Real-time detection of ventilatory-threshold (VT) and predicting VO_2max based on VT

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Abstract

Real-time detection of ventilatory-threshold (VT) and predicting VO_2max based on VT

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In this dissertation, a novel approach to detect ventilatory-threshold (VT) and to predict VO2max is proposed.

Conventional methods, which detects VT and predicts VO_2max, required laboratory environment with gas respiratory analyzer because of using gas data such as VO_2, VCO_2. And conventional methods can acquire the results only after completing maximal exercise. In this dissertation, 1) Algorithm for detection of VT in real-time using HR is proposed and 2) Regression model for predicting VO_2max based on VT without maximal exercise are proposed.

To develop the prediction model and validate the new model, 108 healthy, nontrained subjects(80 male, 28 female), aged 19-58 years, participated in this study. All subjects completed a submaximal treadmill GXT according to modified balke protocol. During exercise testing, VT is detected by V-slope method and VO_2max is measured by gas respiratory analyzer. To verify the proposed approach, it was applied to several statistical methods such as paired t-test, Bland-Altman analysis. Multiple regression equation is used to predict VO_2max using variables of subject's physical characteristics and HR through exercise from exercise start to VT.

In results of paired t-test, there is no significant difference in both males and females between measured and detected VT ($r=0.42$, $P<0.001$; $r=0.66$, $P<0.001$, respectively). In case of males, variables such as VO_2 variation from exercise start to VT, VO_2 at VT level and age were significant in predicting VO_2max and new model of predicting VO_2max based on VT with $R^2=0.690$, SEE=3.62 was developed. In case of females, variables such as age and HR variation from exercise start to VT were significant in predicting VO_2max and new model of predicting VO_2max based on VT with $R^2=0.759$, SEE=2.91 was developed.

From this dissertation, it can conclude that the proposed approach which monitoring slope of HR during initial 3min was useful in detection VT in real-time and VT was useful factor for healthy adults in predicting VO_2max. In this dissertation, proposed approach will be a very promising alternative to detect VT and to predict VO_2max in many applications of exercise physiology and prescription for children and older adults who was hard to do maximal exercise. With HR monitoring equipment, it will be possible to detect VT and predict VO_2max based on VT in both laboratory and filed environment.

Key words: real-time, ventilatory-threshold, VO_2max, maximal oxygen uptake, GXT, exercise testing, Heart Rate, prediction equations

Chapter 1 Introduction

Cardiorespiratory fitness is one of the five important components of health-related physical fitness. Cardiorespiratory fitness (CRF) is the ability to perform dynamic, moderate-to high intensity exercise with the large muscle groups for long periods of time [1]. CRF depends on the respiratory, cardiovascular, and skeletal muscle systems (ACSM). Assessments of CRF can be used to (a) educate participants about the current level of physical fitness relative to health-related norms and age-and gender-matched norms; (b) provide information necessary to develop a safe, appropriate, and effective exercise program for individuals who are beginning a physical activity or exercise program, or increasing their current levels of exercise; and (c) motivate participants by establishing reasonable goals to increase physical activity and improve physical fitness [1][2]. Assessment of CFR can also help stratify the risk for cardiovascular disease [1] [2].

The standard test for determining CRF is the measurement of maximal oxygen uptake (VO_2max) during the performance of a maximal graded exercise test (GXT) [1]. VO_2max is the most accurate way to assess CRF however, the process involves inconvenient methods that require costly equipment, space, and trained personnel. In addition, maximal GXTs are unappealing to some individuals because the test requires strenuous exercise to the point of volitional exhaustion. Because the potential risk for injury is high, this type of maximal exertion is not recommended for some populations (elderly, obese, sedentary, injured, or diseased individuals) without medical supervision [1].

Due to the possible drawbacks of maximal GXT's and the direct measurement of VO_2max, many submaximal exercise tests are available to predict VO_2max. Submaximal tests have certain advantages over maximal tests in that groups of participants can be tested at one time, specialized lab equipment is unnecessary, and test administrators require less training.

In addition, the gas exchange or ventilatory threshold (VT) has had a long history in exercise science and cardiorespiratory medicine. The concept of VT has persisted, as it continues to be regarded by many as a useful practical marker of cardiorespiratory fitness and endurance capacity, a more appropriate, individually tailored criterion for exercise prescriptions compared to various arbitrary percentages of maximal capacity, and a meaningful non-invasive clinical measure of cardiorespiratory health. In fact, it could be argued that the gas exchange threshold would have enjoyed a much greater popularity among scientists and practitioners if it was not for certain difficulties related to its determination. First, the difficulty lies in the fact that the scientific literature contains a wide variety of possible indices of the gas exchange threshold and the comparative evaluations of the validity and reliability of these indices do not always agree. The diversity of approaches is remarkable. The literature includes proposals focused on VCO_2 by VO_2 plots, the ventilatory equivalents, excess CO_2 production, the respiratory exchange ratio, ventilation and ventilatory frequency, and heart rate, among several others [3][4]. Second, most of the proposed indices rely on subjective criteria for determining a "breakpoint," or change in the slope of plotted ventilatory data. Given the often erratic nature of such data, this subjectivity commonly leads to guesswork, a situation that makes trained scientists feel uncomfortable. As a solution to the problems associated with the subjective nature of the traditional methods of determination, there have been several attempts to develop computerized methods, based on certain "objective" criteria. Specifically, such attempts have focused on (a) piecewise (2- or 3-phase) linear regression analyses, to identify a piecewise solution that provides a better fit to the data compared to a singular linear solution [5], (b) time series analyses (combined with various other methods, such as hidden Markov chains), to identify a breakpoint while accounting for serially correlated noise in the data [6], (c) fitting smoothing spline functions and examining the form of the derivatives [7], and others. While these approaches constitute significant advances, most have not found their way into day-to-day practice because (a) some of the mathematical concepts involved are complex and far-from-easy to implement independently and (b) the researchers who proposed these methods have not made any software programs to perform the necessary computations publicly available. Furthermore, previously reported studies for determining VT were determined only after finishing incremental exercise because VT determination was used all data from exercise start to exercise end on relationship of VCO_2 and VO_2.

1.1 Purpose

The purpose of this study is to (1) introduce a Heart Rate (HR) -based, real-time algorithm which can detect ventilatory-threshold (VT) during treadmill exercise in an healthy, nontrained adults, not aerobically trained individuals; (2) assess the proposed approach for determining VT; (3) develop a VT -based VO_2max equation in an healthy, nontrained(i.e., not aerobically trained individuals) adults,; and (4) assess the VO_2max prediction equation.

1.2 Research Hypotheses

It was hypothesized that:

1) It will be not differ between VT determined using slope of HR variation and VT determined by metabolic gas analyzer using V-slope method.

2) Significant correlation relationship will be found between VT and VO_2max and it will be possible to estimate VO_2max using variables based on VT.

1.3 Definition of Terms

1) Ventilatory threshold : The break point where a rapid increase occurs in ventilation (VE) and the volume of expired carbon dioxide (VCO_2) relative to oxygen consumption (VO_2), or in the ventilatory equivalent for O_2 (VE/VO_2) without an increase in the ventilatory equivalent for CO_2 (VE/VCO_2)

2) Cardiorespiratory Fitness(CRF) : Ability of the circulatory and respiratory systems to adequately provide nutrients and oxygen to the cells of the body in order to sustain moderate to high intensity exercise for extended amounts of time.

3) Maximum oxygen consumption (VO_2max): Maximum amount of oxygen transported and utilized by the body per minute during whole-body exercise, expressed as either: $ml \cdot min^{-1}$ or $ml \cdot kg^{-1} \cdot min^{-1}$.

4) Graded Exercise Test (GXT): A test to assess an individuals' cardiorespiratory endurance where exercise intensity is gradually increased until one reaches fatigue.

5) Age Predicted Maximum Heart Rate: Estimate of maximum heart rate by subtracting ones age from 220.

6) Bland-Altman plot: A statistical method of data plotting used in analysing the agreement between two different assays.

Chapter 2 REVIEW OF LITERATURE

This chapter describes basic knowledge that is necessary in order for readers to understand this dissertation. This chapter consists of two parts: '2.1. Methods for predicting maximum oxygen uptake (VO_2max)' introduces various methods that have been used for estimating individual exercise capacity in a noninvasive way. '2.2 Methods for determining Ventilatory-threshold (VT)' introduces various methods that have been used for determining Ventilatory-threshold in mathematical approach.

2.1 Methods for predicting maximum oxygen uptake (VO_2max)

2.1.1 The concept of VO_2max

Cardiorespiratory fitness (CRF) is typically described in terms of maximal ability to consume oxygen during strenuous exercise and is an important component in assessing individual health [1]. CRF relies on the functional state of the respiratory, cardiovascular, and skeletal muscle systems to perform physical activity and work [1]. Maximal oxygen uptake (VO_2max) defines the upper limits of the cardiovascular system to deliver oxygen to the active skeletal muscle mass and the ability of the skeletal muscle tissue to use the oxygen in aerobic metabolic pathways for the regeneration of adenosine triphosphate (ATP). VO_2max is the best measure of CRF [1][8]. The Fick equation defines the parameters of oxygen uptake:

$$VO_2 = Q \times av - O_2 difference$$

where Q = cardiac output, which is the product of stroke volume (SV) and heart rate (HR) and av-O_2 difference = arterio-venous difference, which represents the amount of oxygen (ml) that is used by metabolically active tissues per deciliter of blood flow. During incremental aerobic exercise, HR, SV, Q, arterio-venous oxygen difference, and VO_2 increase until maximal values are attained. The Fick equation can be modified to depict the parameters of VO_2max:

$$VO_{2\max} = Q_{\max} \times av - O_2 difference$$

A number of health-related outcomes are influenced by CRF level, or VO_2max. Knowledge of an individual's VO_2max is important in the evaluation of cardiovascular function. Highly fit individuals have a greater capacity to transport oxygen to the body's active tissues and therefore have high VO_2max values [9]. Individuals who are sedentary or less active have lower VO_2max values, and are at greater risk for cardiovascular disease and all-cause mortality [10]. Thus, VO_2max is a useful criterion in assessing one's fitness level and risk for cardiovascular disease. Knowledge of VO_2max can also be used to make appropriate recommendations to improve individual health, functional capacity and athletic performance [1]. The gold standard for determining CRF is the direct measurement of VO_2max during a maximal GXT. Maximal GXTs provide the most accurate method for assessing an individuals' aerobic capacity. Several maximal exercise tests [1] [11] [12] exist and although each test has its advantages, performing a maximal GXT is not practical in many situations. The process involves inconvenient methods that require costly equipment, space, trained personnel and exercise to the point of volitional fatigue. To alleviate some of the disadvantages associated with maximal GXTs, alternative methods have been devised to estimate VO_2max. These include a variety of maximal and submaximal exercise tests, exercise protocols based on VT, and non-exercise protocols [13] [14] [15] [16] [17].

2.1.2 Exercise Tests

Submaximal clinical tests are similar to maximal tests in that they both involve methods that require costly equipment, space, and trained personnel. In addition, the number of submaximal tests to be performed at one time is limited by the test protocol. Although submaximal tests are not as precise as maximal tests they are recognized as valid predictors of VO_2max and CRF [1]. Moreover, submaximal tests offer many advantages to maximal tests in that they are performed at a lower cost, reduced risk, and require less time and effort from the participant [1]. Submaximal laboratory tests use a variety of exercise modes including cycle ergometry, and walking, jogging or running on a treadmill. Commonly used modes for exercise testing include field tests, treadmill tests, cycle ergometry tests, and step tests.

1) Field tests consist of walking or running a certain distance in a given time (i.e., 12-minute and 1.5 mile [2.4 km] run tests, and the 1- and 6-minute walk test) [18] [19]. The advantages of field tests are that they are easy to administer to large numbers of individuals at one time and little equipment (e.g., a stopwatch) is needed. The disadvantages are that they all potentially could be maximal tests, and by their nature, are unmonitored for BP and HR. An individual's level of motivation and pacing ability also can have a profound impact on test results. These all-out run tests may be inappropriate for sedentary individuals or individuals at increased risk for cardiovascular and musculoskeletal complications. However, VO2max can be estimated from test results. Two of the most widely used running tests for assessing CR fitness are the Cooper 12-minute test and the 1.5 mile (2.4 km) test for time. The objective in the 12-minute test is to cover the greatest distance in the allotted time period; for the 1.5 mile (2.4 km) test, it is to run the distance in the shortest period of time. VO_2max can be estimated from the equations. The Rockport One-Mile Fitness Walking Test has gained wide popularity as an effective means for estimating CR fitness. In this test, an individual walks 1 mile (1.6 km) as fast as possible, preferably on a track or a level surface, and HR is obtained in the final minute [20]. An alternative is to measure a 10-second HR immediately on completion of the 1

mile (1.6 km) walk, but this may overestimate the VO_2max compared with when HR is measured during the walk. VO_2max is estimated from a regression equation based on weight, age, sex, walk time, and HR [21]. In addition to independently predicting morbidity and mortality [22], the 6-minute walk test has been used to evaluate CR fitness within some clinical patient populations (e.g., persons with chronic heart failure or pulmonary disease). Even though the test is considered submaximal, it may result in near maximal performance for those with low fitness levels or disease. Patients completing <300 meters during the 6-minute walk demonstrate a limited short-term survival [23]. Several multivariate equations are available to predict peak VO_2 from the 6-minute walk [23].

2) Motor driven treadmills can be used for submaximal and maximal testing and often are used for diagnostic testing. They provide a common form of exercise (i.e., walking) and can accommodate the least fit to the fittest individuals across the continuum of walking to running speeds. Nevertheless, a practice session might be necessary in some cases to permit habituation and reduce anxiety. On the other hand, treadmills usually are expensive, not easily transportable, and make some measurements (e.g., BP) more difficult. Treadmills must be calibrated to ensure the accuracy of the test. In addition, holding on to the support rail should not be permitted to ensure accuracy of the metabolic work.

The primary exercise modality for submaximal exercise testing traditionally has been the cycle ergometer, although treadmills have been used in many settings. The same endpoint (70% HRR or 85% of age-predicted maximal HR) is used, and the stages of the test should be 3 minutes or longer to ensure a steady-state HR response at each stage. The HR values are extrapolated to age-predicted maximal HR, and VO_2max is estimated using the formula from the highest speed and/or grade that would have been achieved if the person had worked to maximum. Most common treadmill protocols can be used, but the duration of each stage should be at least 3 minutes.

3) Mechanically braked cycle ergometers are excellent test modalities for submaximal and maximal testing [24][25][26][27][28][29]. They are relatively inexpensive, easily transportable, and allow BP and the ECG (if appropriate) to be measured easily. The main disadvantage is that cycling is a less familiar mode of exercise, often resulting in limiting localized muscle fatigue. Cycle ergometers provide a non–weight-bearing test modality in which work rates are easily adjusted in small work-rate increments, and subjects tend to be least anxious using this device. The cycle ergometer must be calibrated and the subject must maintain the proper pedal rate because most tests require that HR be measured at specific work rates. Electronic cycle ergometers can deliver the same work rate across a range of pedal rates, but calibration might require special equipment not available in most laboratories. Some electronic fitness cycles cannot be calibrated and should not be used for testing.

The Astrand-Rhyming cycle ergometer test is a single-stage test lasting 6 minutes [30]. For the population studied, these researchers observed that at 50% of VO_2max the average HR was 128 and 138 beats·min-1 for men and women, respectively. If a woman was working at a VO_2 of 1.5 $L{\cdot}min^{-1}$ and her HR was 138 $beats{\cdot}min^{-1}$, then her VO_2max was estimated to be 3.0 $L{\cdot}min^{-1}$. The suggested work rate is based on sex and an individual's fitness status (unconditioned / conditioned). The pedal rate is set at 50 rpm. The goal is to obtain HR values between 125 and 170 $beats{\cdot}min^{-1}$ and HR is measured during the fifth and sixth minute of work. The average of the two heart rates is then used to estimate VO_2max from a nomogram. This value must then be adjusted for age (because maximal HR decreases with age) by multiplying the VO_2max value by the correction factors [31]. In contrast to the single-stage test, Maritz et al. [32] measured HR at a series of submaximal work rates and extrapolated the response to the subject's age- predicted maximal HR. This has become one of the most popular assessment techniques to estimate VO_2max, and the YMCA test is a good example [33]. The YMCA protocol uses two to four 3-minute stages of continuous exercise. The test is designed to raise the steady-state HR of the subject to between 110 beats·min-1 and 70% HRR (85% of the age-predicted maximal HR) for at least two consecutive stages. It is important to remember that two consecutive HR measurements must be obtained within this HR range to predict VO_2max. In the YMCA protocol, each work rate is performed for at least 3 minutes, and HRs are recorded during the final 15 to 30 seconds of the second and third minutes. The work rate should be maintained for an additional minute if the two HRs vary by more than 5 beats·min^{-1}. The test administrator should recognize the error associated with age-predicted maximal HR and monitor the subject throughout the test to ensure the test remains submaximal. The HR measured during the last minute of each steady-state stage is plotted against work rate. The line generated from the plotted points is then extrapolated to the age-predicted maximal HR (e.g., 220 – age), and a perpendicular line is dropped to the x-axis to estimate the work rate that would have been achieved if the person had worked to maximum. VO_2max can be estimated from the work rate using the formula. These equations are valid to estimate oxygen consumption at submaximal steady-state workloads from 300 to 1,200 kg·m·min^{-1}; therefore, caution must be used if extrapolating to workloads outside of this range.

4) Step testing is an inexpensive modality for predicting CR fitness by measuring the HR response to stepping at a fixed rate and/or a fixed step height or by measuring post-exercise recovery HR. Step tests require little or no equipment; steps are easily transportable; stepping skill requires little practice; the test usually is of short duration; and stepping is advantageous for mass testing [34]. Post-exercise (recovery) HR decreases with improved CR fitness, and test results are easy to explain to participants [35]. Special precautions might be needed for those who have balance problems or are extremely deconditioned. Some single-stage step tests require an energy cost of seven to nine metabolic equivalents (METs), which may exceed the maximal capacity of the participant [31] . The workload must be appropriate to the fitness level of the client. In addition, inadequate compliance to the step cadence and excessive fatigue in the lead limb may diminish the value of a step test. Most tests are unmonitored because of the difficulty of measuring HR and BP during a step test.

Step tests have also been used to estimate VO_2max. Astrand and Ryhming [30] used a single-step height of 33 cm (13 in) for women and 40 cm (15.7 in) for men at a rate of 22.5 steps·min^{-1}. These tests require oxygen uptakes of about 25.8 and 29.5 mL·kg^{-1}·min^{-1}, respectively. Heart rate is measured as described for the cycle test, and VO_2max is estimated from the nomogram. In contrast, Maritz et al. [32] used a single-step height of 12 inches (30.5 cm) and four-step rates to systematically increase the work rate. A steady-state HR was measured for each step rate, and a line formed from these HR values was extrapolated to age-predicted maximal HR; the maximal work rate was determined as described for the YMCA cycle test. VO_2max can be estimated from the formula for stepping. Such step tests should be modified to suit the population being tested. The Canadian Home Fitness Test has demonstrated that such testing can be performed on a large scale and at low cost [21][30][31][32][33][35][36]. Instead of estimating VO_2max from HR responses to several submaximal work rates, a wide variety of step tests have been developed to categorize cardiovascular fitness on the basis of a person's recovery HR following a standardized step test. The 3-Minute YMCA Step Test is a good example of such a test. This test uses a 12-inch (30.5 cm) bench, with a stepping rate of 24 $steps \cdot min^{-1}$ (estimated oxygen cost of 25.8 $mL \cdot kg^{-1} \cdot min^{-1}$). After exercise is completed, the subject immediately sits down and HR is counted for 1 minute. Counting must start within 5 seconds at the end of exercise. Heart rate values are used to obtain a qualitative rating of fitness from published normative tables [33].

5) Other methods that do not require exercise are also available to predict VO2max [1]. Non-exercise (N-EX) regression equations provide a convenient estimate of CRF without the need to perform a maximal or submaximal exercise test [37][38][39]. This approach is inexpensive, time-efficient, and realistic for large groups. To date, N-EX predictor variables include age, gender, body mass index (BMI), percent body fat, physical activity rating (PA-R) [40][41] and perceived functional ability (PFA) [42]. The PFA includes simple questions which ask individuals to rate their ability to exercise at a comfortable pace for one and three miles. Studies show N-EX equations are relatively accurate and provide a quick and easy way to predict VO2max [40][41][42]. To date, PAR has been validated in a large sample of 18-70 year-old men and women, but PFA has only been validated in a sample of college-aged men and women. Thus, there is a need to further evaluate PFA as a predictor variable in estimating

CRF with a broader age range.

2.2 Methods for determining Ventilatory-threshold (VT)

2.2.1 Mathematical algorithms for determining VT

1) The Jones and Molitoris (1984) algorithm, as implemented by Schneider et al. (1993). This method considers two regressions, y = b0 + b1x and y = b0+b1x0+b3(x-x0), and then searches for the value of x0 that minimizes the residual sum of squares [43] [44].

2) The "brute force" algorithm proposed by Orr et al. (1982). This method consists of calculating regression lines through all possible divisions of the data into two contiguous groups, and finding the pair of lines yielding the least pooled residual sum of squares [45].

3) The "V-slope" algorithm proposed by Beaver et al. (1986). This method consists of dividing the VCO_2 by VO_2 curve into two regions, fitting linear regressions through them, and identifying the point at which the ratio of the distance of the intersection point from a single regression line through the data to the mean square error of regression is maximized [5].

4) The "Dmax" algorithm proposed by Cheng et al. (1992). This method consists of calculating a third-order polynomial regression curve to fit the data and drawing a straight line connecting the first and last data points. The breakpoint is then defined as the point yielding the maximal distance between the curve and the straight line [46].

5) The "simplified V-slope" algorithm proposed by Sue et al. (1988) and Dickstein et al. (1990). This method again calculates regression lines through all possible divisions of the data

into two contiguous groups, and finds a breakpoint at which the first regression has a slope of less than or equal to 1 and the second regression has a slope higher than 1 [47][48].

2.2.2 Conventional Methods for determining VT

1) Visual method: This method was determined by eye from graphs of ventilation versus time. In order to minimize subjectivity three independent experienced observers were used and the means of their results were taken as the standard value of the ventilatory threshold.

2) The v-slope method: This method consists of plotting CO_2 production over O_2 utilization and identifying a breakpoint in the slope of the relationship between these two variables. The level of exercise intensity corresponding to this breakpoint is considered the gas exchange threshold.

3)The method of the ventilatory equivalents: This method consists of plotting the ventilatory equivalents for O_2(VE/VO_2) and CO_2 (VE/VCO_2) over time or over O_2 utilization and identifying the level of exercise intensity corresponding to the first rise in VE/VO_2 that occurs without a concurrent rise in VE/VCO_2.

4) The Excess CO_2 method: This method has been operationalized in various ways. In WinBreak, the operationalization of Excess CO_2 follows that proposed by Gaskill et al. (2001). According to their definition, Excess $CO_2 = (VCO_2 / VO_2) - VCO_2$. When Excess CO_2 is plotted over time or over O_2 utilization, the gas exchange threshold is thought to occur at the level of exercise intensity corresponding to an increase in Excess CO_2 from steady state [49].

5) The CUSUM method: This methods is based on an observed increase in the variability of V_E or VCO_2 data above the ventilatory threshold in a graph of V_E or VCO_2 versus time. The

absolute value of the difference between two consecutive measurements of V_E or VCO_2 is added to the sum of the previous differences to produce the cumulative sum [50]. That is:

$$CUSUM = \sum_{n=F}^{n=L} \left(\left| V_{n+1} - V_n \right| \right)$$

where n = the number of the physiological parameter, F = the first physiological parameter and L = the last physiological parameter. The CUSUM is then graphed against time and a distinct increase in the slope of V_E or VCO_2 graph is then detected. The deflection point was taken as the time of the ventilatory threshold, and was determined by the investigator by eye.

6) Combined method: Deflection points of the graphs of V_E or VCO_2 versus time using CUSUM method were detected by the D_{max} method and corresponded VO_2 values were taken as VT [51].

7) HRDP method: This method consists of plotting HR (beats/min) over Work load (watts) and identifying a breakpoint in the slope of the relationship between these two variables. The level of exercise intensity corresponding to this loss of linearity between HR and an initial running speed the ‘deflection velocity’ is considered the gas exchange threshold [52][53].

Chapter 3 METHODS

In this chapter, subjects, experimental procedure, exercise protocol, algorithm for determining VT in real-time, VO_2max equation based on VT and statistical analysis were described.

3.1 Subjects

108 healthy, nontrained subjects (i.e., those reporting no regular physical activity in the past year) volunteered to participate in this study from Yonsei University and surrounding areas. Subjects who had medical history or physical or laboratory findings of cardiac, respiratory, metabolic, or neuromuscular diseases were excluded from the study. Subjects, aged 19-58 years (80 male, 28 female, age 19-58 yrs) had the following characteristics (Table 3.1).

Before data collection, all subjects were given a brief explanation of all test protocols, signed a written informed consent document, completed the Physical Activity Readiness Questionnaire (IPAQ). All methods and procedures of the study were approved by the Yonsei university Medical ethics committee for the use of Human Subjects.

Table 3.1. Physical characteristics and physiological parameters of the studied subjects

Variable	**Total** **N=108**	**Male** **n=80**	**female** **n=28**
Age (years)	37.12±11.09	34.35±9.93	45.03±10.56
Height (cm)	167.88±8.12	171.54±5.48	157.42±4.51
Weight (kg)	67.73±11.97	71.98±9.94	55.57±8.47
BMI (kg/m2)	23.892.90	24.42±2.71	22.37±2.95
BMR	1664.09±255.87	1769.13±196.98	1364.00±140.83
Obesity (kg)	112.78±12.78	112.32±12.46	113.53±14.35
Percent bodyfat (%)	22.94±6.29	20.83±5.30	28.12±5.56
Mass bodyfat (kg)	15.60±5.21	15.41±5.42	15.91±5.08
SBP at resting (mmHg)	121.61±12.45	124.38±11.32	117.25±13.43
DBP at resting (mmHg)	74.78±10.79	75.06±10.77	74.25±11.47
HR at resting (beats/min)	80.01±12.08	80.76±12.09	77.88±12.00
VO_2 at resting (ml/kg/min)	3.92±0.98	4.10±0.90	3.39±0.99
HR at VT (beats/min)	133.89±14.51	134.06±14.02	133.42±16.10
VO_2 at VT (ml/kg/min)	23.08±4.26	23.95±3.91	20.62±4.30
Time at VT (min)	16.18±2.32	16.69±1.03	15.85±1.55
percent of VO_2max at VT (%)	66.12±6.90	65.14±6.47	68.92±7.42
HRmax (beats/min)	175.19±13.72	176.89±12.60	170.35±15.74
VO_2max (ml/kg/min)	35.84±6.84	37.71±6.31	30.50±5.34
METs	10.21±1.94	10.74±1.79	8.70±1.53

All data = mean ± SD

n = sample size; BMI = body mass index; BMR = basal metabolic rate; HR = Heart Rate;

VO_2 = oxygen uptake(ml/kg/min); % VO_2max = percentage maximal oxygen uptake;

3.2 Experimental procedure

All subjects completed a maximal treadmill GXT. Prior to testing, subjects were instructed to (1) wear comfortable clothing and shoes appropriate for exercise; (2) drink plenty of fluids over the 24-hour period preceding the test to ensure normal hydration prior to testing; (3) refrain from eating food other than water, and from using tobacco, alcohol, and caffeine for at least three hours prior to their test, (4) avoid exercise or strenuous physical activity the day of the testing; and (5) get at least 6 to 8 hours of sleep the night before the test.

3.2.1 Pre-Exercise Testing

Before data collection, subjects were given a brief explanation of all test protocols, signed a written informed consent document (Appendix 1, 2), completed Questionnaire (Appendix 3), the International Physical Activity Questionnaire (IPAQ: Appendix 4). All methods and procedures of the study were approved by the Yonsei Univ. Institutional Review Board for Human Subjects.

Each subject’s height (cm) and weight (kg) was measured and recorded using DS-102 (D.S. JENIX). Body fat percentage and Fat mass was measured using Boca X2(Medigate, S.Korea). HR at rest and resting blood pressure was measured. Body mass index (BMI, kg/m2) was calculated from measured height and weight values. Obesity were calculated using Paul Broca formula. Basal Metabolic Rate (BMR) was calculated using metric BMR formula.

$$Obesity = \frac{Weight - ideal.weight}{ideal.weight} \times 100$$

Male : $Ideal.weight = (height - 100) \times 0.92$

Female : $Ideal.weight = (height - 100) \times 0.86$

$$\text{Male}: BMR = 66 + (13.7 \times weight) + (5 \times height) - (6.8 \times age)$$

$$\text{Female}: BMR = 655 + (9.6 \times weight) + (1.8 \times height) - (4.7 \times age)$$

3.2.2 Incremental Exercise Testing

Equipment calibration

Metabolic and ventilatory responses to exercise were measured using a TrueOne® 2400 metabolic cart (Parvo Medics, USA). The gas analyzer was calibrated before each test using ambient air, which was assumed to possess 20.9% oxygen and 0.03% carbon dioxide, and a gas of known carbon dioxide concentration (5%; BOC, Guilford, UK). Gas concentrations in ambient room air analyzed in several laboratories have been found to demonstrate very high consistency with a mean (SD) oxygen concentration of 20.939 (0.0037) percent and a carbon dioxide concentration of 0.031 (0.0016) percent [54]. The turbine volume transducer was calibrated according to the manufacturer's instructions using a 3-L syringe. The metabolic cart was programmed to display and print metabolic and ventilatory data every 15 seconds.

Table 3.2. TrueOne® 2400

	O_2 Analyzer	CO_2 Analyzer	Flow / Volume Measurement
Method	Paramagnetic	Infrared	Rudolph screen pneumotach
Range	Range: 0-100%	0-10%	0-800 Liters/minutes
Accuracy	0.1%	0.1%	+/-2%
Response	< 500 ms	< 90 ms	

Table 3.3. Q-Stress

Protocols	Standard	Bruce, Modified Bruce, Modified Balke, Naughton, USAF/SAM 2.0, USAF/SAM 3.3, Rampedlow, Ramped-medium, Ramped high, Astrand(ergometer), Persantine (pharmacological)
	Custom	Unlimited custom protocols can be created
Patient Module		AHA 10-electrode with pinch or snap connectors IEC 10-electrode with pinch or snap connectors

Table 3.4. Measuring Instruments

Instrument	Model Name	Purpose
Gas Analyzer	TrueOne 2400, PARVO MEDICS	To analyze respiratory gas during exercise
Treadmill	TM55 Q-stress, QUINTON	To measure ecg raw signal and Blood Pressure, and to control exercise load
Automatic Measurer of Height and Weight	DS-102, D.S. JENIX	To measure heights and weights
Measurer of Body Fat	BoCA X2, MEDIGATE	To measure BMI

Figure 3.1. Experimental environment

Submaximal exercise test

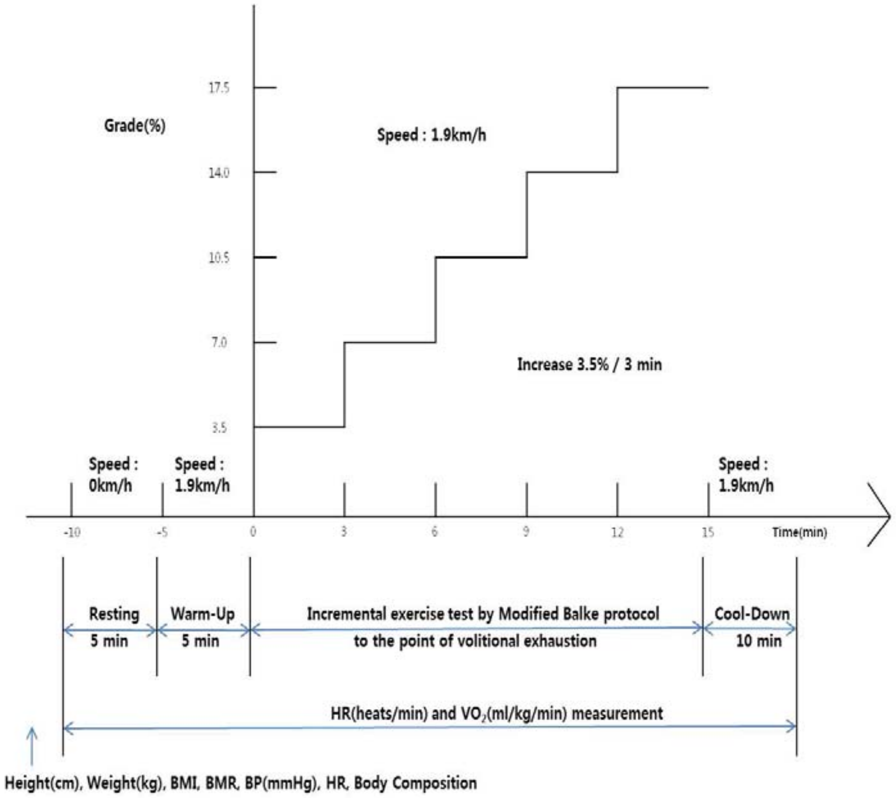


Figure 3.2. Exercise testing procedure

Each subject performed an incremental exercise test to exhaustion on a motor-driven treadmill (TM55, Quinton, USA) to determine maximal oxygen consumption (VO_2max). During exercise testing, heart rate was monitored using a TM55 treadmill.

Each subject was performed a exercise testing consisting of four stages corresponding to resting for 5 minutes, warm-up for 5 minutes, a incremental exercise and cool-down for 10 minutes(Figure 3.2). In all stages, HR and Metabolic gas data were continuously recorded. In resting stage, subjects sit down on a chair for 5 minutes. In warm-up stage, subjects walked on a treadmill for 5 minutes at 1.9km/h speed while maintaining a comfortable pace. In a incremental exercise stage, each subject was performed a GXT according to the Modified Balke protocol (see Table 3.5). With this protocol, the treadmill speed was remained constant during the remaining stages of the exercise test as the grade was increased 3.5% every 3 minute. Protocol was continued until at least two of the test termination criteria were met. Finally, in cool-down stage, subjects walked at a 1.9km/h speed without grade for 10 minutes.

Table 3.5. Modified Balke protocol

Stage	Duration(min)	Speed(*km/h*)mph	Grade(%)
Rest	-	2.0	0
1	3	2.0	3.5
2	3	2.0	7.0
3	3	2.0	10.5
4	3	2.0	14.0
5	3	2.0	17.5
6	3	2.0	21.0

During the submaximal GXT, metabolic gases were collected using a TrueOne® 2400 metabolic measurement system.

Subjects' HR, VO_2, and respiratory exchange ratio (RER) was averaged and analyzed by the computer every 15 seconds. Maximal HR was defined as the highest single HR value recorded during the GXT and VO_2max was defined as the highest 15-s averageVO_2 value during the final minutes of the GXT. To be considered a valid maximal test, at least two of the following three criteria were met [1] [55]:

1. no further increase in HR despite an increase in workload or a maximal HR that is no less than 15 beats below age-predicted maximal HR
2. Respiratory exchange ratio (RER) equal to or greater than 1.10.
3. No increase in VO_2 with an increase in work load.
4. Physical signs of fatigue or volitional termination of the exercise test despite verbal encouragement
5. RPE >17 as one of the subjective indicators of maximal effort
   (RPE: rating of perceived exertion)

Exclusion criteria include any known conditions that may reduce the participants' tolerance to exercise or increase the risk of untoward cardiovascular, pulmonary, or metabolic events during the maximal graded exercised test. Subjects who fail to meet at least two of these criteria will be dropped from the study.

3.3 Algorithm for Ventilatory-threshold (VT) determination in real-time

Figure 3.3 shows the flowchart of the proposed algorithm for VT determination in real-time.

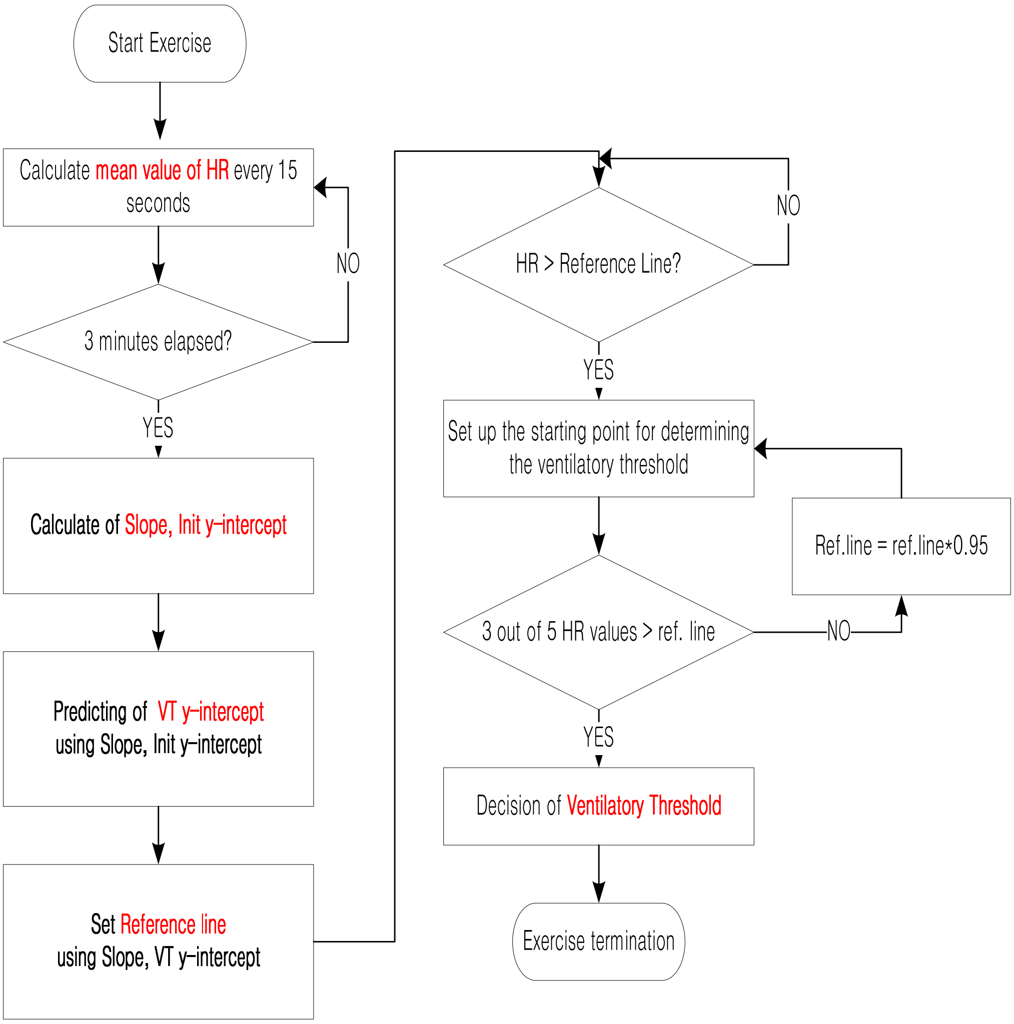


Figure 3.3. Flowchart of the proposed algorithm for VT determination

The proposed Algorithm consists of three parts: 1) Setting Initial straight line; 2) Setting reference line; 3) VT determination

(Step 1) Setting Initial straight line

(1.1)The heart rate (HR) data for each test were averaged at 15-second intervals, the HR vs time relationship was displayed graphically.

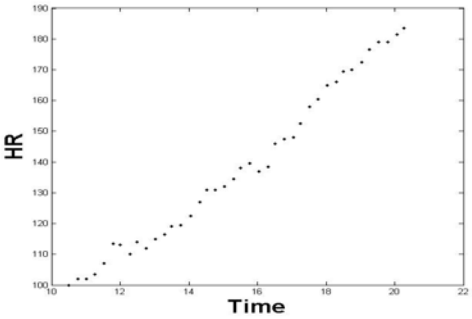


Figure 3.4. HR vs Time plot

(1.2) During initial three minutes, slope of HR variation every 15-second intervals was calculated. And then, mean of HR slope was calculated.

(1.3) Slope was calculated.

$$Slope = \frac{HR_{mean} - HR_{\min}}{\Delta Time}$$

where ΔTime = 3 minutes ;

(1.4) Init y-intercept was calculated.

$$Y_{init} = HR_{\min} - slope \times Time$$

where Time = time at HRmin

(1.5) Initial line is generated using mean of slope and init y-intercept (see Figure 3. 5)

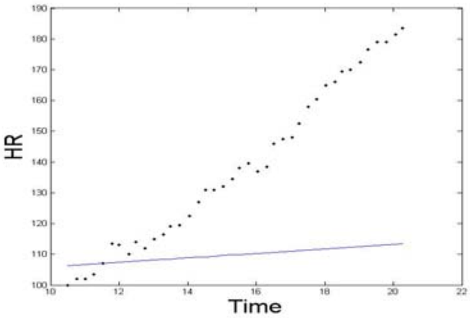


Figure 3.5. HR vs Time plot with initial line (black line)

(Step 2) Setting reference line

(2.1) Predicting VT y-intercept

Hierarchical multiple regression analysis was used to determine the statistical strength and contribution of possible independent variables(i.e., variables relevant to VT and variables of subject's physiological characteristics) in the prediction of VT y-intercept. Regression model summary and coefficients were presented in next section (3.4). Regression equation for VT y-intercept in both males and females was presented as following:

In case of males

$$\begin{aligned} VT_{\text{y-intercept}} &= 74.463 + 0.771 \times age - 6.239 \times slope \\ &\quad + 0.771 \times Initial_{\text{y-intercept}} - 3.856 \times smoking \end{aligned}$$

In case of females

$$\begin{aligned} VT_{\text{y-intercept}} &= 64.313 - 0.434 \times age \\ &\quad - 4.270 \times slope + 0.872 \times Initial_{\text{y-intercept}} \end{aligned}$$

(2.2) Reference line is generated using slope and VT y-intercept (see Figure 3.6)

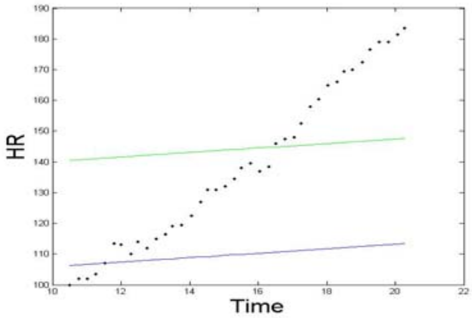


Figure 3.6. HR vs Time graph with reference line (green line)

(Step 3) VT determination

IF HR, which was averaged at 15-second intervals, is larger than reference line, the point was became a one of candidates of VT. After candidate of VT was determined, it was investigated whether following HR is larger than reference line. If three HR out of following five HR are larger than reference line, the candidate was determined as VT. Figure 3.7 shows VT determined by the proposed algorithm

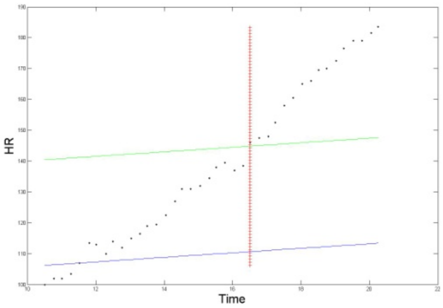


Figure 3.7. HR vs Time graph with VT determination (red line)

3.4 Regression model for VT y-intercept

3.4.1 Reference line in male

Pearson correlations between subject's physiological variables and VT y-intercept was presented in Table 3.6

Table 3.6. Pearson's correlations between physiological variables and VT_I in males (N=80)

		VT_I
slope	Pearson Correlation	-.793 **
	sig. (2-tailed)	.000
initial y-intercept	Pearson Correlation	.886 **
	sig. (2-tailed)N	.000
age	Pearson Correlation	-.176
	sig. (2-tailed)N	.128
height	Pearson Correlation	-.056
	sig. (2-tailed)N	.629
weight	Pearson Correlation	-.008
	sig. (2-tailed)N	.945
BMI	Pearson Correlation	.016
	sig. (2-tailed)N	.891
BMR	Pearson Correlation	.055
	sig. (2-tailed)N	.636
smoking	Pearson Correlation	-.021
	sig. (2-tailed)N	.860
drinking	Pearson Correlation	-.119
	sig. (2-tailed)N	.306

VT_I = Intercept at ventilatory-threshold y determined by metabolic gas analyzer

**p<0.01

Regression model summary and coefficients for VT_I in males were presented in Table 3.7 and Table 3.8, respectively.

Table 3.7. Summary of regression model of VT y-intercept in males

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
	.923^{d}	.852	.844	8.88858	1.961

Dependent Variable: VT_I

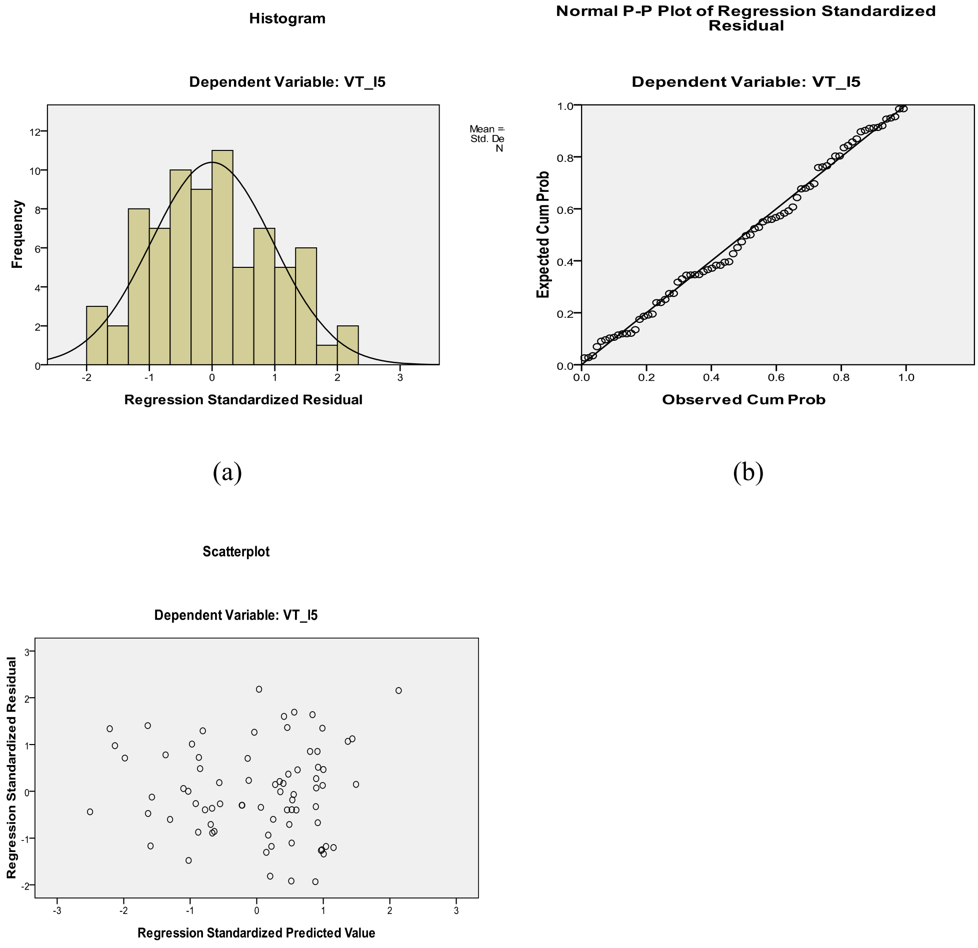
Table 3.8. Coefficients of regression model of VT y-intercept in males

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
(Constant)	74.463	11.074		6.724	.000	52.381	96.544		
Min_I	.771	.094	.661	8.199	.000	.583	.958	.320	3.130
Age	-.467	.107	-.204	-4.380	.000	-.679	-.254	.955	1.047
Slope	-6.239	1.772	-.288	-3.522	.001	-9.772	-2.707	.312	3.206
smoking	-3.856	1.901	-.094	-2.029	.046	-7.646	-.067	.960	1.041

Dependent Variable: VT_I

The multiple regression model was generated in this study predicts VT_I accurately (r = 0.923; R^2 = 0.852; adjusted R^2 = 0.844; SEE = 8.89 mL·kg-¹·min-¹) in this sample of male (N=80). Multiple linear regression generated the following VT y-intercept prediction equation

$$\begin{aligned} VT_{\text{y-intercept}} &= 74.463 + 0.771 \times age - 6.239 \times slope \\ &\quad + 0.771 \times Initial_{\text{y-intercept}} - 3.856 \times smoking \end{aligned}$$



(a)

(b)

(c)

Figure 3.8. Results of residual analyses of VT y-intercept in males (N=80): (a) Histogram, (b) Normal probability plot and (c) scatterplot of regression model

3.4.2 Reference line in female

Pearson's correlations between subject's physiological variables and VT y-intercept are presented in Table 3.9.

Table 3.9. Pearson's correlations between physiological variables and VT_I in female (N=28)

		VT_I
slope	Pearson Correlation	-.557 **
	sig. (2-tailed)	.002
initial y-intercept	Pearson Correlation	.893 **
	sig. (2-tailed)	.000
age	Pearson Correlation	-.348
	sig. (2-tailed)	.075
height	Pearson Correlation	.233
	sig. (2-tailed)	.242
weight	Pearson Correlation	-.169
	sig. (2-tailed)	.398
BMI	Pearson Correlation	-.313
	sig. (2-tailed)	.112
BMR	Pearson Correlation	.057
	sig. (2-tailed)	.777
smoking	Pearson Correlation	-.112
	sig. (2-tailed)	.577
drinking	Pearson Correlation	.055
	sig. (2-tailed)	.785

VT_I = Intercept at ventilatory-threshold y determined by metabolic gas analyzer

**$p<0.01$

Regression model summary and coefficients for VT_I in females were presented in Table 3.10 and Table 3.11, respectively.

Table 3.10. Summary of regression model of VT y-intercept in females

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
	.888[b]	.789	.761	9.61810	2.617

Dependent Variable: VT_I

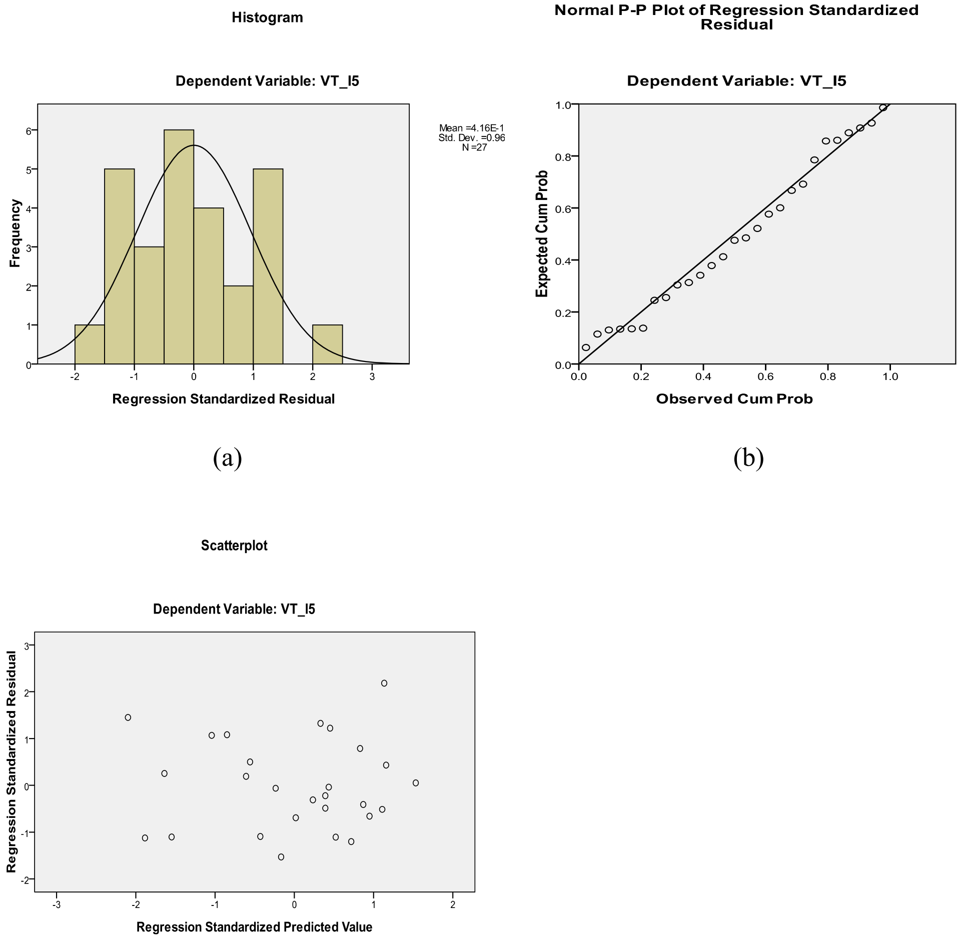
Table 3.11. Coefficients of regression model of VT y-intercept in females

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
(Constant)	64.313	18.278		3.519	.002	26.503	102.123		
Slope5	-4.270	2.488	-.185	-1.716	.100	-9.417	.878	.789	1.268
Min_I5	.872	.143	.685	6.077	.000	.575	1.168	.722	1.385
age	-.434	.186	-.236	-2.333	.029	-.819	-.049	.900	1.112

a. Dependent Variable: VT_I5

The multiple regression model was generated in this study predicts VT_I accurately (r = .888; R^2 = .789; adjusted R^2 = .761; SEE = 9.91 mL·kg-^{1}·min-^{1}) in this sample of female (N=28). Multiple linear regression generated the following VT y-intercept prediction equation

$$\begin{aligned} VT_{\text{y-intercept}} &= 64.313 - 0.434 \times age \\ &\quad -4.270 \times slope + 0.872 \times Initial_{\text{y-intercept}} \end{aligned}$$



(a)

(b)

(c)

Figure 3.9. Results of residual analyses of VT y-intercept in females (N=28): (a) Histogram, (b) Normal probability plot and (c) scatterplot of regression model

3.5 VO_2 (ml/kg/min) Regression using HR

In this section, Regression model for VO_2 is demonstrated. This regression model will be used for prediction of VO_2max in chapter 4.

3.5.1 VO2 regression using HR in male

Results of multiple linear regression for VO_2 in males were presented in Table 3.12 and Table 3.13. HR and time data were used as Independent variables.

Table 3.12. Summary of regression model of VO_2 in males

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
	.910	.829	.829	2.40181	0.673

Predictors: HR, time

Dependent Variable: vo_2.kg

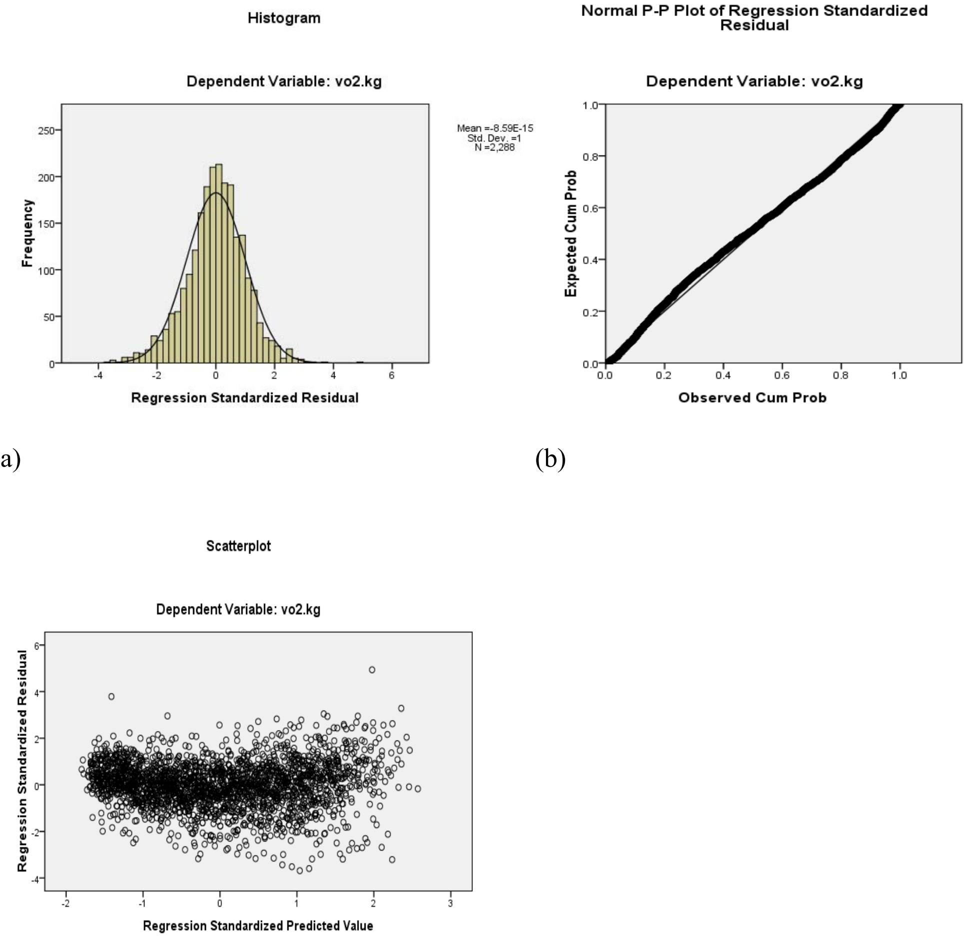
Table 3.13. Coefficients of regression model of VO_2 in males

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
(Constant)	4.385	.374		11.715	.000	3.651	5.119		
HR	.031	.004	.095	7.882	.000	.023	.039	.517	1.932
time	2.236	.032	.842	70.023	.000	2.173	2.299	.517	1.932

Dependent Variable: vo_2.kg

$$VO_2 (ml/kg/\min) =$$
$$4.385 + 0.031 \times HR + 2.236 \times time$$

where HR(bests/min), and time(min)



(a)

(b)

(c)

Figure 3.10. Results of residual analyses of VO_2 in males (N=80): (a) Histogram , (b) Normal probability plot and (c) scatterplot of regression model

3.5.2 VO_2 regression using HR in female

Results of multiple linear regression for VO_2 in females were presented in Table 3.14 and Table 3.15. HR and time data were used as Independent variables.

Table 3.14. Summary of regression model of VO_2 in females

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
	.747[b]	.558	.556	3.75348

Predictors: (Constant), HR, time

Dependent Variable: VO_2.kg

Table 3.15. Coefficients of regression model of VO_2 in females

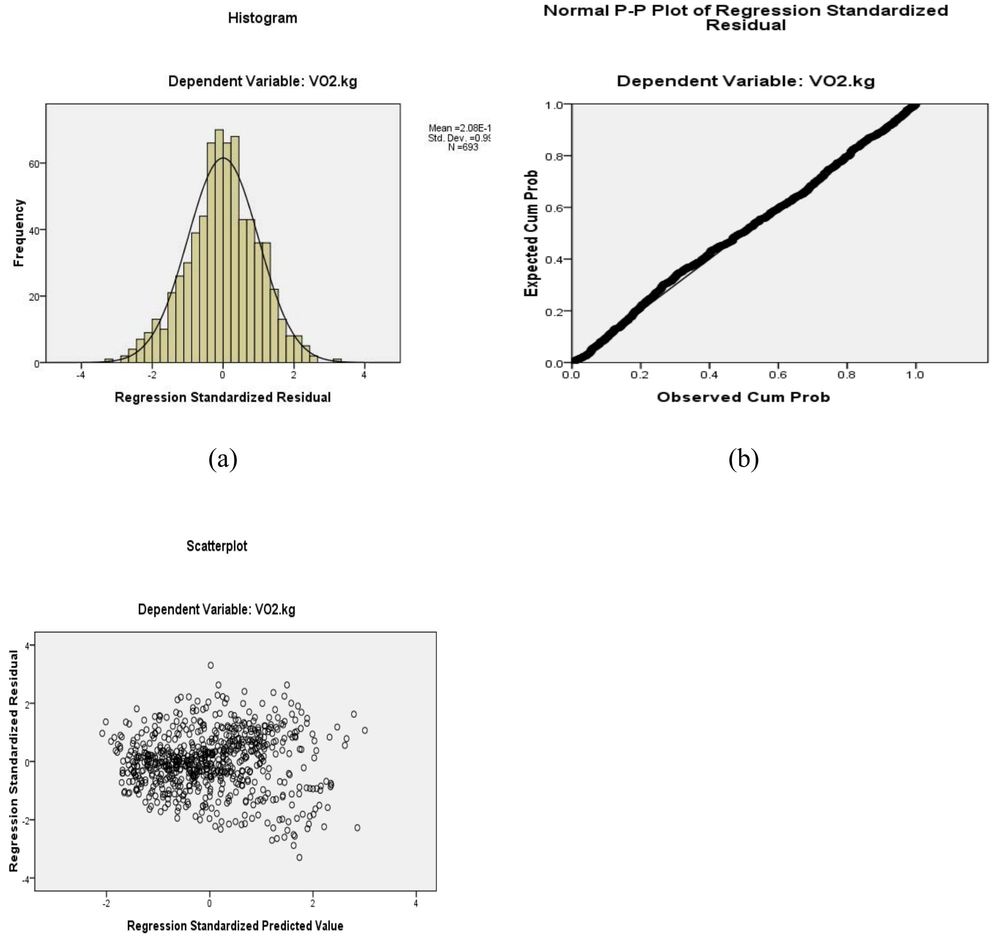
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
(Constant)	-3.379	.724		-4.665	.000	-4.802	-1.957		
HR	.122	.007	.498	17.564	.000	.109	.136	.798	1.253
time	1.008	.076	.376	13.277	.000	.859	1.158	.798	1.253

Dependent Variable: VO_2.kg

$$VO_2(ml/kg/\min) =$$

$$-3.379 + 0.112 \times HR + 1.008 \times time$$

where HR(bests/min), and time(min)



(a) (b)

(c)

Figure 3.11. Results of residual analyses of VO_2 in females (N=28): (a) Histogram , (b)Normal probability plot and (c)scatterplot of regression model

3.6 Statistical analyses

All of the analyses were performed using the SPSS 15.0 for Windows (SPSS, Inc., Chicago, Illinois, USA) and Medcalc 11.0.0.0 (Mariakerke, Belgium). Descriptive statistics were calculated for all data and were expressed as a mean value ±SD. All measured physiological variables were tested for normality and associations between selected variables. Kolmogorov-Smirnova and Shapiro-Wilk test was used to test normality. The paired T-tests Test and Wilcoxon Signed Ranks Test analyses were used to discern any significant difference between measured VT by metabolic equipment and estimated VT by proposed approach. The Pearson product moment correlation coefficient(r) used to assess relationships between measured VT and estimated VT. Bland-Altman plot was also used to assess the agreement between two methods [56].

The Pearson product moment correlation coefficient (r) and a Hierarchical multiple regression analysis was used to determine the statistical strength and contribution of possible independent variables(i.e., age, gender, height, body mass, body mass index (BMI), HR, obesity, SBP, HR, VO_2, exercise time) in the prediction of VO_2max (ml/kg/min). Multicollinearity was examined using variance inflation factor (VIF). To check independence, normality, equal variance and linearity of regression model used residual analyses. To assess the predictive accuracy of the regression equation, coefficient of determination (R^2), adjusted R^2 and standard error of estimates (SEE) values were presented. Bland-Altman plot was also used to assess the agreement between measured and estimated VO2max (ml/kg/min). P values smaller than 0.05 were considered statistically significant.

Chapter 4 RESULTS

In this chapter, it is presented as following:

1) verification of Ventilatory-threshold(VT) detection using proposed algorithm, which use a slope of HR variation during initial 3 minutes

2) development of VO_2max prediction equation based on both VT measured by gas analyzer and VT estimated by regression model

3) verification of predicting VO_2max based on VT estimated in real-time

For verification of VT determination, it was used statistical methods such as correlation analyses, paired T-test, and Bland-Altman plot. For verification of VO_2max estimation model, it was presented value of r, R^2, adj R^2 and SEE and correlation plot and Bland-Altman plot between measured and estimated VO_2max

4.1 Verification of Determination of the Ventilatory-threshold (VT)

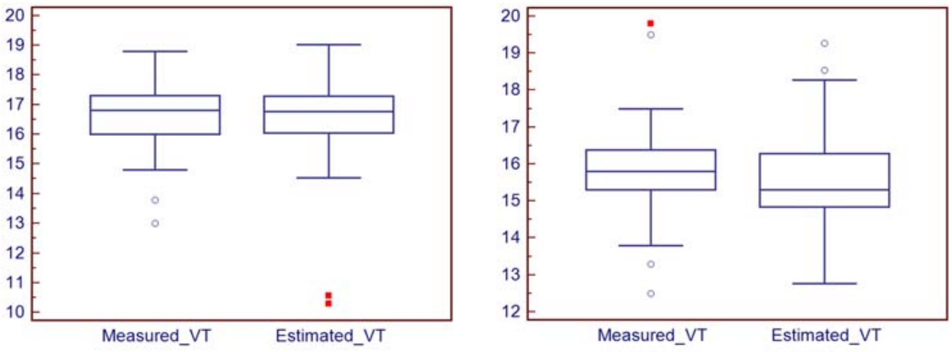
Description of measured VT from gas analyzer using V-slope method and estimated VT from proposed approach are presented in Table 4.1. Correlation and difference between measured and estimated VT were investigated.

Table 4.1. Description of measured VT and estimated VT (min)

	Measured VT	Estimated VT	Difference	r
Male(n=80)	16.6882 ± 1.0502	16.7378 ± 0.9266	0.04964 ± 1.0678	0.42***
Female(n=28)	15.8074 ± 1.5716	15.7331 ± 1.4859	0.07426 ± 1.2549	0.66***

***p<0.001; Data are presented as mean±SD; r = correlation coefficient between measured and estimated VT

Estimated VT was overestimated as compared with measured VT in male and was underestimated in female. There was significant Correlation between measured and estimated VT in both male and female (r=0.42, P<0.001; r=0.66, P<0.001, respectively). Figure 4.1 shows comparison of values between measured and estimated VT.



(a) male (N=80) (b) female (N=28)

Figure 4.1. Measured and estimated VT (min) in (a) male and (b) female

Results of the paired samples t-test and the wilcoxon signed ranks in males were presented in Table 4.2 and Table 4.3, respectively. Results indicate no significant difference between measured and estimated VT in males (p>0.05).

Table 4.2. Paired Samples Test results between measured and estimated VT in males (N=80)

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Estimated VT - Measured VT	.04964	1.06775	.12248	-.19435	.29364	.405	75	.686

SEE = Standard error of estimate;

Table 4.3. Wilcoxon Signed Ranks Test results between measured and estimated VT in males (N=80)

	Measured VT - Estimated VT
Z	-.544[a]
Asymp. Sig. (2-tailed)	.587

Results of the paired samples t-test and the wilcoxon signed ranks in females were presented in Table 4.4 and Table 4.5, respectively. Results indicate no significant difference between measured and estimated VT in females (p>0.05).

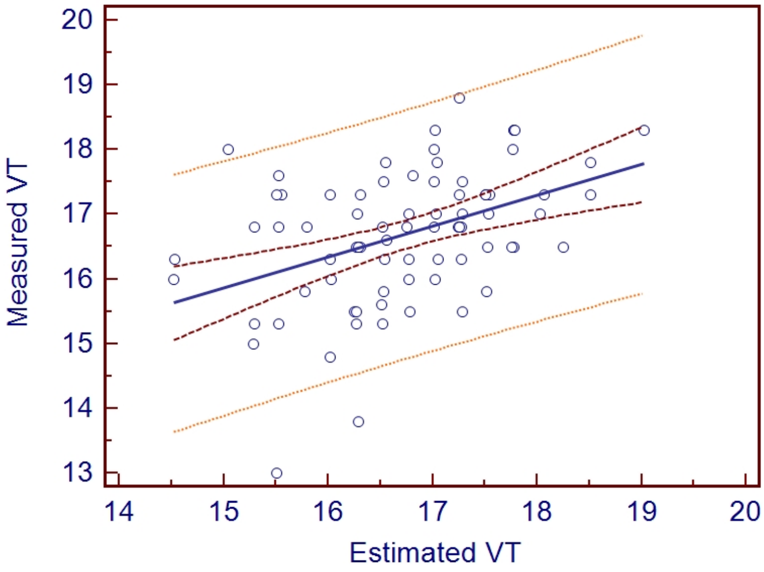
Table 4.4. Paired Samples Test results between measured and estimated VT in females (N=28)

	Paired Differences							
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
				Lower	Upper			
Measured_VT - Estimated_VT	.07426	1.25487	.24150	-.42215	.57067	.307	26	.761

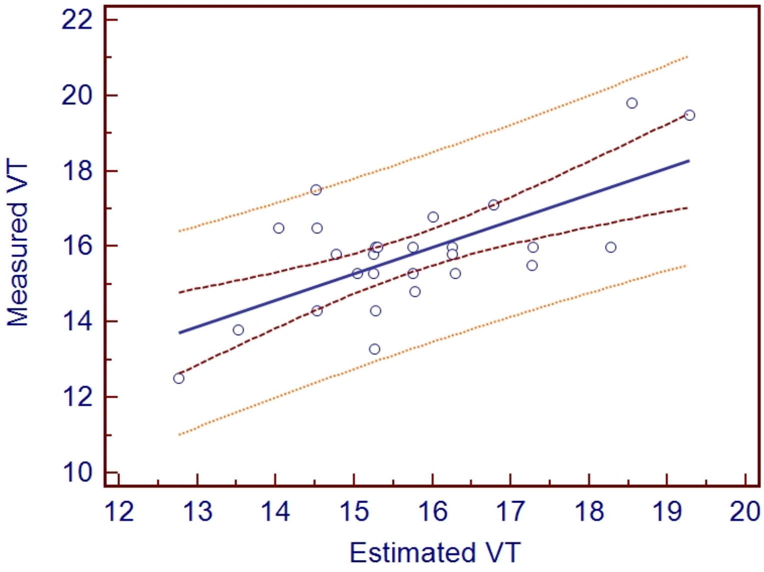
Table 4.5. Wilcoxon Signed Ranks Test results between measured and estimated VT in females (N=28)

	Estimated VT - Measured VT
Z	-.288[a]
Asymp. Sig. (2-tailed)	.773

Figure 4.2 shows a relationship between measured and estimated VT (min). Pearson product-moment correlation coefficients (r) demonstrate positively significant relationships between measured and estimated time at VT in both (a) males (N=80, r = 0.42, p< 0.001) and (b) females (N=28, r = 0.66, p< 0.001). Outside line indicate 95% prediction interval for prediction model. Figure 4.3 shows Bland-Altman plot with estimated mean bias and 95% limits of agreement for difference in time at VT between measured and estimated VT, as plotted against the mean value.

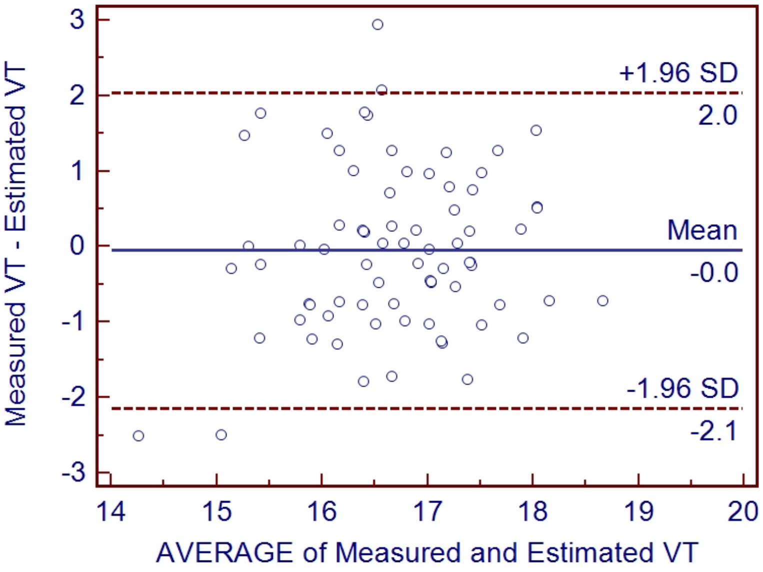


(a) male (N=80)

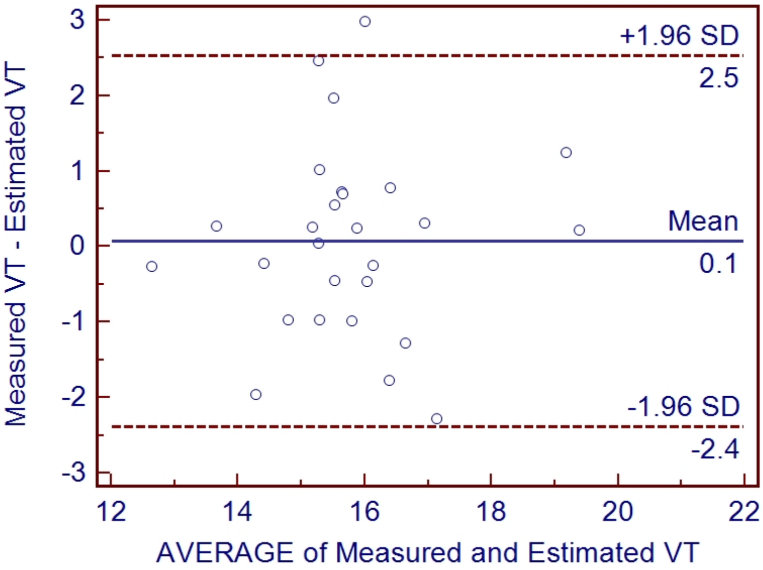


(b) female (N=28)

Figure 4.2. Scatter plot graphs of relationship between measured and estimated VT (min) with 95% prediction interval line(orange) and 95% confidence interval line (brown) in (a) male and (b) female



(a) male (N=80)



(b) female (N=28)

Figure 4.3. Bland-Altman plot with estimated mean bias and 95% limits of agreement for difference between measured and estimated VT (min), plotted against the mean in (a) male and (b) female.

4.2 VO_2max prediction equation based on VT measured by gas analyzer

In chapter 3, we developed regression equation for VO_2 (ml/kg/min) using HR. All variable relevant to VO_2 are used values transformed from regression equation using HR.

4.2.1 VO_2max prediction equation based on VT measured by gas analyzer in males (N=80)

The relationships between variables relevant to VT and VO_2max in males were presented in Table 4.6. Time variation from exercise start to VT ($r=0.565$, $p<0.01$), HR variation from exercise start to VT($r=0.332$, $p<0.01$), VO_2 at rest($r=0.450$, $p<0.01$), VO_2 variation from exercise start to VT ($r=0.751$, $p<0.01$), Slope of VO_2 vs time from exercise start to VT($r=0.534$, $p<0.01$), VO_2 at VT($r=0.375$, $p<0.01$), and Time at VT($r=0.495$, $p<0.01$) among variables relevant to VT were significantly related to VO_2max. Age, weight, BMI, BMR, waist($r=-0.303$, $p<0.01$; $r=-0.429$, $p<0.01$; $r=-0.422$, $p<0.01$; $r=-0.411$, $p<0.01$; $r=-0.429$, $p<0.01$, respectively), obesity, percent bodyfat, bodyfat mass, Percent abdominal Fat(%)($r = -0.413$, $p<0.01$; $r = -0.441$, $p<0.01$; $r = -0.490$, $p<0.01$; $r = -0.425$, $p<0.01$, respectively), SBP and DBP($r = -0.267$, $p<0.05$; $r = -0.321$, $p<0.01$, respectively) among variables of subject's physiological characteristics were significantly related to VO_2max. HRmax and HR reserve (HRR) ($r=0.303$, $p<0.01$; $r=0.369$, $p<0.01$, respectively) among variables relevant to calculated HRmax (i.e., estimated HRmax = 220-age) were significantly related to VO_2max.

Table 4.6. Correlation between variables relevant to VT and VO_2max (ml/kg/min) in males (N=80)

		VO2max
HR at VT	Pearson Correlation	.140
	Sig. (2-tailed)	.217
time variation from exercise start to VT	Pearson Correlation	.565**
	Sig. (2-tailed)	.000
HR at resting	Pearson Correlation	-.186
	Sig. (2-tailed)	.099
HR variation from exercise start to VT	Pearson Correlation	.332**
	Sig. (2-tailed)	.003
VO_2 at rest	Pearson Correlation	.450**
	Sig. (2-tailed)	.000
VO_2 variation from exercise start to VT	Pearson Correlation	.751**
	Sig. (2-tailed)	.000
Slope of VO_2 vs time from exercise start to VT	Pearson Correlation	.534**
	Sig. (2-tailed)	.000
Slope of HR vs time from exercise start to VT	Pearson Correlation	-.043
	Sig. (2-tailed)	.707
VO_2 at VT	Pearson Correlation	.375**
	Sig. (2-tailed)	.001
Time at VT	Pearson Correlation	.495**
	Sig. (2-tailed)	.000
HRmax (beats/min)	Pearson Correlation	.303**
	Sig. (2-tailed)	.006

HRR (beats/min)	Pearson Correlation	.369**
	Sig. (2-tailed)	.001
Percent HRR(%)	Pearson Correlation	.156
	Sig. (2-tailed)	.167
percent HR at VT(%)	Pearson Correlation	-.010
	Sig. (2-tailed)	.931
Age(yr)	Pearson Correlation	-.303**
	Sig. (2-tailed)	.006
Height(cm)	Pearson Correlation	-.167
	Sig. (2-tailed)	.140
Weight(kg)	Pearson Correlation	-.429**
	Sig. (2-tailed)	.000
BMI(kg/cm^2)	Pearson Correlation	-.422**
	Sig. (2-tailed)	.000
BMR	Pearson Correlation	-.411**
	Sig. (2-tailed)	.000
Waist(cm)	Pearson Correlation	-.429**
	Sig. (2-tailed)	.000
Obesity	Pearson Correlation	-.413**
	Sig. (2-tailed)	.000
Percent Bodyfat (%)	Pearson Correlation	-.441**
	Sig. (2-tailed)	.000
Bodyfat mass(kg)	Pearson Correlation	-.490**
	Sig. (2-tailed)	.000
Percent abdominal Fat (%)	Pearson Correlation	-.425**

	Sig. (2-tailed)	.000
SBP(mmHg)	Pearson Correlation	-.267[*]
	Sig. (2-tailed)	.017
DBP(mmHg)	Pearson Correlation	-.321[**]
	Sig. (2-tailed)	.004
Smoking	Pearson Correlation	-.134
	Sig. (2-tailed)	.235
Drinking	Pearson Correlation	-.169
	Sig. (2-tailed)	.135

[**]P<0.01; [*]P<0.05

Hierarchical multiple regression analysis was used to determine the statistical strength and contribution of possible independent variables(i.e., variables relevant to VT, variables of subject's physiological characteristics, and variables relevant to age predicted maximum HR) in the prediction of VO_2max (ml/kg/min). Regression model summary and coefficients were presented in Table 4.7 and Table 4.8, respectively.

Table 4.7. Summary of regression model of VO_2max in males

R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
.853	.727	.700	3.45714	2.451

Table 4.8. Coefficients of regression model of VO_2max in males

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
(Constant)	32.222	11.531		2.794	.007	9.234	55.209		
bodyfat_mass	-.421	.207	-.362	-2.037	.045	-.833	-.009	.120	8.300
age	-.168	.052	-.264	-3.222	.002	-.272	-.064	.565	1.770
obesity	.155	.088	.307	1.759	.083	-.021	.331	.125	8.014
var.VO2.kg.rest.VT	1.489	.220	.846	6.760	.000	1.050	1.929	.242	4.126
VO2.kg.rest	1.729	.481	.248	3.596	.001	.770	2.687	.795	1.258
Time.VT	-1.576	.693	-.258	-2.274	.026	-2.957	-.194	.295	3.393
HR.VT	-.075	.034	-.167	-2.191	.032	-.143	-.007	.656	1.525

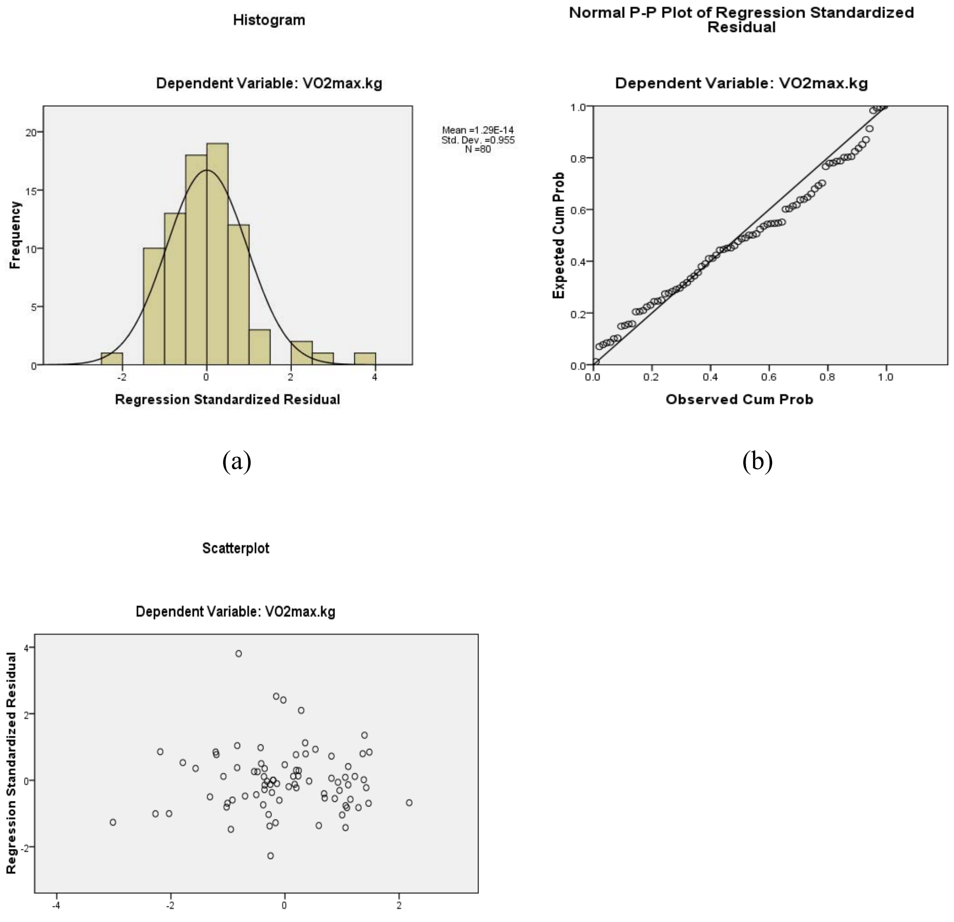
Dependent Variable: VO2max

Multiple linear regression generated the following regression equation ($r = 0.853$, $R^2 = 0.727$, adj $R^2 = 0.700$, SEE = 3.45 ml·kg^{-1}·min^{-1}) in males (N=80).

$$\begin{aligned} VO_2\max(ml/kg/\min) = {} & 32.222 - 0.421 \times bodyfat\_mass - 0.168 \times age \\ & +0.155 \times obesity + 1.489 \times \mathrm{var}.VO_2 + 1.729 \times VO_2.rest \\ & -1.576 \times time.VT - 0.075 \times HR.VT \end{aligned}$$

where var.VO_2(ml/kg/min) = difference of VO_2 value from exercise start to VT level, VO_2.rest(ml/kg/min) = VO_2 value at resting, time.VT(min) = time at vt level, and HR.VT(bests/min) = Heart Rate at vt level.

Each predictor variable was significant ($p < 0.05$) in predicting VO_2max and the resulting regression equation accounted for 72.7% of the shared variance of measured VO_2max. Standardized β-weights showed the variable (i.e., VO_2 variation from exercise start to VT) (0.846) to be the most effective at predicting VO_2max. To assess independence, normality, equal variance and linearity of regression model used residual analyses. Figure 4.4 shows results of residual analyses of regression model.



(a) (b)

(c)

Figure 4.4. Results of residual analyses of VO_2max in males (N=80): (a) Histogram , (b)Normal probability plot and (c) scatterplot of regression model

4.2.2 VO_2max prediction equation based on VT measured by gas analyzer in females (N=28)

The relationships between variables relevant to VT and VO_2max in females were presented in Table 4.9. HR.VT(r=0.411, $p<0.05$), Time variation from exercise start to VT (r=0.542, $p<0.01$), HR variation from exercise start to VT(r=0.564, $p<0.01$), VO_2 at rest(r=0.515, $p<0.01$), VO_2 variation from exercise start to VT (r=0.831, $p<0.01$), and VO_2 at VT(r=0.872, $p<0.01$) among variables relevant to VT were significantly related to VO_2max. Age(r=-0.486, $p<0.01$) and percent bodyfat, (r = -0.435, $p<0.05$) among variables of subject's physiological characteristics were significantly related to VO_2max. HRmax(r=0.486, $p<0.01$) among variables relevant to calculated HRmax (i.e., estimated HRmax = 220-age) was significantly related to VO_2max.

Table 4.9. Correlation between variables relevant to VT and VO_2max(ml/kg/min) in females (N=28)

		VO2max
HR at VT	Pearson Correlation	.411*
	Sig. (2-tailed)	.030
Time variation from exercise start to VT	Pearson Correlation	.542**
	Sig. (2-tailed)	.003
HR at resting	Pearson Correlation	.152
	Sig. (2-tailed)	.441
HR variation from exercise start to VT	Pearson Correlation	.564**
	Sig. (2-tailed)	.002
VO_2 at resting	Pearson Correlation	.515**
	Sig. (2-tailed)	.005

VO_2 variation from exercise start to VT	Pearson Correlation	.831**
	Sig. (2-tailed)	.000
Slope of VO_2 vs time from exercise start to VT	Pearson Correlation	.238
	Sig. (2-tailed)	.223
Slope of HR vs time from exercise start to VT	Pearson Correlation	-.104
	Sig. (2-tailed)	.598
VO_2 at VT	Pearson Correlation	.872**
	Sig. (2-tailed)	.000
Time at VT	Pearson Correlation	.223
	Sig. (2-tailed)	.254
HRmax (beats/min)	Pearson Correlation	.486**
	Sig. (2-tailed)	.009
HRR (beats/min)	Pearson Correlation	.245
	Sig. (2-tailed)	.209
Percent HRR (%)	Pearson Correlation	.268
	Sig. (2-tailed)	.168
Percent HR at VT (%)	Pearson Correlation	.193
	Sig. (2-tailed)	.325
Age (yr)	Pearson Correlation	-.486**
	Sig. (2-tailed)	.009
Height (cm)	Pearson Correlation	.185
	Sig. (2-tailed)	.347
Weight (kg)	Pearson Correlation	-.090
	Sig. (2-tailed)	.650
BMI	Pearson Correlation	-.214

	Sig. (2-tailed)	.274
BMR	Pearson Correlation	.036
	Sig. (2-tailed)	.857
Waist (cm)	Pearson Correlation	-.169
	Sig. (2-tailed)	.390
Obesity	Pearson Correlation	-.279
	Sig. (2-tailed)	.150
Percent Bodyfat (%)	Pearson Correlation	-.435*
	Sig. (2-tailed)	.021
Bodyfat mass (kg)	Pearson Correlation	-.326
	Sig. (2-tailed)	.091
Percent abdominal Fat (%)	Pearson Correlation	-.195
	Sig. (2-tailed)	.320
SBP (mmHg)	Pearson Correlation	-.370
	Sig. (2-tailed)	.053
DBP (mmHg)	Pearson Correlation	-.128
	Sig. (2-tailed)	.517
Smoking	Pearson Correlation	-.153
	Sig. (2-tailed)	.438
drinking	Pearson Correlation	.063
	Sig. (2-tailed)	.751

*P<0.05; **P<0.01

Hierarchical multiple regression analysis was used to determine the statistical strength and contribution of possible independent variables(i.e., variables relevant to VT, variables of subject's physiological characteristics, and variables relevant to age predicted maximum HR) in the prediction of VO_2max (ml/kg/min). Regression model summary and coefficients were presented in Table 4.10 and Table 4.11, respectively.

Table 4.10. Summary of regression model of VO_2max in females

R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
.890	.792	.766	2.58861	2.389

Table 4.11. Coefficients of regression model of VO_2max in females

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
(Constant)	20.274	6.982		2.904	.008	5.865	34.684		
age	-.073	.052	-.144	-1.392	.177	-.181	.035	.810	1.234
SBP	-.053	.039	-.133	-1.363	.185	-.133	.027	.909	1.100
vo2.kg.VT	.957	.134	.771	7.134	.000	.680	1.233	.744	1.345

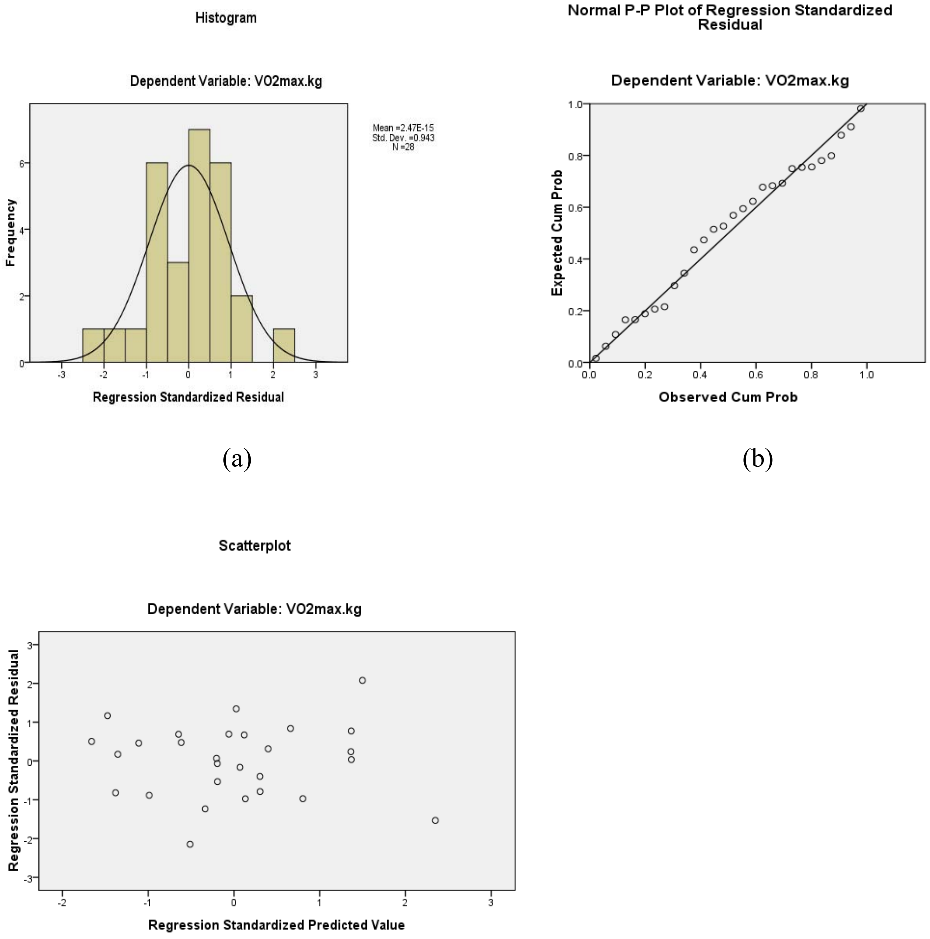
Dependent Variable: VO_2max.kg

Multiple linear regression generated the following regression equation (r = 0.890, R^2 = 0.792, adj R^2 = 0.766, SEE = 2.58 ml·kg-¹·min-¹) in females (N=28).

$$VO_2\max(ml/kg/\min) = \\ 20.247 - 0.073 \times age - 0.053 \times SBP + 0.957 \times VO_2.VT$$

where SBP(mmHg) = systolic Blood Pressure, and VO_2.VT(ml/kg/min) = VO_2 value at VT level

The resulting regression equation accounted for 79.2% of the shared variance of measured VO_2max. Standardized β-weights showed the variable (i.e., VO_2 value at VT) (0.771) to be the most effective at predicting VO_2max. To assess independence, normality, equal variance and linearity of regression model used residual analyses. Figure 4.5 shows results of residual analyses of regression model.



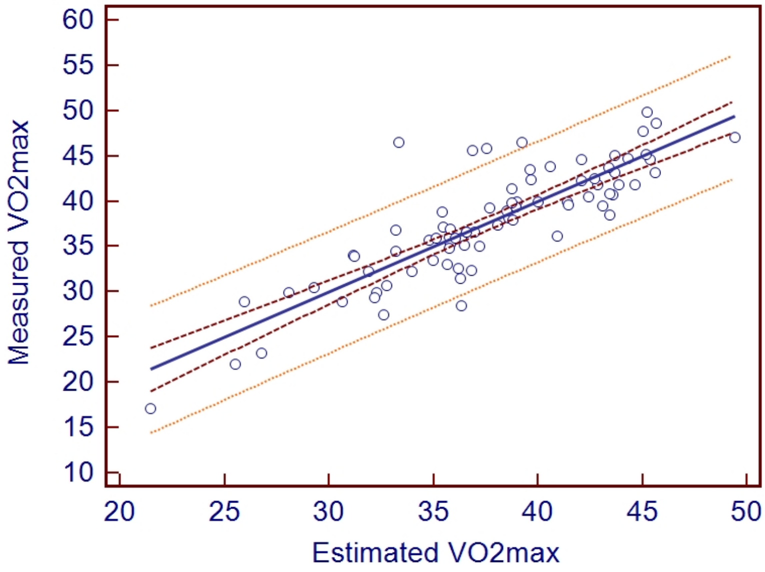
(a) (b)

(c)

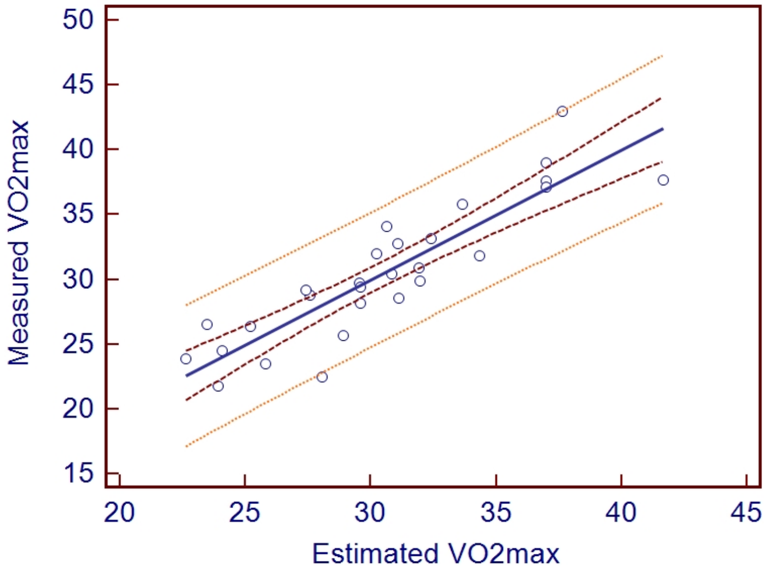
Figure 4.5. Results of residual analyses of VO_2max in females (N=28): (a) Histogram, (b) Normal probability plot and (c) scatterplot of regression model

4.2.3 Verification of VO_2max prediction equation based on VT measured by gas analyzer

For the verification of VO_2max prediction equation, Scatter plot graphs and Bland-Altman plot were presented. Figure 4.6 demonstrated positively significant relationships between measured and estimated VO_2max in both (a) males (N=80, r = 0.85, p< 0.001, 95% confidence interval for r =0.77 to 0.90) and (b) females (N=28, r = 0.89, p< 0.001, 95% confidence interval for r =0.77 to 0.94). Outside line (orange) indicate 95% prediction interval for prediction model. Figure 4.7 shows Bland-Altman plot with estimated mean bias and 95% limits of agreement for difference in values between measured and estimated VO_2max, as plotted against the mean value.

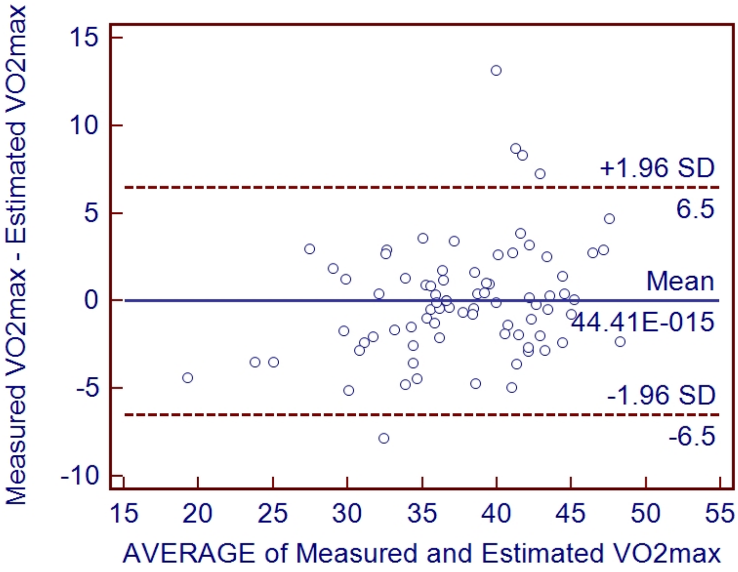


(a) male (N=80)

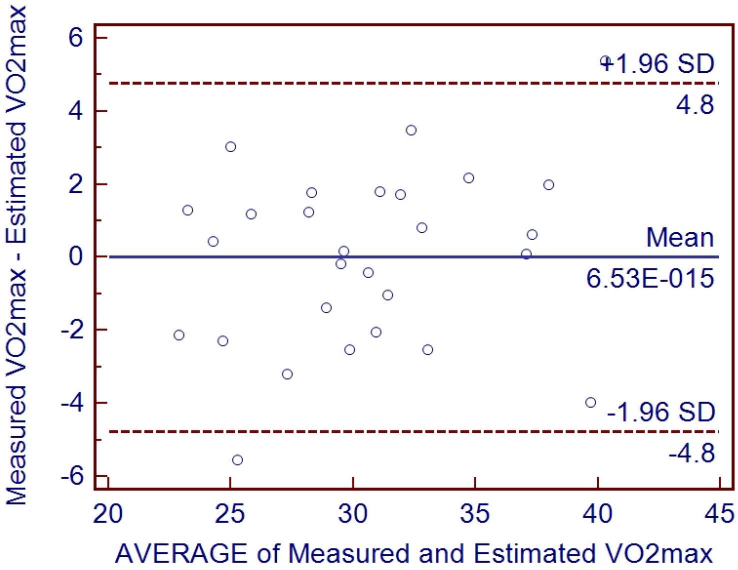


(b) female (N=28)

Figure 4.6. Scatter plot graphs of relationship between measured and estimated VO_2max (ml/kg/min) with 95% prediction interval line(orange) and 95% confidence interval line (brown) in (a) male and (b) female



(a) male (N=80)



(b) female (N=28)

Figure 4.7. Bland-Altman plot with estimated mean bias and 95% limits of agreement for difference between measured and estimated VO_2max (ml/kg/min), plotted against the mean in (a) male and (b) female.

4.3 VO_2max prediction equation based on VT estimated by regression model

In previous chapter 3, we developed regression equation for VO_2 (ml/kg/min) using HR. All variable relevant to VO_2 are used values transformed from regression equation using HR.

4.3.1 VO_2max prediction equation using VT estimated by regression model in males

The relationships between variables relevant to VT and VO_2max in males were presented in Table 4.12. Time variation from exercise start to VT ($r=0.538$, $p<0.01$), HR variation from exercise start to VT($r=0.332$, $p<0.01$), VO_2 at rest($r=0.450$, $p<0.01$), VO_2 variation from exercise start to VT ($r=0.356$, $p<0.01$), Slope of VO_2 vs time from exercise start to VT($r=-0.645$, $p<0.01$), VO_2 at VT($r=0.521$, $p<0.01$), and Time at VT($r=0.538$, $p<0.01$) among variables relevant to VT were significantly related to VO_2max. Age, weight, BMI, BMR, waist($r=-0.303$, $p<0.01$; $r=-0.429$, $p<0.01$; $r=-0.422$, $p<0.01$; $r=-0.411$, $p<0.01$; $r=-0.429$, $p<0.01$, respectively), obesity, percent bodyfat, bodyfat mass, Percent abdominal Fat(%)($r = -0.413$, $p<0.01$; $r = -0.441$, $p<0.01$; $r = -0.490$, $p<0.01$; $r = -0.425$, $p<0.01$, respectively), SBP and DBP($r = -0.267$, $p<0.05$; $r = -0.321$, $p<0.01$, respectively) among variables of subject's physiological characteristics were significantly related to VO_2max. HRmax and HR reserve (HRR) ($r=0.303$, $p<0.01$; $r=0.369$, $p<0.01$, respectively) among variables relevant to calculated HRmax (i.e., estimated HRmax = 220-age) were significantly related to VO_2max.

Table 4.12. Correlation between variables relevant to VT and VO_2max (ml/kg/min) in males (N=80)

		VO2max
HR at VT	Pearson Correlation	.140
	Sig. (2-tailed)	.217
time variation from exercise start to VT	Pearson Correlation	.538**
	Sig. (2-tailed)	.000
HR at resting	Pearson Correlation	-.186
	Sig. (2-tailed)	.099
HR variation from exercise start to VT	Pearson Correlation	.332**
	Sig. (2-tailed)	.003
VO_2 at rest	Pearson Correlation	.450**
	Sig. (2-tailed)	.000
VO_2 variation from exercise start to VT	Pearson Correlation	.356**
	Sig. (2-tailed)	.001
Slope of VO_2 vs time from exercise start to VT	Pearson Correlation	-.645**
	Sig. (2-tailed)	.000
Slope of HR vs time from exercise start to VT	Pearson Correlation	-.043
	Sig. (2-tailed)	.707
VO_2 at VT	Pearson Correlation	.521**
	Sig. (2-tailed)	.000
Time at VT	Pearson Correlation	.538**
	Sig. (2-tailed)	.000
HRmax (beats/min)	Pearson Correlation	.303**
	Sig. (2-tailed)	.006

HRR (beats/min)	Pearson Correlation	.369**
	Sig. (2-tailed)	.001
Percent HRR(%)	Pearson Correlation	.156
	Sig. (2-tailed)	.167
Percent HR at VT(%)	Pearson Correlation	-.010
	Sig. (2-tailed)	.931
Age(yr)	Pearson Correlation	-.303**
	Sig. (2-tailed)	.006
Height(cm)	Pearson Correlation	-.167
	Sig. (2-tailed)	.140
Weight(kg)	Pearson Correlation	-.429**
	Sig. (2-tailed)	.000
BMI(kg/cm^2)	Pearson Correlation	-.422**
	Sig. (2-tailed)	.000
BMR	Pearson Correlation	-.411**
	Sig. (2-tailed)	.000
Waist(cm)	Pearson Correlation	-.429**
	Sig. (2-tailed)	.000
Obesity	Pearson Correlation	-.413**
	Sig. (2-tailed)	.000
Percent Bodyfat (%)	Pearson Correlation	-.441**
	Sig. (2-tailed)	.000
Bodyfat mass(kg)	Pearson Correlation	-.490**
	Sig. (2-tailed)	.000
Percent abdominal Fat (%)	Pearson Correlation	-.425**

	Sig. (2-tailed)	.000
SBP(mmHg)	Pearson Correlation	-.267*
	Sig. (2-tailed)	.017
DBP(mmHg)	Pearson Correlation	-.321**
	Sig. (2-tailed)	.004
Smoking	Pearson Correlation	-.134
	Sig. (2-tailed)	.235
Drinking	Pearson Correlation	-.169
	Sig. (2-tailed)	.135

**P<0.01; *P<0.05

Hierarchical multiple regression analysis was used to determine the statistical strength and contribution of possible independent variables(i.e., variables relevant to VT, variables of subject's physiological characteristics, and variables relevant to age predicted maximum HR) in the prediction of VO$_2$max (ml/kg/min). Regression model summary and coefficients were presented in Table 4.13x and Table 4.14, respectively.

Table 4.13. Summary of regression model of VO2max in males

	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
	.831	.690	.664	3.62091	1.780

Dependent Variable: VO_2max

Table 4.14. Coefficients of regression model of VO2max in males

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
(Constant)	71.946	10.352		6.950	.000	51.304	92.587		
bodyfat_mass	-.775	.199	-.678	-3.885	.000	-1.173	-.377	.143	6.991
age	-.181	.054	-.289	-3.356	.001	-.289	-.074	.588	1.699
obesity	.279	.087	.559	3.200	.002	.105	.452	.143	6.994
waist	-.055	.075	-.066	-.740	.462	-.205	.094	.556	1.797
slope.VO_2.kg.time.rest.vt	-17.424	2.584	-.515	-6.742	.000	-22.578	-12.271	.748	1.337
var.HR.rest.VT	.148	.038	.289	3.906	.000	.073	.224	.796	1.257

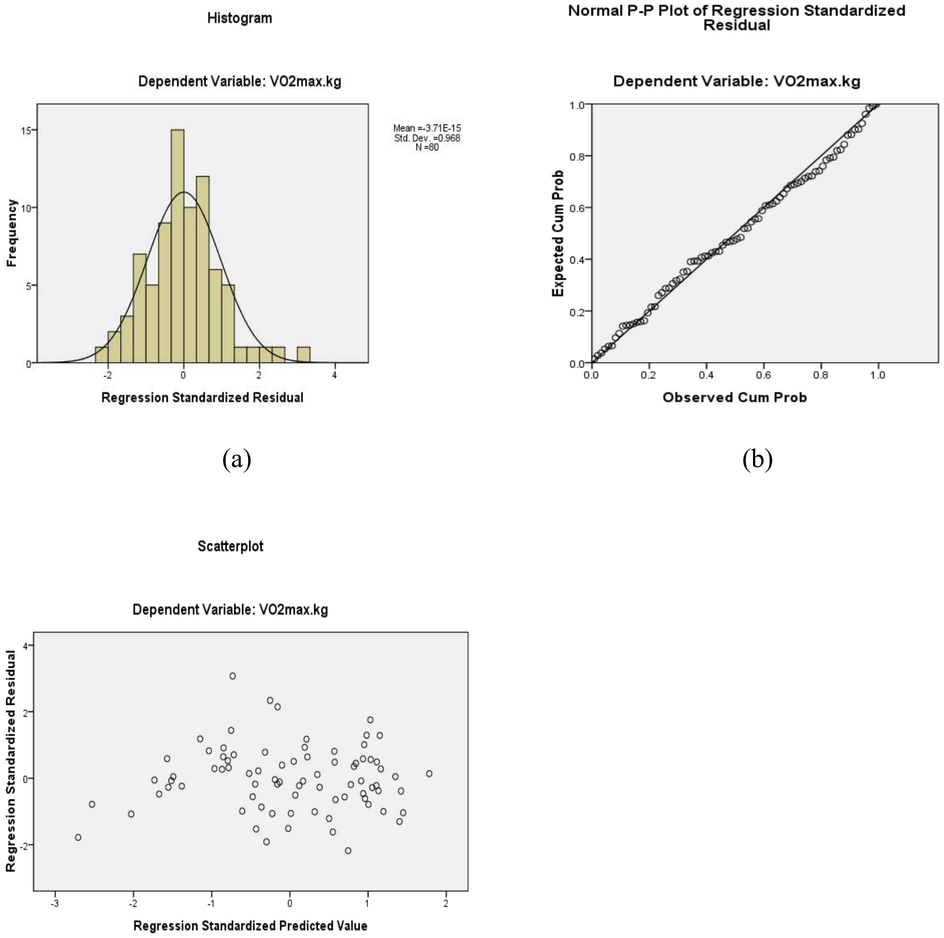
Dependent Variable: VO_2max.kg

Multiple linear regression generated the following regression equation (r = 0.831, R^2 = 0.690, adj R^2 = 0.664, SEE = 3.62 ml·kg-¹·min-¹) in males (N=80).

$$
\begin{aligned}
VO_2 \max(ml/kg/\min) = {} & 71.946 - 0.775 \times bodyfat\_mass - 0.181 \times age \\
& +0.279 \times obesity - 0.055 \times waist - 17.424 \times slope.VO_2 \\
& +0.148 \times \mathrm{var}.HR
\end{aligned}
$$

where waist(cm), slope.VO_2(ml/kg/min) = slope of VO_2 vs time from exercise start to VT level, and var.HR(bests/min) = HR variation from exercise start to VT level

Each predictor variable was significant ($p < 0.05$) in predicting VO_2max and the resulting regression equation accounted for 69.0% of the shared variance of measured VO_2max. Standardized β-weights showed the variables (i.e., bodyfat mass among subject's physiological characteristics, Slope of VO_2 vs time from exercise start to VT among variables based on VT, -0.678, -515, respectively) to be the most effective at predicting VO_2max. To assess independence, normality, equal variance and linearity of regression model used residual analyses. Figure 4.8 shows results of residual analyses of regression model.



(a)

(b)

(c)

Figure 4.8. Results of residual analyses of VO_2max in males (N=80): (a) Histogram, (b)Normal probability plot and (c) scatterplot of regression model

4.3.2 VO_2max prediction equation based on VT estimated by regression model in females

The relationships between variables relevant to VT and VO_2max in females were presented in Table 4.15. HR.VT(r=0.411, $p<0.05$), Time variation from exercise start to VT (r=0.542, $p<0.01$), HR variation from exercise start to VT(r=0.564, $p<0.01$), VO_2 at rest(r=0.515, $p<0.01$), and VO_2 at VT(r=0.432, $p<0.05$) among variables relevant to VT were significantly related to VO_2max. Age(r=-0.486, $p<0.01$) and percent bodyfat, (r = -0.435, $p<0.05$) among variables of subject's physiological characteristics were significantly related to VO_2max. HRmax(r=0.486, $p<0.01$) among variables relevant to calculated HRmax (i.e., estimated HRmax = 220-age) was significantly related to VO_2max.

Table 4.15. Correlation between variables relevant to VT and VO_2max (ml/kg/min) in females (N=28)

		VO2max.kg
HR at VT	Pearson Correlation	.411*
	Sig. (2-tailed)	.030
Time variation from exercise start to VT	Pearson Correlation	.542**
	Sig. (2-tailed)	.003
HR at resting	Pearson Correlation	.152
	Sig. (2-tailed)	.441
HR variation from exercise start to VT	Pearson Correlation	.564**
	Sig. (2-tailed)	.002

VO$_2$ at resting	Pearson Correlation	$.515^{**}$
	Sig. (2-tailed)	.005
VO$_2$ variation from exercise start to VT	Pearson Correlation	.240
	Sig. (2-tailed)	.219
Slope of VO$_2$ vs time from exercise start to VT	Pearson Correlation	-.240
	Sig. (2-tailed)	.218
Slope of HR vs time from exercise start to VT	Pearson Correlation	-.104
	Sig. (2-tailed)	.598
VO$_2$ at VT	Pearson Correlation	$.432^{*}$
	Sig. (2-tailed)	.022
Time at VT	Pearson Correlation	.223
	Sig. (2-tailed)	.254
HRmax (beats/min)	Pearson Correlation	$.486^{**}$
	Sig. (2-tailed)	.009
HRR (beats/min)	Pearson Correlation	.245
	Sig. (2-tailed)	.209
Percent HRR (%)	Pearson Correlation	.268
	Sig. (2-tailed)	.168
Percent HR at VT (%)	Pearson Correlation	.193
	Sig. (2-tailed)	.325
Age (yr)	Pearson Correlation	$-.486^{**}$
	Sig. (2-tailed)	.009
Height (cm)	Pearson Correlation	.185
	Sig. (2-tailed)	.347
Weight (kg)	Pearson Correlation	-.090

	Sig. (2-tailed)	.650
BMI	Pearson Correlation	-.214
	Sig. (2-tailed)	.274
BMR	Pearson Correlation	.036
	Sig. (2-tailed)	.857
Waist (cm)	Pearson Correlation	-.169
	Sig. (2-tailed)	.390
Obesity	Pearson Correlation	-.279
	Sig. (2-tailed)	.150
Percent Bodyfat (%)	Pearson Correlation	-.435*
	Sig. (2-tailed)	.021
Bodyfat mass (kg)	Pearson Correlation	-.326
	Sig. (2-tailed)	.091
Percent abdominal Fat (%)	Pearson Correlation	-.195
	Sig. (2-tailed)	.320
SBP (mmHg)	Pearson Correlation	-.370
	Sig. (2-tailed)	.053
DBP (mmHg)	Pearson Correlation	-.128
	Sig. (2-tailed)	.517
Smoking	Pearson Correlation	-.153
	Sig. (2-tailed)	.438
drinking	Pearson Correlation	.063
	Sig. (2-tailed)	.751

*P<0.05; **P<0.01

Hierarchical multiple regression analysis was used to determine the statistical strength and contribution of possible independent variables(i.e., variables relevant to VT, variables of subject's physiological characteristics, and variables relevant to age predicted maximum HR) in the prediction of VO$_2$max (ml/kg/min). Regression model summary and coefficients were presented in Table 16 and Table 17, respectively.

Table 4.16. Summary of regression model of VO2max in females

R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
.871	.759	.704	2.90849	2.470

Table 4.17. Coefficients of regression model of VO2max in females

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
(Constant)	24.534	7.640		3.211	.004	8.690	40.379		
age	-.076	.060	-.150	-1.264	.219	-.201	.049	.774	1.292
SBP	-.089	.044	-.224	-2.028	.055	-.180	.002	.898	1.114
VO$_2$.kg.rest	2.443	.593	.456	4.117	.000	1.213	3.674	.893	1.120
time.start.VT	3.786	.904	.881	4.188	.000	1.911	5.661	.248	4.036
time10.VT	-1.604	.694	-.473	-2.310	.031	-3.043	-.164	.261	3.830

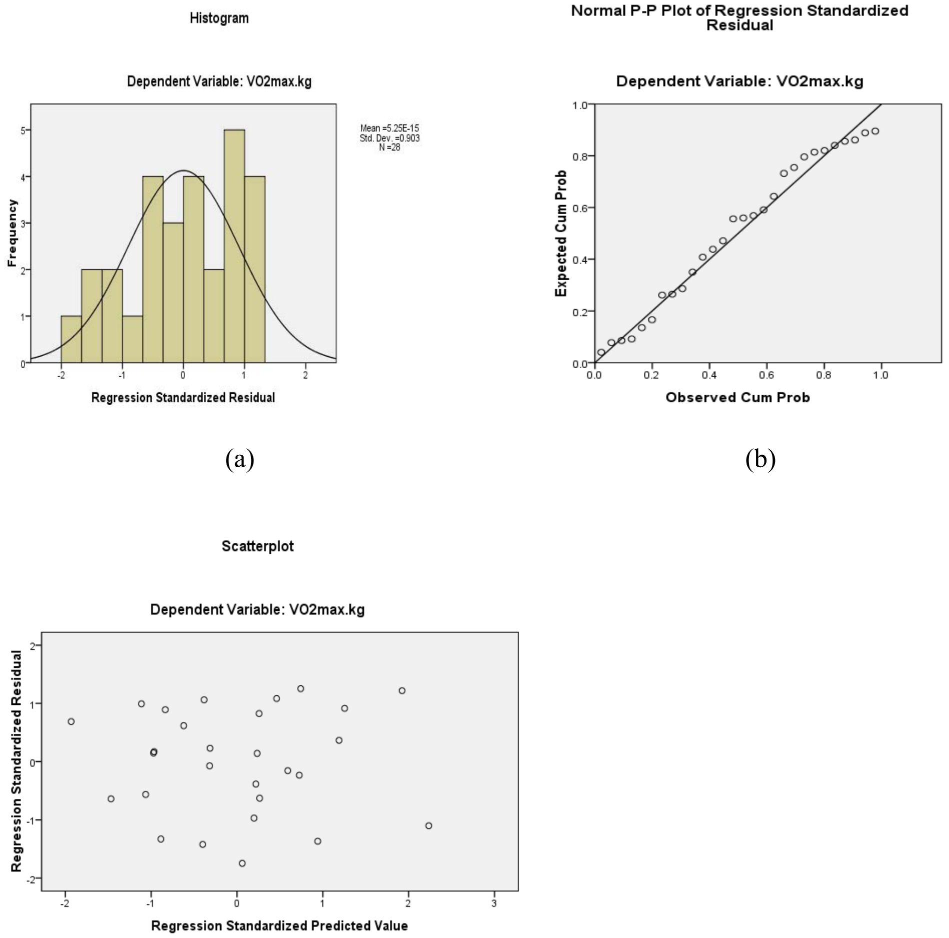
Dependent Variable: VO$_2$max

Multiple linear regression generated the following regression equation ($r = 0.871$, $R^2 = 0.759$, adj $R^2 = 0.704$, SEE = 2.90 ml·kg-¹·min-¹) in females (N=28).

$$
\begin{aligned}
VO_2 \max(ml/kg/\text{min}) = \\
& 24.534 - 0.076 \times age - 0.089 \times SBP + 2.443 \times VO2.rest \\
& +3.786 \times \text{var}.time - 1.604 \times time.VT
\end{aligned}
$$

where SBP(mmHg) = systolic Blood Pressure, VO_2.rest(ml/kg/min) = VO_2 value at resting, var.time(min) = time variation from exercise start to VT level, and time.VT(min) = time at VT level

The resulting regression equation accounted for 75.9% of the shared variance of measured VO_2max. Standardized β-weights showed the variable (i.e., time variation from exercise start to VT) (0.881) to be the most effective at predicting VO_2max. To assess independence, normality, equal variance and linearity of regression model used residual analyses. Figure 4.9 shows results of residual analyses of regression model.



(a)

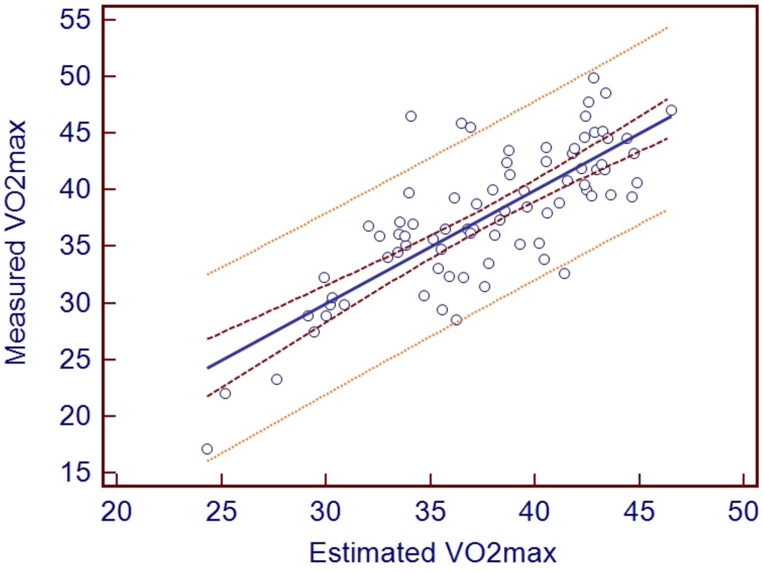
(b)

(c)

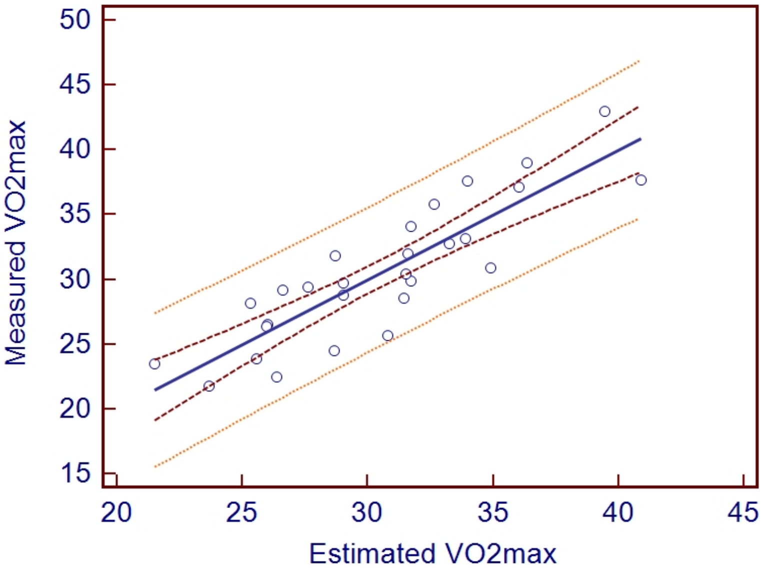
Figure 4.9. Results of residual analyses: (a) Histogram, Normal probability plot and scatterplot of regression model in females (N=28)

4.3.3 Verification of VO_2max prediction equation based on VT estimated by regression model

For the verification of VO_2max prediction equation, Scatter plot graphs and Bland-Altman plot were presented. Figure 4.10 demonstrated positively significant relationships between measured and estimated VO_2max in both (a) males ($N=80$, $r = 0.83$, $p< 0.001$, 95% confidence interval for $r =0.75$ to 0.89) and (b) females ($N=28$, $r = 0.87$, $p< 0.001$, 95% confidence interval for $r =0.73$ to 0.93). Outside line(orange) indicate 95% prediction interval for prediction model. Figure 4.11 shows Bland-Altman plot with estimated mean bias and 95% limits of agreement for difference in values between measured and estimated VO_2max, as plotted against the mean value.

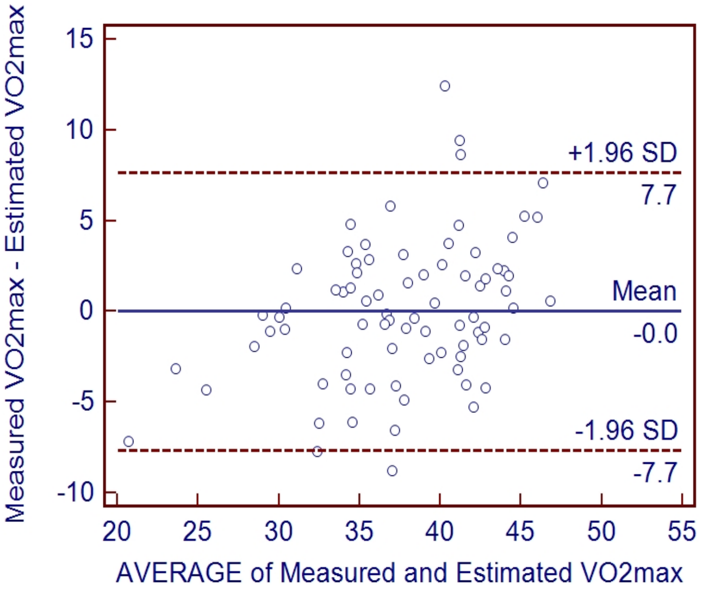


(a) male (N=80)

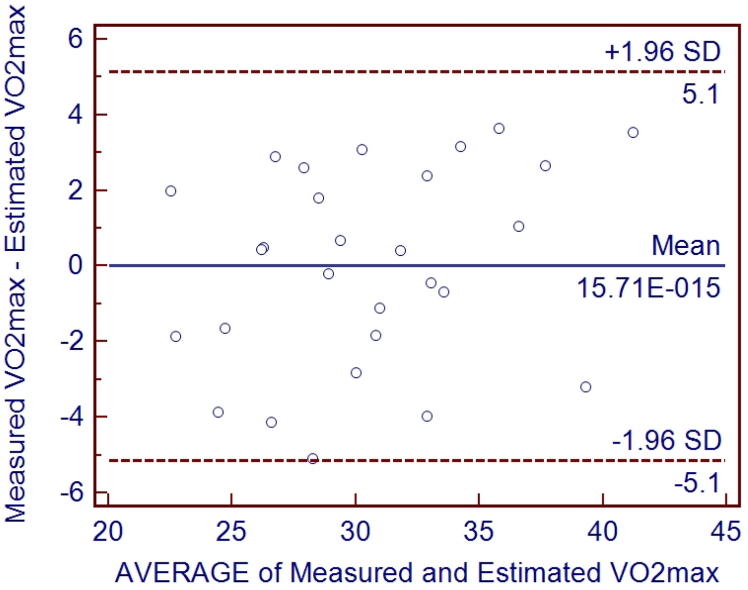


(b) female (N=28)

Figure 4.10. Scatter plot graphs of relationship between measured and estimated VO_2max (ml/kg/min) with 95% prediction interval line(orange) and 95% confidence interval line (brown) in (a) male and (b) female



(a) male (N=80)



(b) female (N=28)

Figure 4.11. Bland-Altman plot with estimated mean bias and 95% limits of agreement for difference between measured and estimated VO_2max (ml/kg/min), plotted against the mean in (a) male and (b) female.

Chapter 5 Discussion

The purpose of this study is to (1) introduce a Heart Rate (HR) -based, real-time algorithm which can detect ventilatory-threshold (VT) during treadmill exercise in an healthy, nontrained adults, not aerobically trained individuals; (2) assess the proposed approach for determining VT; (3) develop a VT -based VO_2max equation in an healthy, nontrained(i.e., not aerobically trained individuals) adults; and (4) assess the VO_2max prediction equation.

Algorithm for VT determination in real-time. Many attempts have been made to determine mathematically VT [45-46][48-51][53][57-75].

The conventional methods for determining VT (e.g., V-slope, D-max, CUSUM and Combined method) have a limitation, which VT was determined only after finishing a maximal exercise. To overcome the problem, new algorithm for VT detection was proposed. Sequence of proposed algorithm is as follows. 1) Calculate slope and min y-intercept using HR during initial 3min treadmill exercise; 2) Estimate VT y-intercept using variables, which consisted of subject's physiological characteristics, Slope, and initial y-intercept.; 3) Set reference line using slope and VT y-intercept 4) Determine VT if present HR is larger than reference line. To assess proposed Algorithm, time at VT from metabolic gas analyzer using V-slope method (gold standard method for determining VT) was used. Estimated VT was overestimated as compared with measured VT in male (16.73±0.92 vs 16.68±1.05) and was underestimated in female (15.73 ± 1.48 vs 15.80 ± 1.57). The paired samples t-test and the wilcoxon signed ranks demonstrate no significant difference between measured and estimated VT in both males and females ($p>0.05$). In addition, pearson product-moment correlation coefficients (r) demonstrated positively significant relationships between measured and estimated time at VT in both (a) males ($N=80$, $r = 0.42$, $p< 0.001$) and (b) females ($N=28$, $r = 0.66$, $p< 0.001$). Bland-Altman analysis was also used to demonstrate agreement in time at VT between measured and estimated VT.

VO_2max prediction models. All variable relevant to VO_2 are used values transformed from regression equation using HR. Before developing VO_2max regression equation, Pearson correlation test was investigated using possible independent variables (i.e., variables relevant to VT, variables of subject's physiological characteristics, and variables relevant to age predicted maximum HR). In case of males, Variables, which is the most significant relationship to VO_2max, were Time variation from exercise start to VT and Time at VT($r=0.538$, $p<0.01$; $r=0.538$, $p<0.01$, respectively). In case of females, Variables, which is the most significant relationship to VO_2max, were HR variation from exercise start to VT($r=0.564$, $p<0.01$). In this study, multiple linear regression for VO_2max, based on predicted VT, was generated in males and females ($R^2=0.69$, SEE=3.62; $R^2=0.75$, SEE=2.90, respectively). Pearson correlation coefficients demonstrate significant relationships between measured and estimated VO_2max in both (a) males ($N=80$, $r = 0.83$, $p< 0.001$, 95% confidence interval for $r =0.75$ to 0.89) and (b) females ($N=28$, $r = 0.87$, $p< 0.001$, 95% confidence interval for $r =0.73$ to 0.93). Bland-Altman plot also demonstrate agreement in values between measured and estimated VO_2max.

A number of studies, for predicting VO_2max based exercise (EX) and non-exercise (N-EX) model, have reported [37-41] [76-85]. There are various advantages and disadvantages to EX and N-EX regression models. An important feature of EX models is the actual exercise test. As the test progresses from a low-to-high exercise intensity the participant’s HR and RPE response can be used in developing a safe and effective aerobic exercise prescription. In addition, EX models yield relatively accurate VO_2max predictions. However, EX tests take time to complete, often require expensive equipment, and may not allow for testing large groups of people at the same time. However, N-EX models serve as a valuable alternative to EX tests. Such models predict CRF through questionnaire based data and are administered without expensive administrative costs and time restraints. N-EX models are a practical method for assessing VO_2max in large populations and may be useful in large epidemiological studies. Because of the subjective nature of N-EX models, but, they are not suitable for settings where CRF or the functional capacity of the person must be measured (e.g., when qualifying for the military, civil service, or police academy). VO_2max prediction model based on VT, proposed in this study, are easy, objective, convenient, and non-expensive EX-method with nature of N-EX. A proposed approach will be useful method for predicting VO_2max. But because the relatively small sample size in female used in the present study, further research with greater sample sizes is required to substantiate these findings before conclusions can be made as to the extent of the influence. The prediction equation generated in this study will be applicable for use only with healthy adults 19–58 years old with physical characteristics similar to the study group.

Chapter 6 Conclusions

In this dissertation, a new approach to determine the ventilatory-threshold (VT) in real-time and a new model to estimate VO_2max based on VT were proposed.

It could be concluded from the studies that 1) Significant differences were not found between VT from metabolic gas analyzer using V-slope method and VT from proposed algorithm using HR variation. Bland-Altman analysis shows agreement between two methods.; 2) There is a significant correlation between predicted VT and VO_2max.; 3) The new VO_2max prediction model based on VT was developed. HR, time and subject's physiological characteristics without metabolic gas data were used as predictors.

In summary, the proposed approach has shown the following advantage and characteristics over the conventional ones: 1) It requires no metabolic gas analyzer; 2) It is easy, convenient method compared with conventional methods using metabolic gas data; 3) It is possible to determine VT in real-time; 4) It is possible to estimate VO_2max based on VT without requiring a maximal effort from maximal exercise test.; 5) It is objective method based on mathematical approach.

The proposed approach is possible to apply to application in both exercise testing and prescription. The proposed approach can be potentially used for exercise test for children or older adults with difficulty from maximal exercise. It can also be used for exercise prescription using treadmill in public fitness center.

In the future, more studies should be continued. Developments of portable, precise HR monitoring equipment will enhance overall efficiency of the proposed approach. In addition, to get more generality, the proposed approach should be applied to more other exercises such as cycle ergometer, to trained athletes, and to patients with various chronic health conditions (i.e. diabetes, asthma and cystic fibrosis).

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Abstract (in Korean)

실시간 환기역치 시점 검출과 환기역치에 근거한 VO_2max 예측

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본 학위 논문에서는 1)심박수를 이용하여 실시간으로 환기역치 시점을 검출할 수 있는 알고리즘을 제안하고, 2) 최대운동을 하지 않고, 환기역치 시점까지의 운동만을 통해 최대산소섭취량을 예측할 수 있는 회귀모형을 제시한다.

환기역치 시점을 검출하고 최대산소섭취량을 측정하는 기존의 방법들은 호흡가스분석기의 VO_2, VCO_2 등의 가스 데이터를 이용하기 때문에 고가의 호흡가스 분석기가 갖춰있는 실험실 환경에서 피험자가 최대 운동을 마친 이후에만 검출되는 제약이 있다. 본 학위 논문에서는 실시간으로 환기역치 시점을 검출하기 위해 운동 초기 3분동안의 심박수의 기울기 변화를 모니터링하는 방법을 제안하였다. 실험은 108명의 건강한 성인(남자 80명, 37.12±11.09yr, 여자 28명, 34.35±9.93yr)을 대상으로 트레드밀에서 modified balke protocol에 따라 최대하 운동을 실시하였다. 환기역치 시점은 V-Slope 방법으로 검출하였고, 최대산소섭취량은 가스호흡분석 장비를 사용하여 측정하였다. 환기역치 시점 검출방법은 V-Slope 방법으로 결정된

환기역치 결과와 대응표본 t-test, Bland-Altman 분석을 이용하여 검증하였다. 또한 환기역치 시점까지의 운동만으로 얻어진 심박수와 피실험자의 물리적 정보를 이용하여 최대산소섭취량을 추정하기 위한 다중 회귀식을 산출하였다.

대응표본 t-test 결과 남자와 여자 모두에서, 검출된 환기역치 시점과 측정된 환기역치 시점간에는 유의한 차이가 없었다(r=0.42, P<0.001; r=0.66, P<0.001, respectively). 최대산소섭취량과 변인들간의 상관관계는 남자의 경우에는 환기역치 시점까지의 VO_2 변화량, 환기역치 시점에서의 VO_2, 나이 변인이 최대산소섭취량과 유의한 상관관계를 보였고, 여자의 경우에는 환기역치 시점까지의 심박수의 변화량과 나이 변인이 최대산소섭취량과 유의한 상관관계를 보였다. 환기역치에 근거한 새로운 최대산소섭취량 예측 방정식은 남자 $R^2=0.690$, SEE=3.62, 여자 $R^2=0.759$, SEE=2.91 의 결정계수 값을 보였다.

본 학위 논문에서는 심박수의 기울기를 이용한 환기역치 시점 검출 알고리즘이 실시간으로 환기역치 시점을 검출할 수 있음을 확인할 수 있었다. 또한, 실시간으로 검출된 환기역치 시점이 건강한 성인에 있어서 최대산소섭취량을 예측하기 위한 유용한 요인이라는 것을 확인할 수 있었다. 본 논문에서 제안된 방법은 많은 운동생리학, 운동처방 적용 분야에서 가스호흡 분석기 없이 환기역치, 최대산소섭취량을 예측하기 위한 대안으로서 널리 사용될 것으로 기대된다. 또한 최대운동이 어려운 노인, 유아, 신체활동이 불편한 사람들을 위한 운동처방에 사용 가능할 것이다.

주요어: 실시간, 환기역치, 최대산소섭취량, 예측모델, 운동처방, 심박수

Appendix 1 – Consent to be a Research Subject

운동의학 검사 동의서

귀하는 건강증진을 위한 의학적 검사와 운동능력 평가를 받고, 그 결과에 따라 귀하의 건강 및 운동능력에 알맞은 운동처방을 받으시게 됩니다.

1. 의학적 문진

문진을 통하여 개인의 병력과 가족의 병력을 검사 받고,생활습관으로 흡연습관,음주습관,식생활습관,운동습관등을 검사받게 됩니다.

2. 의학적 검사

귀하는 건강관련 체력측정과 운동 시 심혈관계 반응과 기능, 그리고 최대산소섭취능력을 통한 심폐적성을 정확히 알아보기 위하여 운동부하 검사를 받게 됩니다.

이 검사는 트레드밀을 이용하여 실시하며, 누구나 쉽게 수행할 수 있는 낮은 강도에서부터 시작하여 점차 강도를 높임으로써 귀하의 심폐기능, 심장질환의 유무 및 예측, 운동능력을 평가받게 됩니다.

운동부하검사 중에 갑작스런 혈압상승, 현기증, 가슴통증, 심장기능 이상 등이 발생할 수 있으며, 따라서 귀하가 검사 중 심한 흉통, 호흡곤란, 현기증 등의 이상증상이 있어 검사를 계속 할 수 없다고 여기시면 언제라도 검사를 중지 할 수 있습니다. 또한 저희가 관찰 결과 귀하가 느끼지 못하는 이상이 발견될 시에도 검사를 중단하게 됩니다.

이와 같이 의학적인 검사를 토대로 운동처방을 실시하는 것은 운동부하검사 중이나 평소 운동 중에 발생 할 수 있는 위험 부담을 줄이고 소기의 목적을 달성하기 위함입니다.

검사 동의서

본인은 운동의학 처방에 대하여 잘 이해하고, 이에 응할 것을 동의합니다.

20 년 월 일
성명

운동 의학 연구실

Appendix 2 – Consent

동 의 서

❖ 제목 : 실시간 환기역치 시점 검출과 이를 통한 VO_2max 예측

본 연구의 목적은 개인별 운동 중 실시간으로 운동능력(환기역치시점)을 평가할 수 있는 방법과 환기역치시점까지의 운동만으로 최대운동능력을 평가할 수 있는 방법을 제시하고자 하는 연구입니다.

귀하의 정보는 기초자료로 이용하고 연구 이외의 목적으로는 이용되지 않을 것이며 기밀이 보장 될 것입니다. 또한 연구에 참가하기로 동의한 경우라도 본인이 원할 경우 언제든지 동의를 철회할 수 있습니다.

연구에 참여해 주시는 귀하께 감사의 말씀을 드리며 이 연구에 동의하시면 아래에 서명해 주십시오.

지원자 서명란 날짜:____________성명 :___________(사인)

연구자 서명란 날짜:____________성명 :___________(사인)

Appendix 3 – Questionnaire

INFORMATION

1. Personal History

*이름: *주민번호: - *성별:
*주소:
*전화번호:
*키: *몸무게:
*과거력:

*현재 복용중인 약물:

*가족력:

2. Life Style

*흡연: / 일 *기간: 년
(금연기간: 년)
*술
종류: 빈도: 양:
술을 먹은 기간:
(금주기간: 년)

3. 식사습관

*즐겨 먹는 음식: ① 야채 ② 육류
*평소 음식의 간: ① 짜게 먹는 편이다.
② 보통이다.
③ 싱겁게 먹는 편이다.

4. 운동

*종류: *양: 시간
*빈도: /주

Appendix 4 – IPAQ

국제 신체 활동 설문지(IPAQ)_

❖지난 7 일간 격렬한 활동 (힘들게 움직인 활동으로 평소보다 숨이 훨씬 더 차게 만드는 활동)을 한 번에 적어도 10 분이상 지속한 활동만을 생각하여 응답하여 주시기 바랍니다.

1. 지난 7 일간 무거운 물건 나르기, 달리기, 에어로빅, 빠른 속도로 자전거타기 등과 같은 격렬한 신체 활동을 며칠간 하였습니까?

일주일에 ( ) 일

◇ 격렬한 신체활동 없었음 ➢ 3 번으로 가세요.

2. 그런 날 중 하루에 격렬한 신체활동을 하면서 보낸 시간이 보통 얼마나 됩니까?

하루에 ( )시간 ( )분

◇ 모르겠다/확실하지 않다

❖ 지난 7 일간 중간정도의 신체활동 (평소보다 숨이 조금 더 차게 만드는 활동)을 한 번에 적어도 10 분이상 지속한 활동만을 생각하여 응답하여 주시기 바랍니다.

3. 지난 7 일간 가벼운 물건나르기, 보통속도로 자전거타기, 복식 테니스 등과 같은 중간정도의 신체활동을 며칠간 하였습니까?(걷기는 포함시키지 마세요)

일주일에 ( )일

◇ 중간정도의 신체활동이 없었음. ➢ 5 번으로 가세요.

4. 그런 날 중 하루에 중간정도의 신체활동을 하면서 보낸 시간이 보통 얼마나 됩니까?

하루에 ( )시간 ( )분

◇ 모르겠다/확실하지 않다

❖ 지난 7 일간 걸은 시간을 생각해 보세요. 직장이나 집에서 혹은 오락활동, 스포츠, 운동, 여가시간에 걸은 것도 포함됩니다.

5. 지난 7 일간 한 번에 적어고 10 분 이상 걸은 날은 며칠입니까?

일주일에 ( )일

◇ 걷지 않았음. ➢ 7 번으로 가세요.

6.그런 날 중 하루에 걸으면서 보낸 시간은 보통 어마나 됩니까?

하루에 ( )시간 ( )분

◇ 모르겠다/확실하지 않다

❖ 지난 7 일간 앉아서 보낸 시간에 관한 것입니다. 책상에 앉아 있거나 친구를 만나거나, 독서를 할 때 앉거나, TV 를 앉아서 또는 누워서 시청한 시간이 포함됩니다.

7. 지난 7 일간 주중에 앉아서 보낸 시간이 보통 얼마나 됩니까?

하루에 ( )시간 ( )분

◇ 모르겠다/확실하지 않다