm) due to non-convergence. Rather than converging on an inaccurate result, it did not converge at all. Meaning, each time the model is run, it gives a vastly different output for HR max. This major limitation will be discussed later.

VO_2 Max Estimations

VO_2 max estimations from previously cited methods had a great degree of variability. As seen in **Table 4**, even the best method, which involved an exercise bout, had a SEE of almost 9 ml/kg/min[25]. It is worth noting that these methods may have been particularly innacurate for the subject pool in the present study most likely due to a narrow age range and exceptionally high fitness. Regardless, the non-exercise equations, single-stage treadmill test, and Bruce equation (an equation using data collected during the CPET) provided less than ideal estimates of VO_2 max. Interestingly, the Bruce equation performed very poorly, despite the fact that it uses data from a maximal bout.

Just as with HR, the current model gave inconsistent VO_2 max predictions for both walking and running. Although there is potential for a DSM to be used in conjunction with a heuristic parameter estimation method to predict VO_2 max, the current model has not been optimized. When using predictions from the ANN, the accuracy decreased for walking and running which again, had poor results due to issues with the model. These issues will now be addressed. These predictinos were especially bad, as many of the predictions hit the upper bound limit of 85 ml/kg/min (**Figure 8)**.

Potential Issues

The current model is able to accurately predict HR/VO_2 responses to varied exercise intenisties, but not maximal values. Although it can fit the data quite well, it is doing so with artificial rather than real-world solutions. For instance, the resting HR and HR max may be wrong for an individual, but the model can find alternative values for C_0-C_5 that allow the prediction to fit the data rather well. Although this solution has low residual error, it does not represent physiological reality since we know the HR values of the estimations are off.

One potential reason for this is that the model may still be missing a parameter. Perhaps adding stride length, cadence, or acceleration to the model would improve its accuracy. Biomechanical efficiency varies greatly from person to person, and the current model may be unable to account for this. Another likely issue is overly-broad parameter bounds. Since the parameters represent real-world values (eg. C_1 is the degree to which the speed of the treadmill alters the HR/VO_2 response), it makes sense that each value should remain within certain limits. Although the precise values will vary from person to person, there may be an optimal range that would allow the model to converge more consistently. If the model is able to latch onto a "good" (ie. low-error) solution based on physiological reality, it may be able to more consistently converge on HR/VO_2 max and avoid "good" (ie. low-error) solutions with unrealistic values (based on physiology). Even if the time series data and overall error is slightly higher, this would represent a "better" solution, since the goal is to model physiological responses rather than simply find a mathematical solution that matches measured data. Currently, if the model is run multiple times, it will yield different results for HR/VO_2 max each time. Thus, the issue is not that it is converging on the wrong result and has poor accuracy. Rather, it is not converging at all, and is giving any HR/VO_2 max value that, in combination with the other parameters, will give a low-error solution. Although a solution may have low error, that does imply that it is a good solution for the current application, since it represents an artificial solution. Further refinement of the model and parameter bounds are needed in order to make this DSM-GA usable for the prediction of HR max and VO_2 max.

Practical Applications

Dynamical System Model & Genetic Algorithm

This study elucidates the challenges to using a DSM-GA to capture the non-linear dynamics of HR and VO_2 responses during walking and running. However, if these challenges can be overcome, a model of this type would be extremely useful for the prediction of physiological functions. As stressed in the introduction, VO_2 max is a critical metric for the assessment of fitness in athletes and clinical populations alike. Accurately VO_2 max estimates without the need for a maximal exercise test would be invaluable, especially in clinical settings where lack of time, money, and space are major obstacles. Once optimized for the treadmill, this model could be adapted to other forms of exercise such as stair stepping or swimming. While a properly converging DSM-GA may be a useful tool for the prediction of HR kinetics and HR max, it is limited by the fact that is still requires VO_2 measurement. This makes it useful in a laboratory setting, but not in the real world. However, the ANN is able to address this issue, arguably making it the more practical aspect of this study.

Artificial Neural Network

This machine learning approach to VO_2 prediction has significant implications for training, rehabilitation, and evaluation. Athletes and coaches are always seeking to find the balance between high training loads and recovery. An ANN-based approach could potentially enable athletes to monitor their VO_2 response during exercise without the use of expensive and cumbersome equipment. Additionally, many high-level athletes try to train at or around their lactate threshold, which can be difficult without having access to real-time VO_2 data.

For clinical populations, VO_2 kinetics may be used to identify abnormalities in aerobic responses and potential disease development[49]. VO_2 is also important for the assessment of heart failure disease severity and eligibility[50]. Accurate assessment of exercise intensity would increase the efficacy and safety of exercise evaluations and training programs. In healthy individuals, real-time VO_2 estimates may improve the accuracy of energy expenditure estimations in wearable devices, which have had poor accuracy to date[51]. Other predictions can be made from real-time VO_2 estimates during exercise, including cardiac output and stroke volume[52]. Accurate assessment of VO_2 max without the need to perform a maximal cardiopulmonary exercise test would dramatically increase the accessibility of VO_2 max, and potentially allow it to become a vital sign[53]. The current study does not deal directly with these potential applications, but it is a preliminary study demonstrating the usefulness of such a tool for predicting VO_2 responses.

Limitations

The primary limitation of this project is that the model is not yet converging properly. Although the R^2 is very high, the output represents an artificial solution. Further refinement is necessary for this model to have any practical applications. Another key limitation is the narrow demographics of the subject pool. The results can only be generalized to moderately active, healthy males who have typical heart rate responses and cardiovascular physiology. This is especially true for the ANN. A diverse subject pool with data from people of all walks of life and abilities would be needed to train an ANN that works for the population at large. Another limitation, discussed previously, is the Bruce treadmill protocol's appropriateness for the subjects in this study.

The subjective nature of mathematical modeling also had an impact on the present study. For the GA to test parameters and begin converging on a solution, it must be given bounds and initial guesses. There is subjectivity to how wide/narrow to make these bounds and how large to make the mutation standard deviation/generation limit. Increasing the mutation standard deviation and/or the generation limit allows the model to explore more potential solutions, which is helpful so that it does not get stuck at local maximums or minimums. However, it makes the model take longer to run, as initial guesses may be way off from the actual solution. It also increases the likelihood of latching on to an artificial solution that may have low error.

A major limitation to the GA is that it can only predict VO_2 responses from VO_2 data, which is cumbersome to measure. This can potentially be addressed by the ANN (the secondary purpose of this current study), which allows the prediction of VO_2 responses from measured HR data. However, predicting VO_2 max from estimated VO_2 response introduces another level of potential error. Finally, there is subjectivity in the ANN regarding how many hidden neurons to use and what percentage of the data to use for training, testing, and validation.

Future Research

Future research should investigate other parameters that could potentially be added to the model to improve its accuracy. For instance, oxygen saturation sensors on the calves might explain more of the variance in oxygen uptake. If someone has an abnormal HR response, oxygen saturation at the calf may be a meaningful was to see how much oxygen is actually being utilized during activity. Perhaps even the delay in oxygen delivery to the working muscle (relative to the increase in intensity or HR) would provide meaningful information about how the cardiorespiratory system is functioning. Additionally, easy-to-obtain gait metrics should be added to the model to see if they can account for individual differences in biomechanical efficiency and help the model converge properly.

Future research should explore other methods of mathematical modeling and machine learning to predict physiological outcomes. Wearables are becoming increasingly popular and collecting substantial amounts of data[51]. Mathematical modeling and machine learning can be used to decipher meaningful information amidst the noise. For instance, Apple Watches and FitBits have continuous access to HR and accelerometer data. These metrics can be used to estimate VO_2 max without the need for a specific exercise protocol, but current methods have a large degree of error. This could make VO_2 max accessible to their health care providers with virtually no added time or burden.

Conclusions

The purpose of this study was to predict HR max, VO_2 max, and HR/VO_2 kinetics during walking and running at various intensities using a DSM and GA. HR/VO_2 responses during submaximal intensities were tracked very well by the DSM and ANN, however the estimations of HR max and VO_2 max encountered significant challenges, resulting in less than optimum accuracy. This study provided preliminary data and brought to light some of the potential issues with using a model like this to predict HR and VO_2 kinetics. A properly converging model would have numerous applications, the most noteworthy of which would be the ability to predict HR max and VO_2 max with greater accuracy than current methods which rely on a variety of assumptions; VO_2 max predictions are of particular interest. Although somewhat useful, DSM-GA predictions of VO_2 max still require the measurement of VO_2 data, which is a serious limitation outside of the laboratory. Therefore, a secondary purpose of this study was to utilize an ANN to predict VO_2 (and subsequently, VO_2 max) from HR data. ANNs were found to be a useful and simple tool for predicting VO_2 responses in healthy males with reasonable accuracy. Future studies may be able to improve upon this accuracy through refinement of data processing produces and the use of additional sensors. All in all, this study elucidated some of the benefits and challenges of using mathematical modeling and machine learning for the prediction of physiological functions.

APPENDIX A: PRE-ASSESSMENT GUIDELINES

UNIVERSITY OF NORTH CAROLINA AT CHAPEL HILL
Claudio Battaglini, Ph.D. FACSM.
Department of Exercise and Sport Sciences
105 Fetzer Hall, CB # 8700
(919) 843-6045 / Email: claudio@email.unc.edu

Pre-Test Guidelines

1. Avoid eating 2 hours prior to testing.
2. Void completely before testing.
3. Maintain proper hydration prior to testing.
4. Please wear appropriate clothing/shoes for testing (running shorts/shirt/shoes)
5. No exercise 24 hours prior to testing.
6. No alcohol consumption 24 hours prior to testing.
7. No diuretic medications 7 days prior to testing.

APPENDIX B: PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

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 you 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 (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	6.	**Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	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 which 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. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a 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.

No changes permitted. You are encouraged to photocopy 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)

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

APPENDIX C: MEDICAL HISTORY QUESTIONNAIRE

Department of Exercise and Sport Science
Medical History

Subject:____________________________ ID: ___________ Telephone:_______________

Address:____

Occupation:______________________________________ Age:________________________

YES NO

Patient History

1. How would you describe your general health at present?
   Excellent______ Good_______ Fair______ Poor______
2. Do you have any health problems at the present time? _____ _____
3. If yes, please describe:____
____

4. Have you ever been told you have heart trouble? _____ _____
5. If yes, please describe:____
____

6. Is there any chance of you being pregnant at this time? Yes: _________No:_________
7. Is there any chance that you may become pregnant during span of the study?
   Yes: ________ No: ________
8. Have you had consistent menstrual periods for the last 3 months? Yes:_________ No:________
If no, when was your last period______________________________________
9. Do you ever get pain in your chest? _____ _____
10. Do you ever feel light-headed or have you ever fainted? _____ _____
11. If yes, please describe:____
____

12. Have you ever been told that your blood pressure has been elevated? _____ _____
13. If yes, please describe:____
____

14. Have you ever had difficulty breathing either at rest or with exertion? _____ _____
15. If yes, please describe:____
____

16. Are you now, or have you been in the past 5 years, under a doctor's care for any reason? _____ _____
17. If yes for what reason?____
____

18. Have you been in the hospital in the past 5 years? _____ _____

19. If yes, for what reason?____
____

20. Have you ever experienced an epileptic seizure or been informed that you have epilepsy? _____ _____

21. Have you ever been treated for infectious mononucleosis, hepatitis, pneumonia, or another infectious disease during the past year? _____ _____

22. If yes, name the disease:____

23. Have you ever been treated for or told you might have diabetes? _____ _____ 24. Have you ever been treated for or told you might or low blood sugar? _____ _____

25. Do you have any known allergies to drugs? _____ _____

26. If so, what?____
____

27. Have you ever been "knocked-out" or experienced a concussion? _____ _____

28. If yes, have you been "knocked-out" more than once? _____ _____

29. Have you ever experienced heat stroke or heat exhaustion? _____ _____

30. If yes, when?____
____

31. Have you ever had any additional illnesses or operations? (Other than childhood diseases) _____ _____

32. If yes, please indicate specific illness or operations:______________________________
____

33. Are you now taking any pills or medications? _____ _____

34. If yes, please list:____
____

35. Have you had any recent (within 1 year) difficulties with your:

a. Feet _____ _____
b. Legs _____ _____
c. Back _____ _____

Family History

36. Has anyone in your family (grandparent, father, mother, and/or sibling) experienced any of the following?

a. Sudden death _____ _____
b. Cardiac disease _____ _____
c. Marfan's syndrome _____ _____

Mental History

37. Have you ever experienced depression? _____ _____

38. If yes, did you seek the advice of a doctor? _____ _____

39. Have you ever been told you have or has a doctor diagnosed you with panic disorder, obsessive-compulsive disorder, clinical depression, bipolar disorder, or any other psychological disease? _____ _____

40. If yes, please list condition and if you are currently taking any medication.

Condition Medication

____
____
____

Bone and Joint History

41. Have you ever been treated for Osgood-Schlatter's disease? _____ _____

42. Have you ever had any injury to your neck involving nerves or vertebrae? _____ _____

43. Have you ever had a shoulder dislocation, separation, or other injury of the shoulder that incapacitated you for a week or longer? _____ _____

44. Have you ever been advised to or have you had surgery to correct a shoulder condition? _____ _____

45. Have you ever experienced any injury to your arms, elbows, or wrists? _____ _____

46. If yes, indicate location and type of injury: ____

47. Do you experience pain in your back? _____ _____

48. Have you ever had an injury to your back? _____ _____

49. If yes, did you seek the advice of a doctor? _____ _____

50. Have you ever been told that you injured the ligaments or cartilage of either knee joint? _____ _____

51. Do you think you have a trick knee? _____ _____

52. Do you have a pin, screw, or plate somewhere in your body as the result of bone or joint surgery that presently limits your physical capacity? _____ ____

53. If yes, indicate where: ____

54. Have you ever had a bone graft or spinal fusion? _____ _____

Activity History

55. During your early childhood (to age 12) would you say you were:
    Very active ____ Quite active____ Moderately active____ Seldom active____

56. During your adolescent years (age 13-18) would you say you were:
    Very active ____ Quite active____ Moderately active____ Seldom active____

57. Did you participate in:
    a. Intramural school sports? _____ _____
    b. Community sponsored sports? _____ _____
    c. Varsity school sports? _____ _____
    d. Active family recreation? _____ _____

58. Since leaving high school, how active have you been?
    Very active ____ Quite active____ Active____ Inactive____

59. Do you participate in any vigorous activity at present? _____ _____

60. If yes, please list:

Activity Frequency Duration Intensity

____
____
____
____

61. How would you describe your present state of fitness?
Excellent_____ Good_____ Fair_____ Poor_____
62. Please list the type(s) of work you have been doing for the previous ten years:
Year Work Indoor/Outdoor Location (city/state)

____
____
____
____
____

63. Whom shall we notify in case of emergency?
Name:____
Phone: (Home)_____________________ (Work)_____________________
Address:____
64. Name and address of personal physician:______________________________
____
____

All of the above questions have been answered completely and truthfully to the best of my knowledge.

Signature:___________________________________ Date:_________________

APPENDIX D: PHYSICAL ACTIVITY RATING QUESTIONNAIRE

Physical Activity Rating (PA-R)

Select the number that best describes your general activity level for the **previous month**:

Category 1.
Did not participate regularly in programmed recreational sport or heavy physical activity.

0 - Avoid walking or exertion, e.g., always use elevator, drive whenever possible instead of walking.
1 - Walk for pleasure, routinely use stairs, occasionally exercise sufficiently to cause heavy breathing or perspiration.

Category 2.
Participated regularly in recreation or work requiring modest physical activity, such as horseback riding, calisthenics, gymnastics, table tennis, bowling, weight lifting, yard work.

2 - 10 to 60 minutes per week.
3 - Over one hour per week

Category 3.
Participated regularly in heavy physical exercise such as running or jogging, swimming, cycling, rowing, skipping rope, running in place or engaging in vigorous aerobic activity-type exercise such as tennis, basketball, or handball.

4 - Run less than one mile per week or spend less than 30 minutes per week in comparable physical activity.
5 - Run 1 to 5 miles per week or spend 30 to 60 minutes per week in comparable physical activity.
6 - Run 5 to 10 miles per week or spend 1 to 3 hours per week in comparable physical activity.
7 - Run over 10 miles per week or spend over 3 hours per week in comparable physical activity[29,54].

Physical Activity Rating (PA-R)

Select the number that best describes your general activity level for the **previous 6 months**:

0 avoid walking or exertion; e.g., always use elevator, drive when possible instead of walking

1 **light activity**: walk for pleasure, routinely use stairs, occasionally exercise sufficiently to cause heavy breathing or perspiration

2 **moderate activity**: 10 to 60 minutes per week of moderate activity; such as golf, horseback riding, calisthenics, table tennis, bowling, weight lifting, yard work, cleaning house, walking for exercise

3 **moderate activity**: over 1 hour per week of moderate activity as described above

4 **vigorous activity**: run less than 1 mile per week or spend less than 30 minutes per week in comparable activity such as running or jogging, lap swimming, cycling, rowing, aerobics, skipping rope, running in place, or engaging in vigorous aerobic-type activity such as soccer, basketball, tennis, racquetball, or handball.

5 **vigorous activity**: run 1 mile to less than 5 miles per week, or spend 30 minutes to less than 60 minutes per week in comparable physical activity as described in 4 above.

6 **vigorous activity**: run 5 miles to less than 10 miles per week or spend 1 hour to less than 3 hours per seek in comparable physical activity as described in 4 above

7 **Vigorous activity**: run 10 miles to less than 15 miles per week or spend 3 hours to less than 6 hours per week in comparable physical activity as described in 4 above

8 **Vigorous activity**: run 15 miles to less than 20 miles per week or spend 6 hours to less than 7 hours per week in comparable physical activity as described in 4 above

9 **Vigorous activity**: run 20-25 miles per week or spend 7 to 8 hours per week in comparable physical activity as described in 4 above

10 **Vigorous activity**: run over 25 miles per week or spend over 8 hours per week in comparable physical activity as described in 4 above[28]

APPENDIX E: PERCEIVED FUNCTIONAL ABILITY QUESTIONNAIRE

Perceived Functional Ability (PFA)

Suppose you were going to exercise continuously on an indoor track for 1 mile. Which exercise pace is just right for you –not too easy and not too hard?

1 Walking at a slow pace (18 minutes per mile or more)
2 Walking at a slow pace (17-18 minutes per mile)
3 Walking at a medium pace (16-17 minutes per mile)
4 Walking at a medium pace (15-16 minutes per mile)
5 Walking at a fast pace (14-15 minutes per mile)
6 Walking at a fast pace (13-14 minutes per mile)
7 Jogging at a slow pace (12-13 minutes per mile)
8 Jogging at a slow pace (11-12 minutes per mile)
9 Jogging at a medium pace (10-11 minutes per mile)
10 Jogging at a medium pace (9-10 minutes per mile)
11 Jogging at a fast pace (8-9 minutes per mile)
12 Jogging at a fast pace (7-8 minutes per mile)
13 Running at a fast pace (7 minutes per mile or less)

How fast could you cover a distance of 3 miles and NOT become breathless or overly fatigued? Be realistic.

1 I could walk the entire distance at a slow pace (18 minutes per mile or more)
2 I could walk the entire distance at a slow pace (17-18 minutes per mile)
3 I could walk the entire distance at a medium pace (16-17 minutes per mile)
4 I could walk the entire distance at a medium pace (15-16 minutes per mile)
5 I could walk the entire distance at a fast pace (14-15 minutes per mile)
6 I could walk the entire distance at a fast pace (13-14 minutes per mile)
7 I could jog the entire distance at a slow pace (12-13 minutes per mile)
8 I could jog the entire distance at a slow pace (11-12 minutes per mile)
9 I could jog the entire distance at a medium pace (10-11 minutes per mile)
10 I could jog the entire distance at a medium pace (9-10 minutes per mile)
11 I could jog the entire distance at a fast pace (8-9 minutes per mile)
12 I could jog the entire distance at a fast pace (7-8 minutes per mile)
13 I could run the entire distance at a fast pace (7 minutes per mile or less)[28]

APPENDIX F: BRUCE TREADMILL PROTOCOL

Bruce treadmill test protocol

The Bruce treadmill test protocol was designed in 1963 by Robert. A. Bruce, MD, as non-invasive test to assess patients with suspected heart disease. In a clinical setting, the Bruce treadmill test is sometimes called a stress test or exercise tolerance test.

Today, the Bruce Protocol is also one common method for estimating VO2 max in athletes. VO2 max, or maximal oxygen uptake, is one factor that can determine an athlete's capacity to perform sustained exercise and is linked to aerobic endurance. VO2 max refers to the maximum amount of oxygen that an individual can utilize during intense or maximal exercise. It is measured as "milliliters of oxygen used in one minute per kilogram of body weight" (ml/kg/min).

The Bruce Treadmill Test is an indirect test that estimates VO2 max using a formula rather than using direct measurements that require the collection and measurement of the volume and oxygen concentration of inhaled and exhaled air. This determines how much oxygen the athlete is using.

The Bruce Protocol
The Bruce Protocol is a maximal exercise test where the athlete works to complete exhaustion as the treadmill speed and incline is increased every three minutes (See chart). The length of time on the treadmill is the test score and can be used to estimate the VO2 max value. During the test, heart rate, blood pressure and ratings of perceived exertion are often also collected.

Bruce Treadmill Test Stages

Stage 1 = 1.7 mph at 10% Grade
Stage 2 = 2.5 mph at 12% Grade
Stage 3 = 3.4 mph at 14% Grade
Stage 4 = 4.2 mph at 16% Grade
Stage 5 = 5.0 mph at 18% Grade
Stage 6 = 5.5 mph at 20% Grade
Stage 7 = 6.0 mph at 22% Grade
Stage 8 = 6.5 mph at 24% Grade
Stage 9 = 7.0 mph at 26% Grade

The Bruce Protocol Formula for Estimating VO2 Max

> For Men VO2 max = $14.8 - (1.379 \times T) + (0.451 \times T^2) - (0.012 \times T^3)$
> For Women VO2 max = $4.38 \times T - 3.9$
> T = Total time on the treadmill measured as a fraction of a minute (ie: A test time of 9 minutes 30 seconds would be written as T=9.5).

Because this is a maximal exercise test, it should not be performed without a physician's approval and without reasonable safety accommodations and supervision.

Bruce Protocol Norms for Men

VO2 Max Norms for Men - Measured in ml/kg/min						
Age	**Very Poor**	**Poor**	**Fair**	**Good**	**Excellent**	**Superior**
13-19	<35.0	35.0-38.3	38.4-45.1	45.2-50.9	51.0-55.9	>55.9
20-29	<33.0	33.0-36.4	36.5-42.4	42.5-46.4	46.5-52.4	>52.4
30-39	<31.5	31.5-35.4	35.5-40.9	41.0-44.9	45.0-49.4	>49.4
40-49	<30.2	30.2-33.5	33.6-38.9	39.0-43.7	43.8-48.0	>48.0
50-59	<26.1	26.1-30.9	31.0-35.7	35.8-40.9	41.0-45.3	>45.3
60+	<20.5	20.5-26.0	26.1-32.2	32.3-36.4	36.5-44.2	>44.2
Also See: VO2 Max Norms for Women						

VO2 Max Norms for Women

VO2 Max values for Women as measured in ml/kg/min						
Age	**Very Poor**	**Poor**	**Fair**	**Good**	**Excellent**	**Superior**
13-19	<25.0	25.0-30.9	31.0-34.9	35.0-38.9	39.0-41.9	>41.9
20-29	<23.6	23.6-28.9	29.0-32.9	33.0-36.9	37.0-41.0	>41.0
30-39	<22.8	22.8-26.9	27.0-31.4	31.5-35.6	35.7-40.0	>40.0
40-49	<21.0	21.0-24.4	24.5-28.9	29.0-32.8	32.9-36.9	>36.9
50-59	<20.2	20.2-22.7	22.8-26.9	27.0-31.4	31.5-35.7	>35.7
60+	<17.5	17.5-20.1	20.2-24.4	24.5-30.2	30.3-31.4	>31.4

Taken from: Fitness Tests to Predict VO_2 Max.
https://sites.uni.edu/dolgener/Fitness_Assessment/CV_Fitness_Tests.pdf

APPENDIX G: DATA COLLECTION SHEET

Subject ID:_________

Visit 1

Height (cm):______________ Weight (kg): ______________

RHR: __________________ RBP: __________________

PA-R Score:______________ PFA Score:_______________

Age: __________________ Sleeve Size:______________

VO_2 Max Test Date & Time: _____________

Height (cm):______________ Weight (kg): ______________

RHR: __________________ RBP: __________________

Test Start (Parvo):_________ Test Stop (Parvo):_________

Bruce Protocol

Notes:

Stage	Speed	Grade	HR	RPE
1	1.7	10		
2	2.5	12		
3	3.4	14		
4	4.2	16		
5	5	18		
6	5.5	20		
7	6	22		
8	6.5	24		
9	7	26		

VO_2 max (ml/kg/min):____________ HR max:___________

Lactate (mmol/L):________________ RPE:______________

Plateau: Yes No RER:______________

Subject ID:_________

Submaximal Tests

Date & Time: ____________

Height (cm):_____________

Weight (kg): _____________

RHR: __________________

RBP: __________________

Single-stage Treadmill Test

Predicted HR max:_________

50-70% HR max:__________

Speed (mph): ____________

Steady State HR:__________

Test Start (Time):_________

Test Start (Time):_________

Notes:

Walking Protocol

Test Start (Parvo):_________

Test Start (Garmin):________

Test Start (Time):_________

Stage	Time	Speed	Grade	RPE
Warm up	0:00	2	0	
1	1:00	3.5	12	
2	2:00	2	0	
3	4:00	3.5	14	
4	5:00	2	0	
5	7:00	3.5	16	
6	8:00	2	0	
Cool Down	10:00	0	0	
END	11:00	-	-	

Notes:

Subject ID:_________

Running Protocol

Test Start (Parvo):__________ Test Start (Garmin):________

Test Start (Time):__________

Stage	Time	Speed	Grade	RPE
Warm up	0:00	4.5	0	
1	1:00	6.0	0	
2	2:00	4.5	0	
3	4:00	7.0	0	
4	5:00	4.5	0	
5	7:00	8.0	0	
6	8:00	4.5	0	
Cool Down	10:00	0	0	
END	11:00	-	-	

Notes:

Comments:

APPENDIX H: SINGLE-STAGE TREADMILL TEST

Test Procedure

The subject walks on a treadmill at a 5% grade for 4 min at a speed of 2.0, 3.0, 4.0, or 4.5 mph**. (For this lab, walk at 4.0 mph). The heart rate should be taken at the end of the 4-min stage but prior to stopping the walk**. If the heart rate cannot be obtained until the walk is discontinued, the heart rate should be taken as quickly as possible after stopping. If you are palpating the heart rate, find the pulse as soon as you finish and count for 10 seconds. If you are using a heart monitor, take the heart rate just prior to stopping the test. VO_2 max is computed using the formula

$$VO_{2max}\ (ml \cdot kg^{-1} \cdot min^{-1}) = 15.1 + (21.8 * \text{Speed in mph}) - (0.327 * HR) - (0.263 * \text{Speed} * \text{Age}) + (5.98 * \text{Gender}) + (0.00504 * HR * \text{Age})$$

Where: Gender = 1 for males; 0 for females

Accuracy of Prediction

R= 0.86, SEE= 4.85 $ml \cdot kg^{-1} \cdot min^{-1}$

APPENDIX I: NON-EXERCISE EQUATIONS

The Jackson Non-Exercise Test

Test Procedures

The estimation of VO_{2max} with this test requires a score from a simple exercise history questionnaire in addition to age, height, weight, and gender. No exercise is performed but a measure of past exercise is determined by the questionnaire. The VO_{2max} is computed using the formula

$$VO_{2max}\ (ml \cdot kg^{-1} \cdot min^{-1}) = 56.363 + (1.921 * \text{PA-R}) - (0.381 * \text{AGE}) - (0.754 * \text{BMI}) + (10.987 * \text{Gender})$$

Where: Male = 1, Female = 0
BMI = Weight in kg / $Height^2$ in meters
PA-R = Score on the physical activity questionnaire (see appendix 3.5)

Accuracy of Prediction

R = 0.78 and SEE = 5.7 $ml \cdot kg^{-1} \cdot min^{-1}$

The George Non-Exercise Test

Test Procedures

The estimation of VO_2max from this test is similar to that of the Jackson Non-Exercise test. However, the activity level categories are more extensive for the George test and include a Perceived Functional Ability (PFA) scale as well as an expanded Physical Activity Rating (PA-R) scale. The VO_2max is computed using the following formula:

$$VO_2max\ (ml \cdot kg^{-1} \cdot min^{-1}) = 45.513 + (6.564 * \text{Gender}) - (0.749 * \text{BMI}) + (0.724 * \text{PFA}) + (0.788 * \text{PA-R})$$

Where: Gender = 1 for male and 0 for female; BMI = Weight in kg / $Height^2$ in meters
PFA = sum of both PFA scales on following pages
PA-R = number form PA-R scale on following pages.

Accuracy of Prediction

R = 0.86 and SEE = 3.34 $ml \cdot kg^{-1} \cdot min^{-1}$

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