THE PREDICTION OF MAXIMUM OXYGEN UPTAKE FOR TRAINED AND UNTRAINED MALES FROM MEASUREMENTS MADE DURING SUBMAXIMUM BICYCLE ERGOMETRY

by

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Bachelor of Science, Zoology, U.B.C., 1977

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in the Department

of

Kinesiology

SIMON FRASER UNIVERSITY

December, 1983

APPROVAL

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Degree: M.Sc. Kinesiology

Title of thesis: The Prediction of Maximal Aerobic Capacity for Trained and Untrained Males from Measurements made during Submaximal Bicycle Ergometry

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The Prediction of Maximum Oxygen Uptake FOR TRAINED AND UNTRAINED MALES FROM MEASUREMENTS MADE DURING SUBMAXIMUM BICYCLE ERGOMETRY

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ABSTRACT

The objectives of this study were to investigate the relationships among oxygen uptake ($\dot{V}O_2$), heart rate (HR) and work rate (WR) during submaximal and maximal exercise performed on a bicycle ergometer in an attempt to construct a nomogram for predicting maximal oxygen uptake ($\dot{V}O_2max$) from submaximal work rates. The inherent limitations of the Astrand-Rhyming nomogram, developed in 1954, provided the basis for the investigation.

A new nomogram has been established on groups of trained (n=20) and untrained (n=15) males in the age range 20-29 years. It is based on a linear relationship found to exist between $\dot{V}O_2$ and HR. Group mean data exhibited a linear trend, though data from a few individuals within each group showed the hypothesized non-linear, exponential trend at high rates of work. The newly developed $\dot{V}O_2max$ predictive test began with a standard 5 minute warm-up period on a bicycle ergometer at a pedal rate of 90 rpm and zero load. The mean heart rate attained during the fifth minute provided a baseline heart rate value which was subtracted from every other heart rate to provide a delta heart rate (ΔHR). Immediately following the warm-up, higher power outputs were completed, each of 3 minutes duration, until a heart rate between 145-160 $b \cdot min^{-1}$ was attained and each was expressed as a ΔHR. Predicted $\dot{V}O_2max$ could then be read directly by aligning delta HR on the left of a nomogram with the oxygen equivalent of the work rate depicted on the right hand side of the nomogram. A unique feature of the new Banister-Legge nomogram is its

provision of distinct predictive curves for trained and untrained individuals. For example, a trained individual showing a delta HR of 68 at a work rate of 1200 kpm·minute^{-1} would have a predicted $\dot{V}O_2$max of 4.00 litres·minute^{-1}. A similar response from an untrained individual would correspond to a predicted $\dot{V}O_2$ max of only 3.50 litres·minute^{-1}.

The Banister-Legge nomogram has been cross-validated on two groups of males, similar in age and state of training to the original core group on whom it was originally developed. A correlation coefficient of 0.9791 was determined between observed and predicted $\dot{V}O_2$max values in the former groups. This value contrasts significantly ($p < 0.05$) with the correlation coefficient of 0.8043 obtained between observed and predicted scores obtained by use of the traditional Astrand-Ryhming submaximal, six minute work test. The new nomogram, therefore, provides a more accurate prediction of $\dot{V}O_2$max and it is anticipated that it may replace the Astrand-Rhyming nomogram when trained and untrained males, 20 to 29 years, are tested. Future research will be undertaken to establish predictive $\dot{V}O_2$ max nomograms for both females and males varing in age and state of training.

DEDICATION

This thesis is dedicated to my Mom and Dad, Ken, Carole, Ellen and Marty whose love was "the light at the end of the tunnel".

ACKNOWLEDGMENTS

I would like to thank Dr. Eric Banister for his encouragement, guidance and friendship which he provided me with throughout my years as a graduate student.

Appreciation is extended to Dr. John Wilkinson for his judgement and advice, Nory Ison for his statistical expertise and Dr. Murray Allen for his medical aid. I am grateful to Rob Maskell and Igor Mekjavic for the technical wizardry they performed in the lab. I would like to thank all the cyclists and untrained subjects who gave their time so freely to participate in the study.

I would especially like to acknowledge my fine friends Bahram Gustaspi and Lesley and Tony Kettle who provided me with inspiration during the final and most difficult stages of the thesis.

Finally, I would like to express my gratitude to all the members of the Kinesiology department for their wonderful spirit and the confidence that they instilled in me.

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1. Introduction

The Astrand-Rhyming (A-R) nomogram (1954) is widely used to predict maximal oxygen uptake ($\dot{V}O_2max$) from a steady-state heart rate response to a specifically chosen work rate during submaximal exercise on a bicycle ergometer, treadmill or stepping bench. The principle for the development of the A-R nomogram is based upon four major assumptions. These assumptions are, first, that heart rate is linearly related to oxygen consumption ($\dot{V}O_2$) throughout the entire range of exertional levels up to maximal oxygen uptake and, secondly, that maximal attainable heart rate varies little between individuals of similar age. The third major assumption is that oxygen uptake values obtained during bicycle ergometry are equivalent to those obtained on the treadmill for the same individual and finally, that a precise and uniform protocol is strictly performed in every assessment. On a bicycle ergometer, for example, a single, submaximal work rate is performed at a pedal rate of 50 revolutions per minute (rpm).

Major flaws in each of the basic tenets of the nomogram have been clearly shown by various investigators to limit its power of prediction. More specifically, these deficiencies include the non-linear relationship between $\dot{V}O_2$ and heart rate over the range of 50 to 100 percent $\dot{V}O_2max$ (Wyndham *et al.*, 1959; Rowell *et al.*, 1964; Wyndham *et al.*, 1966; Davies *et al.*, 1968).

Variations in maximal attainable heart rate for individuals of the same age constitutes a major source of error as does the variation in maximum heart rate between age groups (Maritz *et al.*, 1961; Lester *et al.*, 1968; Sidney and Shephard, 1977).

A third limitation in the predictive power of the A-R nomogram is due to the variation in oxygen uptake resulting from changes in the exercise testing apparatus. Maximal oxygen uptake measurements on a treadmill have been shown to be 4 to 18% greater than $\dot{V}O_2max$ values obtained on a bicycle ergometer (Glassford *et al.*, 1965; Hermansen and Saltin, 1969; Kamon and Pandolf, 1972; McArdle and Katch, 1974; McKay and Banister, 1975; Bergh *et al.*, 1976; Matsui, 1978; Pannier *et al.*, 1980; Keren *et al.*, 1980).

Changes in the testing protocol during exercise on a specific testing apparatus also results in variations in measured oxygen uptake and heart rate values. Since a $\dot{V}O_2max$ prediction is based upon a steady state heart rate response to a single submaximal work rate, factors, other than work rate, causing an increased heart rate must be carefully controlled.

Changes in body core temperature as a result of a pre-exercise warm-up period may result in changes in heart rate measurements and, in turn, $\dot{V}O_2max$ predictions (Inbar and Bar-Or, 1975; Ingjer and Stromme, 1979). Submaximal heart rate has also been observed to vary independently of oxygen uptake during periods of emotional stress (Taylor et al., 1955; Rowell et al., 1964; Taylor et al., 1963).

Oxygen uptake has been shown to vary not only with power output but also with variations in the combination of pedal rate and resistance (Banister and Jackson, 1967; Pandolf and Noble, 1973; Hagberg et al., 1975; Gueli and Shephard, 1976; Cafarelli, 1977; Lollgen et al., 1980).

Perceived exertion and "work efficiency" have been shown to be important factors when considering exercise protocols (Borg et al., 1962; Whipp and Wasserman, 1969; Stevens and Cain, 1970; Ekblom and Goldbarg, 1971; Knuttgen et al., 1971; Edwards et al., 1972; Sargeant and Davies, 1973; Gaesser, 1975; Banister, 1976; Cafarelli et al., 1977; Lollgen et al., 1977; Seabury et al., 1977; Lollgen et al., 1980; Stainsby et al., 1980; Borg et al., 1981).

Differences in the fitness level of individuals is yet another factor which limits the predictive capacity of the nomogram. (I. Astrand, 1960; Rowell et al., 1964; Roberts and

Alspaugh, 1972; Holmer and Astrand, 1972; Pechar _et al._, 1974; Magel _et al._, 1975; Stromme _et al._, 1977). I. Astrand (1960) found that when applying the nomogram on data for submaximal oxygen uptake and heart rate, the standard error of prediction from measured $\dot{V}O_2max$ was less than ±10 percent for well-trained, younger persons, and approximately ±15 percent for a mixed ability-age range group of subjects. The difference was due to an increased maximal aerobic capacity of the test group on whom the nomogram was developed. In a similar study, Astrand (1960) found that physical training not only increased maximal aerobic capacity, but also changed the slope of the heart rate/oxygen uptake curve.

Detailed examination of each major limitation imposed by the assumptions associated with the A-R predictive nomogram led to the proposed development of a more accurate method for predicting $\dot{V}O_2max$. The proposed method retained the simple heart rate/workrate relationship as the base from which to make predictions but it recognized the possible existence of a non-linear relationship between heart rate and oxygen uptake. Experimentation determined which mathematical function fit obtained oxygen uptake/heart rate data best.

Pilot data suggested that an exponential function of the form:

$$f(x) = a \cdot e^{kx} \qquad \text{(Equation 1)}$$

where $f(x)$ = oxygen uptake,

a = a constant,

k = a rate constant, and

x = heart rate occasioned by a defined work rate,

would describe the curve most accurately, but this remained to be confirmed in larger groups of subjects.

In the work described in this study, maximal heart rate was measured directly rather than being derived from predictive equations as in the pilot investigations. Pilot work suggested a suitable submaximal exercise testing protocol to modify uncontrolled changes in heart rate due to individual basal heart rate variability by providing a standardized pre-exercise warm-up period. The pedal rate chosen for the submaximal test was 90 rpm, since it had been shown to be perceived as less demanding at high work rates than pedal rates within the range 50 to 80 rpm at equivalent power outputs. Also, pedalling at 90 rpm had been determined to be a less efficient method of producing external work thus assuring maximum engagement of the cardio-respiratory system while reducing perceived exertion and encouraging greater effort from test participants.

Development of a method that seeks to provide a more accurate prediction of $\dot{V}O_2max$ than existing methods for any individual, regardless of age, sex or fitness level, must ideally assess a random sample of individuals from each group composed of every combination of the above factors. Since such a task was beyond the scope of this thesis, a more circumscribed objective was to study one age group of mixed trained and untrained subjects. This was entirely reasonable since the thesis proposed only to measure the accuracy of $\dot{V}O_2max$ prediction by a method based upon sound physiological principles. Even if the accuracy of $\dot{V}O_2max$ prediction was not improved, the study would still have had value for its systematic investigation of the acknowledged imperfections of the A-R nomogram.

This investigation, therefore, specifically:

1)examined a selected Canadian population of males within a delimited age-range (20-29 years) varying in fitness levels (trained and untrained), 2)investigated a possible non-linear relationship between oxygen uptake and heart rate over a range of work rates demanding approximately 50 to 100% $\dot{V}O_2max$ to determine if more accurate formulations of work rate, heart rate and oxygen uptake relationships would allow better predictions of real maximum oxygen uptake values to be made from submaximum work rate and heart rate relationships,

3)determined maximal heart rates directly rather than by calculation from predictive equations, and

4)developed a method to predict maximum oxygen uptake using easily measured physiological responses to submaximum work levels during bicycle ergometry.

2. Literature Review

2.1 Maximal Oxygen Uptake

Maximal oxygen uptake ($\dot{V}O_2max$) measures the maximal functional capacity of the cardiorespiratory system and/or the ability of skeletal muscle to oxidize metabolic substrate. It is generally considered to be the best physiological indicator of one's ability to perform prolonged physical work. $\dot{V}O_2max$ is most accurately assessed from direct measurement in which the subject exercises to exhaustion while expired gases are collected. In fact, the test measurement has a coefficient of reliabitity of 0.95 (Taylor et al., 1955; Rowell, 1974) when $\dot{V}O_2max$ is assessed under standardized conditions which assure involvement of 50% or more of the total muscle mass at a sufficient intensity and duration during an exercise form that is independent of skill or motivation.

Several objective criteria exist which aid in confirming attainment of $\dot{V}O_2max$ in any work test. These include:

1)observation that oxygen uptake reaches a steady state despite increases in work rate. At this steady state level, values of oxygen uptake differ by less than 150 $ml \cdot min^{-1}$ (Taylor et al., 1955). In relative terms, this value is set at 2 $ml \cdot kg^{-1} min^{-1}$ for a typical adult male,

2)blood lactic acid values exceeding 8 to 9mM, or 70 to 80 $mg \cdot 100\ ml^{-1}$ of blood, are reached in samples taken 3 to 5 minutes following the cessation of exercise (Astrand, 1952),

3)determination that the respiratory exchange ratio (R) exceeds 1.15 at the point of exhaustion, and

4)determination that the heart rate approximates an age predicted maximal level, predicted from the formula, HRmax = 220-age.

2.2 Submaximal Exercise Testing

The value of exercise tests in determining an individual's capacity to perform exhaustive work has been well established Taylor et al., 1955; Astrand, 1956; Hettinger et al., 1961; Glassford et al, 1965). Wherever performance of maximally exhaustive exercise is impractical or undesirable, as in the testing of untrained or older individuals or individuals with heart disease, less strenuous or submaximal exercise may be performed and $\dot{V}O_2max$ estimated from an individual's physiological response to carefully chosen work rates (Astrand, 1956; Maritz et al., 1961; Issekutz, 1962; Margaria et al.,1965; Wyndham, 1966). Such indirect methods of assessing $\dot{V}O_2max$ are based upon the assumption that oxygen uptake and any other measured metabolic variable are linearly related throughout an entire range of work rates (Berggren and Christensen, 1950). In addition, submaximal tests are useful since they may be performed in a variety of ways, including treadmill walking or running, bicycle ergometry or bench stepping.

2.2.1 The Astrand-Rhyming Exercise Test

The Astrand-Rhyming (A-R) exercise test in one of the most frequently performed submaximal tests used in the prediction of $\dot{V}O_2max$ (Astrand and Rhyming, 1954). Performance of the A-R exercise test requires a subject to exercise continuously at a predetermined, single, submaximal work rate for 5 to 6 minutes on a treadmill, bicycle ergometer or stepping bench. Suggested work rates are 75 to 100 watts (W) for trained females, 100 to 150 W for trained males and 50 W for untrained individuals. Heart rate is measured at the end of every minute during the test and is required to reach a steady value greater than 130 $b\cdot min^{-1}$ differing by not more than 5 beats per minute throughout the fifth and sixth minute. The test, in fact, is prolonged until a steady state heart rate between 130 and 170 $b \cdot min^{-1}$ is reached. From this working pulse rate, together with the corresponding work rate inducing it, $\dot{V}O_2max$ is estimated. The basis for the test lies in the assumption that a linear relationship exists between oxygen uptake and heart rate and that maximal heart rate varies with age.

The A-R nomogram was originally developed from tests on 86 healthy, well-trained physical education students, 18 to 30 years old. Maximal oxygen uptake, as well as submaximal oxygen uptake, was determined during tests performed by this group both on a bicycle ergometer and a treadmill. A relationship between heart rate and oxygen consumption was thus obtained and found to be essentially linear over a whole range between resting and maximum heart rate. Detailed examination of individual regression lines between oxygen uptake and heart rate for males and females showed that males, on the average, had a pulse rate of 128 $b \cdot min^{-1}$ at an oxygen uptake 50% of $\dot{V}O_2max$ and 154 $b \cdot min^{-1}$ at an oxygen uptake 70% of $\dot{V}O_2max$. Female values were 138 $b \cdot min^{-1}$ at 50% $\dot{V}O_2max$ and 168 $b \cdot min^{-1}$ at 70% of $\dot{V}O_2max$ respectively. Both male and female group means had a standard deviation of ±9 $b \cdot min^{-1}$. On the basis of these data, a nomogram was constucted for predicting $\dot{V}O_2max$ from heart rate responses during standardized, submaximal work.

Many additional groups varying in age, sex and fitness have been studied in this way since 1954 and the original nomogram based upon data from 86 physical education students has remained almost completely unchanged. It must be evident, however, that the accuracy of prediction varies with the degree of correspondence the test conditions and responses of an individual in a current test have with the original test on which the nomogram was developed. The original A-R nomogram predicted $\dot{V}O_2$max from pulse rates ranging from 120 to 170 b·min^{-1}.

These measures were submaximal heart rates for the original 1954 group since their mean maximal heart rate was assumed to be 195 b·min^{-1} for both males and females. The application of the nomogram for the prediction of maximum oxygen uptake, therefore, is by extrapolation to an age related maximum pulse rate. This, itself, is an inherent limitation to widespread applicability. I. Astrand later (1960) modified the original nomogram by introducing an age correction factor to correct a consistent overestimation in predicting $\dot{V}O_2$max for individuals over the age of 25 years because of a decline in their maximum achievable heart rate with age.

2.2.2 Accuracy of Prediction of Astrand-Rhyming Nomogram

Many studies have estimated the accuracy of maximal oxygen uptake predictions from the A-R nomogram against directly measured $\dot{V}O_2$max (Astrand and Rhyming, 1954; Astrand, 1960; Hettinger, 1961; Rodahl and Issekutz, 1962; Rowell _et al_., 1964; Glassford _et al_., 1965; Devries and Klaffs, 1965; Teraslinna _et al_., 1966; Chase, 1966; Davies, 1968; Kavanagh and Shephard, 1976; Coleman, 1976; Jessup *et al*., Cink and Thomas, 1981; Louhevaara *et al*., 1980; Myles and Toft, 1980; Patton *et al*., 1982; Siconolfi *et al*., 1982). Table I illustrates the range of correlation coefficients (r) between predicted and observed $\dot{V}O_2max$ measurements made by various investigators.

Table I: Showing correlation coefficient (r) between directly measured $\dot{V}O_2$ max and predicted $\dot{V}O_2$max, using the A-R nomogram, by different investigators. Variations in experimental protocols and age, sex and fitness of subjects are also shown.

Investigator	Predictive Validity Coefficient	Protocol for Assessing $\dot{V}O_2$max	Subject Data
Astrand and Ryhming, 1954	0.71	Maximal bicycle and treadmill series of experiments over 3 weeks, work intensity varying from low to highest subject could maintain for 5-6 minutes. Submax treadmill- 10 $km \cdot hr^{-1}$, 1 incline, Submax bicycle female-900 kgm/m male-1200 kgm/m	n=86 well trained males and females, age range 18 - 30
Astrand, 1960	0.78	Max and submax bicycle, on at least 2 days, 5-10 min per load, 2-3 min/load at max loads	n=205 (males=129) (females=76) age range 20-68
Rowell *et al.*, 1964	0.76	Max treadmill Taylor increase 2.5% Submax tread 3.5mph,10% 3.5mph,15%	n=22 athletes, sedentary n=10 endurance athletes

deVries and Klafs, 1965	0.74	Max Bicycle 60rpm, 12min WU (6 at 450, 6 at 900 kpm) CE 250kpm min^{-1} increase 250 till exhaustion Submax Bicycle 900 kpm, 60rpm 6 min, precede with 6 min,450kpm	n=16 male P.E. students age range 20-26
Glassford *et al.*, 1965	0.72	Max Tread Taylor,Buskirk Henschel	n=24 males age range 17-33
	0.78	Mitchell, Sproule, Chapman	
	0.65	Max Bicycle Astrand direct Submax Bicycle 50rpm, 900kpm till HR 125-170	
Teraslinna *et al.*, 1966	0.69	Max Bicycle modified Balke Taylor,50rpm 2min 150kpm increase 150 till exhaustion Submax Bicycle 5min WU at 150kpm 2min rest, 5min 900 kpm	n=31 faculty and staff, age range 23-49
Davies, 1968	0.80	Maximal	n=80 male sedentary age range 20-30
Coleman, 1976	0.68	Maximal tread McDonough,	n=15 male P.E.students

		Bruce Submax tread modified Maritz walk	age 22.67 ±1.8
Jessup et al., 1977	0.64 (50rpm) 0.63 (80rpm)	Max Bicycle 6 min each 300,600,900 1200 till 180beats/min then increase rate and resistance Submax bicycle 50 rpm(6 min) 80 rpm(6 min)	n=30 male volunteer students age range 18-24
Cink and Thomas, 1981	0.76	Max Bicycle 60 rpm, 2 min 25W, increase 25W/min till exhaustion Submax bicycle well-trained initial 150W moderate,100W untrained,75W 5-6min, 50 rpm HR 130-170	n=40 male students age range 18-33
Louhevaara et al., 1980	0.73	Max Bicycle following submax, 50rpm inc. resist. 2 min, 1 min 70rpm, 0.5min 100rpm. Submax bicycle Discontinuous, 4-6 min at 3 submax, 3 min rest between each. WR chosen to get HR 130b/m, 130-150, 150-170.	n=22 male mailmen age range 29-41

Myles and Toft, 1980	0.70	Max tread, Taylor, 3, 3 min periods increasing speed and grade till maximum. Submax bicycle Astrand 6 min, 50 rpm, initial 600 kpm·min^{-1}.	n=31 males age range 19-40, army volunteers
Patton et al., 1982	0.78 Tread Male 0.53 Tread Female 0.83 Bicycle Male 0.58 Bicycle Female	Max Tread, Taylor Max Bicycle, discontinuous, 60 rpm,900kpm 180kpm min increase. Submax bicycle Astrand 6 min 50 rpm, HR 120 to 170 b·min^{-1}	n=15 male age 20-41 n=12 female age 18-33 Army staff
Siconolfi et al., 1982	0.76 male 0.79 female	Max bicycle 50 rpm, 150 kpm·min^{-1} Submax bicycle Modified A-R 50 rpm, all female and male over 35, 150kpm inc. 150/2 min male under 35, 300kpm, inc. 300/2 min.	n=35 male n=28 female age 20-70 Hospital personnel

Table I reveals the extremes of variability in methodology among investigators used to assess relevent submaximal heart rates from which to predict $\dot{V}O_2max$. These procedural variations contribute significantly to the differences in predicted values noted above in Table I. Several studies have evaluated the accuracy of predicting from the A-R nomogram by comparison of the $\dot{V}O_2max$ measurements obtained directly with either submaximal treadmill running or submaximal bicycle ergometry (Rowell et al., 1964; Glassford et al., 1965; Coleman, 1976). These are inappropriate comparisons however, since it is well known that treadmill running consistently produces higher $\dot{V}O_2max$ values, on the order of 4 to 18%, than bicycle ergometry (Astrand and Saltin, 1961; Glassford, et al.,1965; Hermansen et al., 1970; McArdle and Magel, 1970; Miyamura and Honda, 1972; McKay and Banister, 1976; Bergh et al., 1976; Keren et al., 1980; Pannier et al., 1980; Miles et al., 1980). Even when the evaluative procedure is the same for both maximal and submaximal procedures, variations in intensity and duration of each work level affect the determined $\dot{V}O_2max$ (McConnell and Sinning, 1980).

Variation in the fitness level of participating subjects is a major source of error in the accuracy of nomogram predictions.

I. Astrand (1960) reported that $\dot{V}O_2max$ predictions for untrained and trained individuals, respectively, were often underestimated or overestimated. Various investigators have observed an improved accuracy in predicting $\dot{V}O_2max$ from the A-R nomogram when subjects were moderately trained (Astrand, 1960; Rowell *et al*).

Athletes trained in a specific manner have also been shown to exhibit variations in predicted $\dot{V}O_2max$ from directly measured $\dot{V}O_2max$ when the testing apparatus on which $\dot{V}O_2max$ was measured simulated their specific sports activity (Astrand, 1960; Rowell *et al*., 1964; Roberts and Alspaugh, 1972; Holmer and Astrand, 1972; Pechar *et al*., 1974; Magel *et al*., 1975; Stromme *et al*., 1977; Verstappen *et al*., 1982). It seems, therefore, that the work test must engage all those muscles which have been specifically trained in order to assess the maximal aerobic capacity of a particular athlete accurately.

2.3 Major Limitations Placed Upon Assumptions of the A-R nomogram

While the above studies have attempted to estimate the accuracy of predictions between tests, among groups etc., the basic assumptions upon which the nomogram was constructed have rarely been questioned. The major assumptions are that:

1. Heart rate is linearly related to oxygen uptake throughout the entire range of exertional levels up to $\dot{V}O_2max$,

2. Maximal attainable heart rate varies little between individuals of similar age,
3. Oxygen uptake values obtained during bicycle ergometry are the same as those obtained on the treadmill for the same individual, and
4. A precise uniform testing protocol is strictly adhered to in every assessment (i.e. a single, submaximal work rate on a bicycle ergometer is performed at 50 rpm).

2.4 Linearity of Heart Rate/Oxygen Uptake Relationship

The underlying basis of the submaximal A-R exercise test is the relationships existing between heart rate and oxygen uptake due to variations in work rate. Oxygen uptake may be defined by the equation:

$$\dot{V}O_2 = (HR \times SV) \times (a-\bar{v})O_2 \text{ diff} \qquad \text{(Equation 2)}$$

where $\dot{V}O_2$ = oxygen uptake,

HR = heart rate,

SV = stroke volume, and

$(a-\bar{v})O_2$ diff = arteriovenous oxygen difference.

Astrand *et al*. (1964) showed that no further increase in stroke volume occurs after the heart rate attains a level of approximately 120 $b \cdot min^{-1}$. At higher rates of work an increase in oxygen uptake depends on an increased heart rate and arteriovenous oxygen difference. The heart rate appears to reach limiting levels before the arteriovenous oxygen difference after which muscle seems able to extract more oxygen from circulating blood to allow oxygen uptake to continue increasing with increasing work rate (Davies,1968). However, since a very early date, Wyndham *et al*. (1959), Rowell *et al*. (1964) and Davies (1968) concluded that at near maximum effort heart rate and oxygen uptake are no longer linearly related. The relationship between heart rate and oxygen uptake fitted an exponential curve as $\dot{V}O_2$ continued to increase while heart rate reached a maximum level. Davies (1968) showed that this nonlinearity in the heart rate/$\dot{V}O_2$ curve occured irrespective of age. The asymptotic nature of the curve results in an underestimation of $\dot{V}O_2max$ using the A-R nomogram and presents a severe limitation to its predictive power.

At heart rates below 120 $b \cdot min^{-1}$, stroke volume may continue to increase and effect an increase in oxygen uptake (Astrand *et al*., 1964). Above 120 $b \cdot min^{-1}$ heart rate increases alone generate increased cardiac output and hence oxygen uptake. The predictive power of the A-R nomogram may be increased as higher heart rates in the range 130 to 170 $b \cdot min^{-1}$ from greater work rates are used in the predictive process (Davies, 1968). Margaria *et al*. (1965) suggested the use of two heart rate values to improve prediction of $\dot{V}O_2max$, however this method did not alleviate the problem stemming from non-linearity in the upper portions of the heart rate/oxygen uptake curve.

Maximal effort on the part of a subject is essential for the direct determination of $\dot{V}O_2max$. Submaximal tests, however, depend upon determining the exact heart rate response to a specific submaximal work rate. It is of the utmost importance, therefore, that changes in heart rate reflect only an alteration in work rate. In this case both heart rate and work rate must be accurately measured.

1. Factors Affecting Heart Rate

Heart rate may be affected by a variety of factors including temperature and assorted non-specific stresses.

a. Temperature

Body temperature, (Tc), may be estimated from rectal temperature (Tr), and mean skin temperature (Ts) as follows;

$$Tc = 0.8Tr + 0.2Ts \qquad \text{(Equation 3)}$$

During exercise, both the circulatory system and heat regulatory mechanisms rise above resting levels. The circulatory system is stressed further by the need to transfer excess heat from the core to the periphery. Elevated body core and muscle temperatures induced by exercise have been shown to increase oxygen uptake and heart rate values above normal (Bergh and Ekblom, 1979). Tanaka *et al*. (1979) described the time course of rising body temperature and heart rate for submaximal bicycle ergometry at 80% of $\dot{V}O_2max$. Body core temperature lagged the increase in heart rate and did not begin to increase until six minutes after exercise onset due to blood redistribution from splanchnic areas to working muscles. Shvartz *et al*. (1978) demonstrated that exercise rectal temperature at elevated ambient temperature depends upon physical fitness (as described by $\dot{V}O_2max$) and a developed thermoregulatory ability, both of which increase heat tolerance.

The above studies indicate a need to monitor and account for changes in body and muscle temperature among populations under test. A pre-exercise warm-up period must be controlled both in terms of intensity and duration. The rise in rectal temperature above resting values may be measured to effect such a control (DeBruyn Prevost and Lefebvre, 1980).

Variations in body temperature within an individual may also be effected by circadian rhythm making it imperative to test each individual at the same time of day (Mills, 1966).

b. Non-specific Stresses

Rowell _et al_. (1964) concluded that submaximal pulse rate during work requiring up to and exceeding 50% of $\dot{V}O_2max$ may vary independently of other attendant physiological changes. The emotional state of the subject may increase the heart rate measurement by as much as 10 $b \cdot min^{-1}$ without perceptibly changing the subject's preparedness for the task in hand. At an oxygen uptake of 2.0 $l \cdot min^{-1}$ such an increase in heart rate would result in a decrease of 550 ml $O_2 \cdot min^{-1}$ in the subject's predicted $\dot{V}O_2max$. Rowell _et al_. (1964) stated that these changes can occur without corresponding increases in maximal pulse rate or true

$\dot{V}O_2max$. The observations are in contrast to those of Astrand _et al_. (1960) who considered that higher submaximal heart rates corresponded to relatively lower aerobic capacity. Taylor _et al_. (1955) noted differences in heart rate responses of a subject to submaximal work on different occasions and attributed it to less anxiety on the part of the subject after an initial test. The effects of non-specific stresses are an important consideration when predicting $\dot{V}O_2max$ from physiological responses to submaximal work rates.

2.5 Constancy of Maximum HR Between and Within Age Groups

Maritz _et al_. (1961) determined that there is little significant individual variation from the population mean maximal heart rate. Thus the use of a common maximal heart rate was considered not to introduce significant errors in the estimate of $\dot{V}O_2max$. Rowell (1964), however, determined a decrease in maximal heart caused by heavy training within a specific age group and concluded that such a decrease in maximal heart rate would prevent the prediction of $\dot{V}O_2max$ from the A-R nomogram in a sub-group differing markedly from the norm of the age group exercise heart rate. Thus maximal heart rate might vary considerably within an age group and a large variation definitely occurs between age groups. The age correction factors determined by Astrand (1960) to correct for inter-age group heart rate variability differ from those determined by Lester *et al.* (1968) and Sidney and Shephard (1977). Both Lester *et al.* (1968) and Sidney and Shephard (1977) found that 65 year old North American males could reach a maximum heart rate 10 to 15 b/min higher than reported by Astrand *et al.* (1959) and I. Astand (1960) on Swedish populations in 1960. The emphasis on physical fitness and the healthy lifestyle precedent set today in North America and around the world probably make data from 1960, on age related heart rate maxima, quite outdated.

2.6 Interchangability of Testing Instrument

It was originally assumed that treadmill running and bicycle ergometry produced similar $\dot{V}O_2max$ values when the A-R nomogram was developed. Many studies have since shown that treadmill running produces a $\dot{V}O_2max$ value between 4 and 18% greater than bicycle ergometry (Table II; Glassford *et al.*, 1965; Hermansen and Saltin, 1969; Hermansen *et al.*, 1970; McArdle and Magel, 1970; Kamon and Pandolf, 1972; Miyamura and Honda, 1972; McArdle and Katch, 1974; McKay and Banister, 1975; Bergh *et al.*, 1976; Boileau *et al.*, 1977; Matsui, 1978; Miles *et al.*, 1980; Pannier *et al.*, 1980; Keren *et al.*, 1980; Verstappen *et al.*, 1982).

Table II: Summary of Mean Difference Between $\dot{V}O_2max$ Recorded During Treadmill Running and Bicycle Ergometry As Determined By Various Investigators. Treadmill Oxygen Uptake is Termed 100%.

Investigator	Treadmill(T)-Bicycle(B) (percent)	Maximal Testing Procedure
Glassford *et al.*, 1965	8.0	T-Taylor Protocol Mitchell, Sproule, Chapman B-Astrand direct A-R indirect
Chase, 1966	15.0	T-Taylor B-Luft modification WU-3min at 300kgm·min^{-1} 50-60rpm, increase 85 to 100kgm·min^{-1} till exhaustion
Hermansen, Saltin, 1969	7.0	T-modified Taylor B-predict from Astrand Saltin, then increase 200kpm·min^{-1}, 50rpm WU for both tests 10 min at work rate 50-70% VO_2MAX
Hermansen, Ekblom, Saltin, 1970	6.0	same as above, 1969, exhaustion 5-7 minutes
McArdle, Magel, 1970	9.9	T-Balke B-continuous, 60rpm increase 180kgm·min^{-1} every 2 min till exhaustion

Kamon, Pandolf, 1972	11.0 males 7.0 females	T-Taylor B-5 min WU at 50% $\dot{V}O_2MAX$ rest 10 min CE at least 3 min at load predicted to yield $\dot{V}O_2MAX$
Miyamura, Honda, 1972	15.0 Discon. 8.0 Cont.	T-constant, speed chosen to exhaust in 4-8 min, 180-200 $m \cdot min^{-1}$ incremental, 2 min 150-170 $m \cdot min^{-1}$ then increase $10 m \cdot min^{-1}$ B-constant, 4-8 min till end 1260-1620 $kpm \cdot min^{-1}$ incremental, 2 min 900-1260 then increase 180 $kgm \cdot min^{-1}$
McArdle, Katch, Pechar, 1973	10.2-11.2	T-discontinuous, 5min,6mph,2,5% 10 min rest, increase 2.5% each 5 min run, 10 min rest -continuous, 2min,6mph,0% increase 2.5% till exhaustion -Balke -Mitchell, Sproule, Chapman B-discontinous,60rpm,5min,2kg 10 min rest, 3 kg, 60 rpm, then increase 180 $kgm \cdot min^{-1}$ each 5 min -continuous, initial 60 rpm no load, than increase 180 $kgm \cdot min^{-1}$ every 2 min.
McKay Banister, 1975	10.5	Treadmill WU 6 min at 60 rpm load eliciting HR 150 b/min CE-0%, 2.5%/min till exhaustion; separate days at 6.0,6.5,7.0,7.5mph Bicycle WU same as treadmill CE 1min 900 2min 1200 3 and 4 1500 5 and 6 1800 7 and 8 2100 9 and 10 2400 Separate days for 60,80, 100 and 120 rpm

Bergh *et al.*, 1976	7.0	WU 6-10 min at 50% $\dot{V}O_2$ max Treadmill-5-8% for 5 min Bicycle-continuous, one workload per work test
Matsui, 1978	18.0	T-WU-120-140m·min^{-1} at 8.6% for a few minutes, rest 2 min CE 8.6%, 2min 100-140m·min^{-1}, increase 10m·min^{-1} till exhaustion B-WU 29-59 W, 2min, rest 2min CE 60rpm, 2min at 29-59W increase 29W/min till exhaustion
Hagberg *et al.*, 1978	-3.7	T-progressive continuous,7,8 or9mph increase 2%/min till exhaustion B-90rpm, 270kpm·min^{-1} after initial load of 810-1350kpm·min^{-1} 20mph of treadmill increase 0.5%/min from initial 2 or 3%
Miles *et al.*, 1980	8.0	T-Balke walk B-incremental, 60rpm, increase 180kpm·min^{-1} every 2min till exhaustion
Keren *et al.*, 1980	6.0	T-Bruce modified B-increase 50W every 3min from initial 600 kpm·min^{-1}, supramax load of 20W added WU all expts., 5min, HR 150-160, 10 min rest

Pannier *et al.*, 1980	12.8	T-constant speed for controls, 12.5 $km \cdot hr^{-1}$ for runners, initial 0%, increase 2.5% every 3min B-Hollman, Venrath initial WU 140W, increase 40W/3min 60-70rpm
Verstappen, 1982	14.0 (runners) -2% (cyclists)	T-speed 11 $km \cdot min^{-1}$, 5 min increase to 12-13 km·min every 2.5 min, then speed constant, increase incline 2.5% every 2.5 min till exhaustion. B-900 $kpm \cdot min^{-1}$ for 5 min then 1200 for 2. 5 min increase 150 $kpm \cdot min^{-1}$ every 2.5 min till exhaustion.

Thus a new method for the prediction of $\dot{V}O_2max$ from physiological responses to submaximal work rate needs development, specifically for use in bicycle ergometry. Predicted $\dot{V}O_2max$ values from this procedure would then be more accurately referred to as $\dot{V}O_2peak$ or $\dot{V}O_2max$ bicycle.

Several factors contribute to the consistently higher $\dot{V}O_2max$ values determined during treadmill running compared to bicycle ergometry. These include variations in cardiac output, muscle blood flow and leg strength.

2.6.1 Cardiac Output

The relationship among cardiac output (Q), arteriovenous oxygen difference ($(a-\bar{v})O_2$ difference) and maximal oxygen uptake may be described by the Fick equation:

$$\dot{V}O_2max = max\ Q \times max(a-\bar{v})O_2\ difference \qquad \text{(Equation 4)}$$

where Q = stroke volume x heart rate.

Cardiac output has been determined to be less during bicycle ergometry compared to treadmill running (Hermansen et al., 1970;

Faulkner *et al*., 1971; Miyamura and Honda, 1972). Hermansen *et al*. (1970) and Faulkner *et al*. (1971) both determined that the stroke volume during bicycle ergometry was significantly less than that during treadmill running. Miyamura and Honda (1972), in contrast to the above investigators, found that stroke volume was the same in both forms of exercise. These authors, however, noted a lower mean maximal heart rate during bicycle ergometry compared to treadmill running and explained this as due to early fatigue of the quadriceps muscles.

2.6.2 Blood Flow to the Lower Limb

Miyamura and Honda (1972) found that treadmill running produced a greater $(a-v)O_2$ difference, as well as cardiac output, compared to bicycle ergometry. This led the authors to conclude that blood flow to the leg was different during treadmill running compared to bicycle ergometry. Matsui *et al*. (1978) investigated blood flow to the lower limb during treadmill running and bicycle ergometry and found that blood flow to the calf was significantly greater during treadmill running compared to cycling. In general, Matsui *et al*. concluded that total leg blood flow was higher following treadmill running.

Faulkner *et al*. (1971) hypothesized that the ballistic nature of running and the short contraction phase were both biomechanical factors that increased blood flow to the leg during treadmill exercise. In cycling, the contraction portion of the contraction-relaxation cycle is relatively prolonged and the peak loads are approximately twice the load setting (Hoes *et al.*, 1968).

2.6.3 Leg Strength

Katch *et al.* (1974) assessed individual differences in ability to exert force with the legs during cycling and the relative size of the legs in an attempt to explain the lower $\dot{V}O_2max$ values consistently obtained during cycling relative to treadmill running. Measurement of dynamic leg forces during maximal cycling was determined under conditions which exactly duplicated the pedalling rate and specific leg movements during the $\dot{V}O_2max$ bicycle test. Leg force was measured by coupling an isokinetic dynamometer (Cybex II) directly to the pedal sprocket of a Monark friction type bicycle ergometer. Factors such as maximum leg force, maximum leg force relative to body weight, leg weight, leg volume, body composition, and absolute $\dot{V}O_2max$, together accounted for only 2% of the 12.4% higher $\dot{V}O_2max$ values obtained during treadmill running compared to bicycle ergometry. The authors concluded that factors other than maximum leg force and leg composition were associated with the higher treadmill $\dot{V}O_2max$.

2.7 Standardization of Submaximal Exercise Protocols

2.7.1 Pedal Rate

A serious limitation of the A-R nomogram is the variation in submaximal oxygen uptake and therefore heart rate at constant power output produced by variation in pedalling rate (Banister and Jackson, 1967). These authors clearly demonstrated that oxygen uptake at high power developed at slow pedalling frequencies and high resistances was equivalent to that at lower power output developed by high pedalling rates against smaller resistances. Thus $\dot{V}O_2max$ was much larger at higher pedalling frequencies reflecting a declining "work efficiency" as individuals pedalled at rates greater than 80 rpm. A power output of 360 $kpm \cdot min^{-1}$ at a pedalling rate of 120 rpm was equivalent physiologically to 1000 $kpm \cdot min^{-1}$ when pedalling at rates of 50, 60, 70 or 80 rpm.

Hermansen and Saltin (1969) also investigated the effect of varying pedal rates at equivalent power outputs on $\dot{V}O_2max$ during bicycle ergometry. In a supplementary experiment using only six subjects, the pedal rates 50, 60 70 and 80 rpm were studied. The authors concluded that pedal frequencies of 60 and 70 rpm produced the highest oxygen uptake during maximal bicycle exercise compared to 50 or 80 rpm. There was no significant increase in $\dot{V}O_2max$ when the pedalling rate was increased from 60 to 70 rpm. Hermansen and Saltin, however, failed to report $\dot{V}O_2max$ values at 80 rpm while concluding that "80 rpm is too high a frequency to obtain the highest possible oxygen uptake on the bicycle."

Knuttgen et al. (1971) examined the effect on oxygen uptake of variations in pedal rates of 20, 60 and 100 rpm at work rates ranging from zero to 150 watts during a seven minute bicycle ride. In general, Knuttgen et al. (1971), Edwards et al. (1972) and Heinrich et al. (1968) concluded that pedalling at rates between 30 and 90 rpm at equivalent power outputs produced similar oxygen uptake values. Higher oxygen uptakes and heart rate values were elicited when pedalling was above or below the intermediate range of pedal rates at a given power output.

Pandolf and Noble (1973) examined the effect of increasing pedal rates for equivalent power outputs on oxygen uptake as well as the rating of perceived exertion. Pedal rates examined were 40, 60 and 80 rpm, rates in the previously defined intermediate range. Power outputs were submaximal for the subjects examined and were 550, 770 and 1075 $kgm \cdot min^{-1}$. No statistically significant difference was found in oxygen uptake for the various cycling sessions at equivalent, submaximal power outputs. These findings were in agreement with Banister and Jackson (1967), Edwards et al. (1972) and Kamon, Metz and

Pandolf (1972). Stamford and Noble (1974), using pedal rates of 40, 60 and 80 rpm and a single power output of 960 $kgm \cdot min^{-1}$ representing approximately 60% $\dot{V}O_2max$, also failed to find significant differences in measured physiological responses which included heart rate, oxygen uptake and minute ventilation.

A wider range of pedalling frequencies was examined by McKay and Banister (1976) and Gueli and Shephard (1976). In the former study, five male subjects performed maximally at pedal rates of 60, 80, 100 and 120 rpm, while the power output was held constant at each rate investigated. Pedal rates of 80 and 100 rpm were found to produce the highest oxygen uptake values with no significant difference between them. Both 80 and 100 rpm produced signifantly greater $\dot{V}O_2max$ values than frequencies of either 60 or 120 rpm. Gueli and Shephard investigated the effect of varying pedalling frequency on the oxygen uptake of ten young men exercising at 60% of $\dot{V}O_2max$. Again the power output was held constant while pedal frequencies of 50, 60, 70, 85 and 100 rpm were examined. Oxygen uptake values were found to be closely related to pedalling frequency. The lowest oxygen uptake values, indicating the highest efficiency, were at rates of 60 to 85 rpm. Both 50 and 100 rpm were found to elicit the highest oxygen uptake values at 60% of the individual's $\dot{V}O_2max$.

Lollgen _et al_. (1980) attempted to differentiate the rating of perceived exertion between central and peripheral factors by the different physiological tasks apparently produced by different speeds of working for equivalent power outputs. $\dot{V}O_2max$ was first determined on the bicylce while pedalling at 60 rpm, then power outputs demanding approximately 70 and 100% $\dot{V}O_2max$ were calculated. The subjects were then tested on four separate occasions using pedalling frequencies of 40, 60, 80 and 100 rpm while holding the power output constant at zero work rate (unloaded pedalling), 70% of $\dot{V}O_2max$ or 100% of $\dot{V}O_2max$. Although rating of perceived exertion was the measure of prime interest to the investigators, oxygen uptake values were shown to increase from 40 to 100 rpm during unloaded pedalling with significant differences at all pedal rates. At 70% $\dot{V}O_2max$, oxygen uptake was significantly greater while pedalling at 100 rpm than at 80 rpm. Pedal rates of 40 and 60 rpm produced oxygen uptake values which were also significantly lower than either 80 or 100 rpm. When exercising at 100% of $\dot{V}O_2max$, no significant differences were found in $\dot{V}O_2max$ but there was a slight tendency for $\dot{V}O_2max$ to be greater at 100 rpm though no definite values were reported.

Heart rate was found to vary with pedal rate during submaximal work. Significant differences in heart rate were found during unloaded pedalling between 40, 60 and 80 versus 100 rpm. At 70% of $\dot{V}O_2max$, heart rate was significantly different at 40 and 60 rpm versus 100 rpm. Heart rates at 100% $\dot{V}O_2max$ were not found to vary with pedal rate.

From the results of these studies, it appears that there exists an intermediate range of pedalling frequencies, between approximately 50 and 85 rpm, within which no significant changes in oxygen uptake or heart rate occur when power output is held constant. This range exhibits a minimum oxygen consumption and therefore a maximum efficiency of external work delivery while pedalling a bicycle. Pedal frequencies above or below this range produce oxygen uptake values which are significantly greater than those in the intermediate range. Pedal frequencies of 50 and 100 or 120 rpm ensure maximal inefficiency of external work delivery and therfore act maximally to engage the cardiorespiratory system. Low pedalling frequencies, however, necessitate relatively large braking forces and anaerobic work may develop. Anaerobic metabolism and therefore lactic acid production is greater at slow pedalling rates due to more sustained contraction and increased muscular ischemia (Pandolf and Noble, 1973; Gueli and Shephard, 1976). Local muscular fatigue may be the limiting factor to performance rather than central, cardiorespiratory insufficiency (Banister and Jackson, 1967; Gueli and Shephard, 1976). Higher pedalling frequencies greater than 85-90 rpm produce greater oxygen uptake values than those in the intermediate range when exercising at constant power output. It has been postulated that less contractile force is exerted per muscle contraction during cycling with high pedal rates and that this may play a role in permitting more muscle blood flow during the period of contraction (Tonneson, 1964). Fewer fast-glycolytic (FG) muscle fibers may also be recruited so that work may be accomplished primarily by the fast-oxidative-glycolytic (FOG) and slow oxidative (SO) fibers (Hagberg *et al*., 1978).

2.7.2 Perceived Exertion

The ability to perform a defined work task is somewhat dependent upon psychological as well as upon physiological factors. The subjective effort or perception of the strain of work will ultimately determine the maximal working level accomplished by an individual. Psychophysics is a term describing the science investigating quantitative relationships between physical stimuli and their corresponding correlates, i.e. the quantitative relationship between stimulus and response. Psychophysical principles have been recently utilized by Stevens and Mack (1959) and Stevens and Cain (1970) to relate perceived exertion to physical exertion. To a first approximation, perceived effort was described by the above authors to grow as a power function of the physical level of exertion; the exponent function of the equation (equalling 1.7) varied little from one exercise task to another (Cafarelli *et al*., 1977) though this has been disputed by Banister (1979).

Borg *et al*. (1962) developed a 15 point rating of perceived exertion scale (RPE) for the perceptive estimation of varying intensities of physical work performed on the bicycle ergometer following the principles first developed by Stevens (1957). The scale was constructed so that each of the 6 to 20 point scale values when multiplied by 10 equalled the heart rate developed by most young subjects during bicycle ergometry of progressive intensity up to maximum exertion. Many studies since 1962 have been conducted to study various factors, including variations in the type of work performed (i.e. eccentric versus concentric muscular contraction) and variations in speed, load, duration and the effects of training (Ekblom and Goldbarg, 1971; Edwards et al., 1972; Henriksson et al., 1972; Gamberale, 1972; Pandolf et al., 1972; Sargeant and Davies, 1973; Cafarelli et al., 1977), which may influence the RPE values during bicycle ergometry. Study of these factors led the proposal of a two-factor model by Ekblom and Goldbarg (1971) which attempted to distinguish between so called central and peripheral feelings of strain.

Variation in pedal rate during bicycle ergometry was found to produce variation in oxygen uptake and heart rate at constant power output (Banister and Jackson, 1967; Hermansen et al., 1969). The interaction between variations in pedalling frequency and rating of perceived exertion was soon studied thereafter. Henriksson et al. (1972) determined that pedalling at a frequency of 30 rpm at a specific submaximal work intensity was perceived to be more difficult during both concentric and eccentric exercise, than pedalling at a frequency of 60 rpm for the same power output. Pandolf and Noble (1973) investigated the ratings of perceived exertion associated with pedalling at rates of 40, 60 and 80 rpm while maintaining a constant, submaximal power output. Pedalling at 40 rpm was found to be more stressful than either 60 or 80 rpm, while RPE values at 60 and 80 rpm did not differ significantly. Stamford and Noble (1974) studied the same problem with 10 highly fit trained males during 15 minutes of continuous work at submaximal work levels of 960 $kgm \cdot min^{-1}$ using pedalling rates of 40, 60 and 80 rpm. Perceived exertion was determined to be significantly less at 60 rpm than at equivalent power outputs performed with 40 or 80 rpm. Lollgen (1975) studied the effects of one minute exercise periods at pedal rates of 40, 60, 80 and 100 rpm and workrates of 300 to 1200 $kpm \cdot min^{-1}$ of RPE. He found that in healthy subjects the RPE decreased with increasing pedal rate at constant power output. Lollgen concluded that when using the RPE scale, pedalling rate must be considered an important factor. Cafarelli (1977) studied two pedal frequencies, 30 and 60 rpm, during 4 minute exercise bouts at levels requiring 35, 50, 65 and 80% of $\dot{V}O_2max$. Perceived exertion at equivalent power outputs pedalling at 30 rpm was always judged to be more difficult than 60 rpm. Growth in feelings of fatigue during the period of effort was found to depend on both pedal resistance and power output. Near the point of exhaustion, pedalling rate positively influenced the relative feelings of effort for a given braking resistance of the pedal. At the beginning of exercise, pedal rate had no effect on the effort-resistance relationship.

Lollgen _et al_. (1980) required six healthy male subjects to exercise at zero power output (unloaded pedalling), submaximal

(70% $\dot{V}O_2max$) and maximal exercise intensities at various pedal rates of 40, 60, 80 and 100 rpm. In general, as power output increased, the RPE decreased as pedal rate increased. At power outputs requiring 70% of $\dot{V}O_2max$, the least stressful pedal rate was 65 rpm, while at power outputs requiring 100% of $\dot{V}O_2max$, a pedal rate of 73 rpm was perceived less stressful.

Examination of the equation proposed by Stevens and Cain (1970) relating effort (Y), static force (P) and duration (T)

$$Y = (k \cdot P) \cdot T \qquad \text{(Equation 5)}$$

where k is a constant, provides a possible explanation for the decrease in RPE scores with increasing pedal rate at high power outputs. Since effort grows much more rapidly as a function of load than of time, a slight reduction in load would allow work to proceed for a longer period of time at a constant level of effort (Cafarelli _et al._, 1977). Bicycle ergometry has a significant inertial component where the contracting muscle must develop enough tension to overcome the brake resistance. This inertial component is greater in slow, high force contractions than during fast, low intensity contractions (Petrofsky _et al._, 1974). High rates of pedalling at constant power outputs would therefore reduce the inertial component and result in a lower RPE score.

The basis of the Borg 15 point RPE scale was the quantitative relationship drawn between heart rate and perceived metabolic strain. Many studies, however, have subsequently investigated this relationship and concluded that the degree of heart rate elevation is not a good measure of one's subjective estimation of the extent of one's physical exertion. Ekblom and Goldbarg (1971) examined the effects of autonomic nervous system blocking agents on the RPE-heart rate relationship. Compared to control conditions, administration of propanolol increased RPE scores at the same heart rate, while atropine administration lowered the RPE scored at the same heart rate level. Pandolf et al. (1972) examined the effects of increased environmental heat on the RPE-heart rate relationship and found no significant increase in RPE though heart rate was increased. Morgan et al. (1973) studied the effects of hypnotic suggestion and its influence on the RPE-heart rate relationship during bicycle ergometry. The investigators found RPE scores to increase with the hypnotic suggestions of light, moderate and heavy work rates despite the fact that the subjects continued to work at a constant submaximal power output of 600 $kpm \cdot min^{-1}$.

Due to these criticisms, Borg devised a new perceived exertion rating scale more closely approximating psychophysical principles (Stevens and Cain, 1970). The new scale is a true ratio scale extending from zero to ten. A zero rating corresponds to the subjective feeling of strain rated as "nothing at all" while a rating of "four" indicates a perceived intensity twice that of a rating of "two", and as "eight" as twice that of a rating of "four" etc. (Borg _et al_., 1981). See Appendix B.

2.7.3 Efficiency of Work

Any study of the effect of variations in pedal rate on the rating of perceived exertion at constant power outputs leads one to question whether the pedal rate perceived to be the least stressful is also the most efficient in terms of its oxygen cost. Studies on the efficiency of power output during bicycle ergometry have been confusing due to the many methods of calculating the oxygen cost of performing work. Efficiency has been defined as prefixes: gross, net, work, delta and instantaneous efficiency (Gaesser, 1975; Stainsby _et al_., 1980). Various formulations describing these definitions are outlined in Appendix A.

Questions arise as to which definition of efficiency is most meaningful in examining the effects of variations in pedal rate at constant power outputs. Work efficiency, as defined by Whipp and Wasserman (1969), provides the best method for bicycle ergometry since the calculation includes only the oxygen uptake necessary to perform measured ergometer work. The oxygen uptake increment for unloaded pedalling acts as the baseline value and is subtracted from the measured oxygen uptake. This baseline value for unloaded pedalling, however, has been found to vary with changes in pedal rate. Banister and Jackson (1967) reported higher energy costs of freewheeling with higher rates of pedalling as did Knuttgen et al., 1977. This variation in baseline oxygen uptake values with changes in work rate has been extensively studied by Stainsby et al. (1980). In order for such baseline subtractions to be truly valid, the energy use representing any baseline pedalling frequency chosen must contribute its partial cost equally throughout all work rates completed at that particular pedal frequency (Wilkie, 1974). The only alternative would be to measure oxygen uptake values for unloaded pedalling for the same duration as the actual testing procedure to allow for changes in gastrointestinal processes, splanchnic metabolism, mean body temperature, the oxygen cost of ventilation, catecholamine levels and lactate levels as outlined by Stainsby et al. (1980) and this is not practicable routinely. Subtraction of oxygen uptake values for unloaded pedalling during each time interval in which $\dot{V}O_2$ is measured from the total oxygen uptake of the interval should result in accurate efficiency calculation.

Many of the experiments attempting to examine the effects of variations in pedal rate at constant power outputs on efficiency have used gross, delta or net efficiency calculations. Knuttgen et al. (1971) calculated efficiency as gross oxygen uptake less freewheeling oxygen consumption and found higher efficiency at higher pedalling frequencies. Gueli and Shephard (1976) found pedal rates of 60 to 85 rpm at submaximal workrates produced a minimum oxygen consumption and hence maximum efficiency. Seabury _et al_. (1977) calculated greatest gross efficiency at highest work rates with faster pedal frequency. Optimal pedal rates increased from 39.7 rpm at zero power output, to 54.2 rpm at 163.4 watts and 62.0 rpm at 326.8 watts. The authors noted, however, that gross efficiency increased at higher workrates due to the relatively less contribution overall of resting metabolism as total metabolism increased.

Lollgen (1977) concluded that in many studies (Stegemann _et al_., 1968; Gaesser _et al_., 1975) muscular efficiency changed in a parabolic manner as speed increased; the minimum oxygen uptake occurred at about 50 rpm. In these experiments pedal frequency producing maximum efficiency differed from the frequency producing minimum perceived exertion.

Several authors have raised the question of pedalling rate and standard methodology in ergometry (Banister and Jackson, 1967; Pandolf and Noble, 1973; Gueli and Shephard, 1976; McKay and Banister, 1976; Lollgen _et al_., 1977). During maximal performance tests, high pedalling rates appear to increase motivation and cooperation of subjects. The limitations imposed by local muscular fatigue and psychological attitude during the assessment of physical working capacity on the bicycle ergometer may be removed by conducting tests for given power outputs at increased pedal rates greater than 85 rpm. A higher pedalling rate will ensure maximal inefficiency of external work delivery and thus maximum engagement of the cardiorespiratory system unimpaired by conditions of premature local fatigue engendered by high peripheral muscle loading. A more accurate assessment of cardiovascular fitness will result.

Overall, the literature seems to define a range of pedal frequencies for equivalent power output over which oxygen uptake measurements are similar (Heinrich et al., 1968; Knuttgen et al., 1971; Edwards et al., 1972). At the extremes of this range but well within a person's capacity, i.e. low pedal rates/high braking force - high pedal rates/low braking force, oxygen uptake measures differ because of the increasing inefficiency with which external work is delivered. Classically, low pedal frequencies have been chosen for international use. However, early high intramuscular force development in this mode may unnecessarily limit achievement of true aerobic capacity because of locally produced muscle fatigue (Tonneson, 1964; Banister and Jackson, 1967; Pandolf and Noble, 1973; Gueli and Shephard, 1976; Hagberg et al., 1978). The perception of exertion and hence fatigue is also different and negatively affecting in low pedal frequency/high braking force tasks. The conclusion to be reached, therefore, is that the high pedal frequency/low brake force mode should be used to define a new and physiologically more appropriate international testing methodology and standards.

3. Methods

3.1 Experimental Groups

Two groups of healthy males 20 to 29 years were subjects in the study. The first group (T) (n=20) were well trained individuals with a mean maximum oxygen uptake equal to 70.3 $ml \cdot kg^{-1} \cdot min^{-1}$ as measured on a bicycle ergometer. The second group (n=19) were relatively untrained having a mean maximum aerobic capacity less than 56 $ml \cdot kg^{-1} \cdot min^{-1}$. Relatively untrained individuals were difficult to recruit. This group, therefore, contained a sub-group (n=4) of moderately trained individuals (MOD) possessing a mean maximum oxygen uptake of 55.4 $ml \cdot kg^{-1} \cdot min^{-1}$. The remaining subjects within this group (UNT) (n=15) possessed a mean oxygen uptake of 46.8 $ml \cdot kg^{-1} \cdot min^{-1}$. Subject data is presented in Table III.

Table III: Subject Data

Group	Age (years)	Weight (kg)	$\dot{V}O_2$ max ($l \cdot min^{-1}$)	$\dot{V}O_2$ max ($ml \cdot kg^{-1} \cdot min^{-1}$)
T (n=20)	22.9 ±2.9	70.9 ±5.0	4.97 ±0.33	70.3 ±4.4
UNT (n=15)	23.2 ±2.1	70.7 ±10.1	3.26 ±0.41	46.8 ±7.4
MOD (n=4)	23.3 ±2.1	69.0 ±5.3	3.80 ±0.12	55.4 ±5.5

Values are means ± standard deviations (SD).

Complete details of the experimental procedures and an explanation of the potential hazards involved to the participant were provided for each volunteer before obtaining his written consent to participate. All subjects then underwent a thorough medical examination before beginning the study.

Trained subjects were competitive cyclists and were tested during their competitive off-season (winter). They were considered to be in a steady state of training and were instructed to avoid dramatic changes in their regular training programs for the duration of the testing period. They were directed to refrain from heavy training or competition two days prior to a testing session and to abstain from any activity on the day of testing. Each cyclist was required to record the type, intensity and duration of his training activity in order to check for any possible reduced or improved maximal performances with excessive training. Such tests were then rejected. Untrained subjects were not actively involved in any type of regular exercise program and had not been for at least 18 months prior to the time of testing. Untrained subjects were instructed to refrain from initiating a training program of any type until all testing was completed.

All subjects were allowed to familiarize themselves with the laboratory environment, testing procedure and equipment during at least two preliminary sessions. This practice was expected to reduce the effects of learning and allow for habituation to take place. All testing was conducted by the same investigator and similar conditions were maintained throughout the testing period. Only those individuals integral to the conduct of the experiment were permitted in the laboratory. The laboratory was equipped with resuscitation equipment and medical personnel were on call at all times. The investigator was also qualified to perform CPR.

All subjects reported to the lab at least two to three hours after their last meal. Smoking and consumption of alcohol and caffeine were prohibited on the days of testing.

3.2 Experimental Design

Subjects within the trained group were randomly assigned to one of two sub-groups: a core test group of 15 (Tcore) and a validation group of five individuals (Tvalid). A similar procedure was followed for the untrained group. Ten subjects comprised the core group (UNTcore), and five the validation group (UNTvalid). The four moderately trained individuals were treated as untrained individuals in that they completed the same work protocols as the untrained subjects. Data collected from this group, however, was used only to cross-validate the predictive accuracy of the nomogram.

All subjects arrived at the laboratory 30 minutes prior to testing and remained seated on the bicycle ergometer for ten minutes to minimize the effects of pre-test activity. Each trained and untrained subject performed a submaximal and a maximal test according to Protocol Ia, Ib and IIa, IIb, respectively, as illustrated in Figures 1 and 2. These protocols were repeated on two occasions for the untrained and three times for the trained groups respectively, each separated by one week's rest. This sequence of testing and re-testing was chosen to allow adequate time for recovery and to ensure insufficient frequency of testing for any training effect to take place. In order to alleviate the effects of weekly and diurnal rhythms, each subject was tested on the same day of the week as well as at the same time of day. In no case did more than two weeks elapse between experimental sessions.

3.3 Test Protocols

3.3.1 Protocol IA and IB: Submaximal Exercise

In the present investigation, work was expressed in units of $kpm \cdot min^{-1}$ rather than in standard international units of watts (W) found in the current literature related to bicycle ergometry. The rationale for the use of $kpm \cdot min^{-1}$ was to allow for a comparison between data measured in the present study with data collected by Astrand and Ryhming in 1954. Work rate expressed in $kpm \cdot min^{-1}$ may easily be converted to watts by the following relationships:

$$
\begin{aligned}
1 \text{ watt} &= 1 \text{ joule} \cdot sec^{-1} \\
&= 6.12 \text{ kpm} \cdot min^{-1} \\
&= 0.74 \text{ ft lb} \cdot sec^{-1}
\end{aligned}
$$

where 1 kpm = 1 kilopondmeter.

A work rate of 600 $kpm \cdot min^{-1}$ may, therefore, be expressed equivalently as 100 watts.

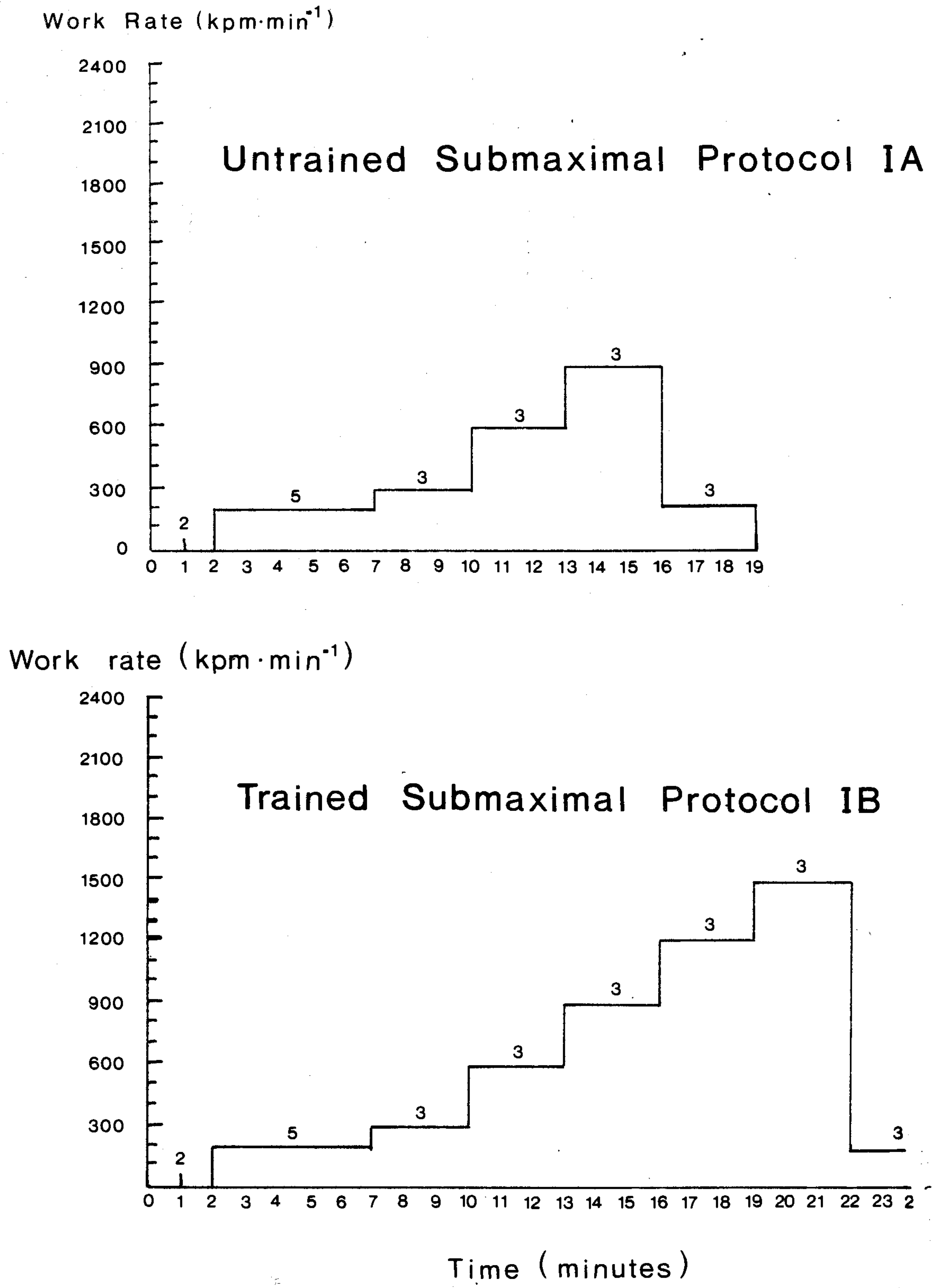

Figure 1: Submaximal Protocols IA and IB shown as work-time profiles.

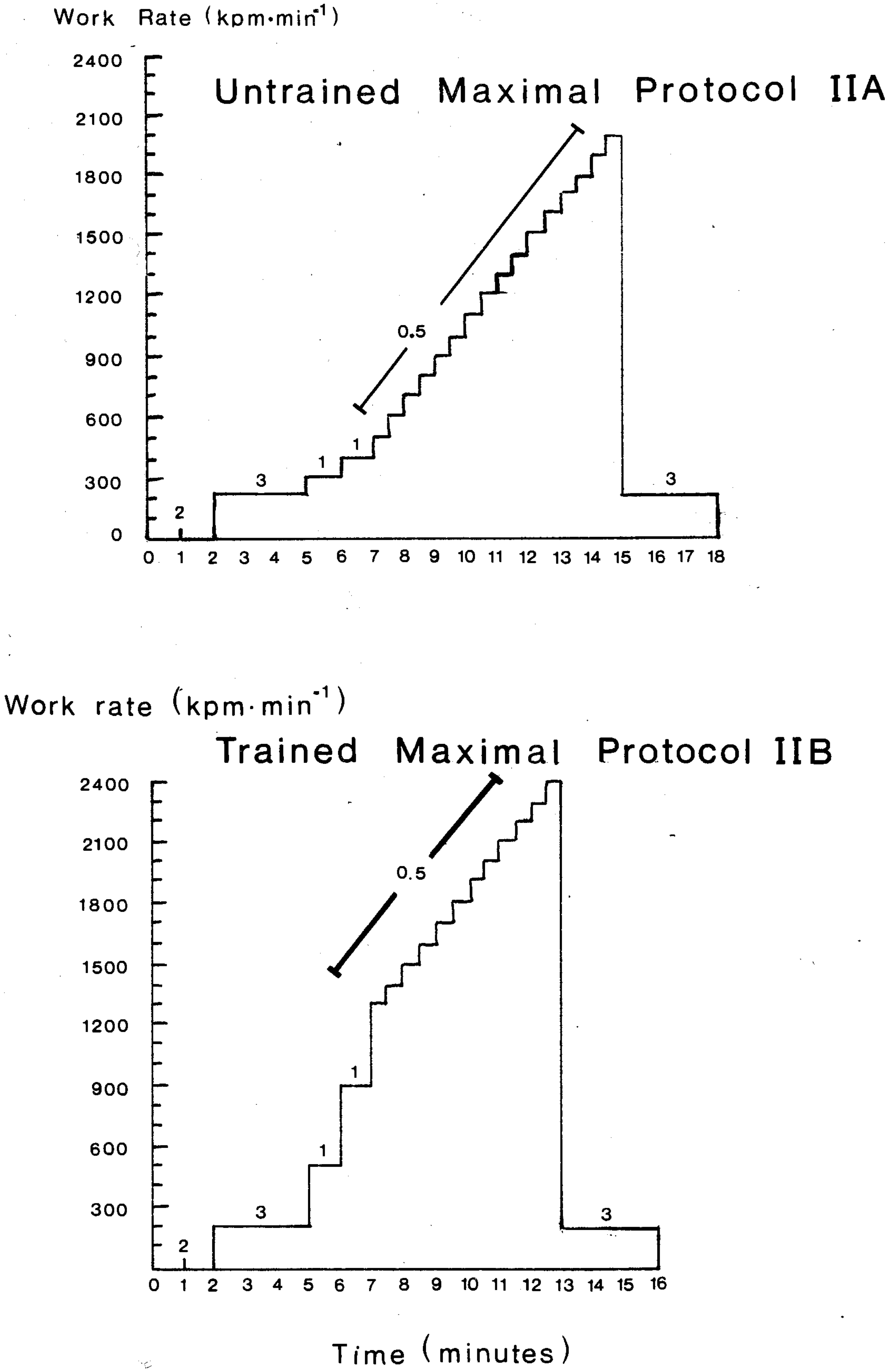

Figure 2: Maximum Protocols IIA and IIB shown as work-time profiles.

Protocol I, began with an initial five minute period of pedalling with no external load imposed (zero load pedalling, unloaded pedalling, 90rpm) on the Quinton electromagnetically braked bicycle. This period acted as a well-defined warm-up period. It was an integral feature of the protocol in that it provided a stable base-line value, reducing the effects of anxiety and variability in heart rate during the initial phase of the submaximal test. This value replaced the traditional and variable resting heart rate usually measured. The protocol allowed for smooth transition from rest to the first work rate. Unloaded pedalling was determined to be approximately equal to 200 $kpm \cdot min^{-1}$.

Protocol Ia, for untrained subjects, consisted of submaximal exercise at work rates of 300, 600 and 900 $kpm \cdot min^{-1}$ during consecutive three minute periods. Work rates were chosen to achieve approximately 80% of an individuals age-predicted heart rate maximum by the end of the third 3 minute period. Three minutes at each work rate has been determined to be sufficient time to allow heart rate to reach a steady state level. A three minute step work rate interval agrees well with what is commonly used in exercise testing (McConnell and Sinning, 1980) and was chosen as a compromise between various time interval options. Three minutes of active unloaded pedalling ended the session.

Protocol Ib, for trained subjects, was identical to that of untrained subjects but due to the group's higher level of fitness or state of training, two additional work rates of 1200 and 1500 $kpm \cdot min^{-1}$ were required to achieve the desired elevation of heart rate (i.e. 70 to 80% of maximum heart rate).

3.3.2 Protocol IIa and IIb: Maximal exercise

Protocol II began with an initial three minute warm-up period of unloaded pedalling. Subsequently, two, one minute work rates were then completed followed by a series of 30 second work rate ramp increments each of 100 $kpm \cdot min^{-1}$. Two step changes of 300 and 400 $kpm \cdot min^{-1}$ were completed by the untrained group after warm-up. The ramp changes in work rate then began and continued to exhaustion. Higher work rates were required for the trained group. After warm-up, trained subjects completed two step increments of 500 and 900 $kpm \cdot min^{-1}$ respectively, after which the 100 $kpm \cdot min^{-1}$ 30 second ramp increase to exhaustion began at 1300 $kpm \cdot min^{-1}$. The initial work rates were chosen to act as a step or aid in alleviating the effects of sudden inertial loading. The ramp increments of Protocols IIA and IIB provided for approximately six to eight minutes of work before exhaustion in both untrained and trained groups.

The detailed protocol and choice of ramp slope in any work test construction, was at the discretion of the investigator since consistent maximal oxygen uptake values are obtained regardless of the precise details of the test (Whipp et al., 1981). However, important constraints are that too steep a slope would cause the work rate to be limited by a subject's ability to generate muscular force despite the oxygen response not yet attaining its maximal value. Too small a ramp produces too long a test and simply "wastes" time (Whipp et al., 1981).

3.3.3 Protocol III: Trained Maximal Exercise

The highest possible work rate able to be provided by the electromagnetically braked bicycle ergometer used in the experiments was 2400 kpm·min^{-1} and several trained subjects were able to attain this work rate without reaching their maximum capacity, a second maximal test was designed for a mechanically braked Monark bicycle ergometer and named Protocol III. If it was established from the final maximum exercise test on the electromagnetically braked Quinton ergometer, that a subject's highest capacity was not demanded by the 2400 kpm·min^{-1} rate of work, Protocol III was scheduled. In this test (Figure III), subjects transferred to the Monark bicycle immediately following completion of a one-half minute work rate of 2400 kpm·min^{-1} of Protocol IIB to continue with higher work rates. A time interval of approximately five minutes was allowed before Protocol III was initiated. Subjects, however, remarked that cycling on the Monark bicycle according to Protocol III seemed quite dissimilar to work on the electromagnetically braked bicycle. Data obtained from the completion of this protocol were used only to check the peak oxygen uptake and heart rate values obtained by Protocol

IIB. In the case that higher physiological values were obtained in Protocol III, however, they were considered maximum values.

Following the cessation of maximal exercise, all subjects were instructed to remain seated on the bicycle and continue pedalling at zero load for an additional three minutes to aid in the recovery process.

3.3.4 Recovery Period between Submaximum and Maximum Tests

Due to the submaximal nature of Protocol I, a recovery period of only 20 to 45 minutes was allowed before beginning the maximal Protocol II. Rectal temperature, which was recorded throughout the entire work test and recovery interval, provided a direct measure on which to base the recovery time interval. The return of rectal temperature to within 0.1°C of the pre-exercise resting level was used as a criterion for beginning a maximal test. On average, untrained individuals required 30 to 45 minutes, while trained individuals required 20 to 30 minutes to reach this standard. All subjects remained seated during the rest period and were not allowed to eat or drink during this time.

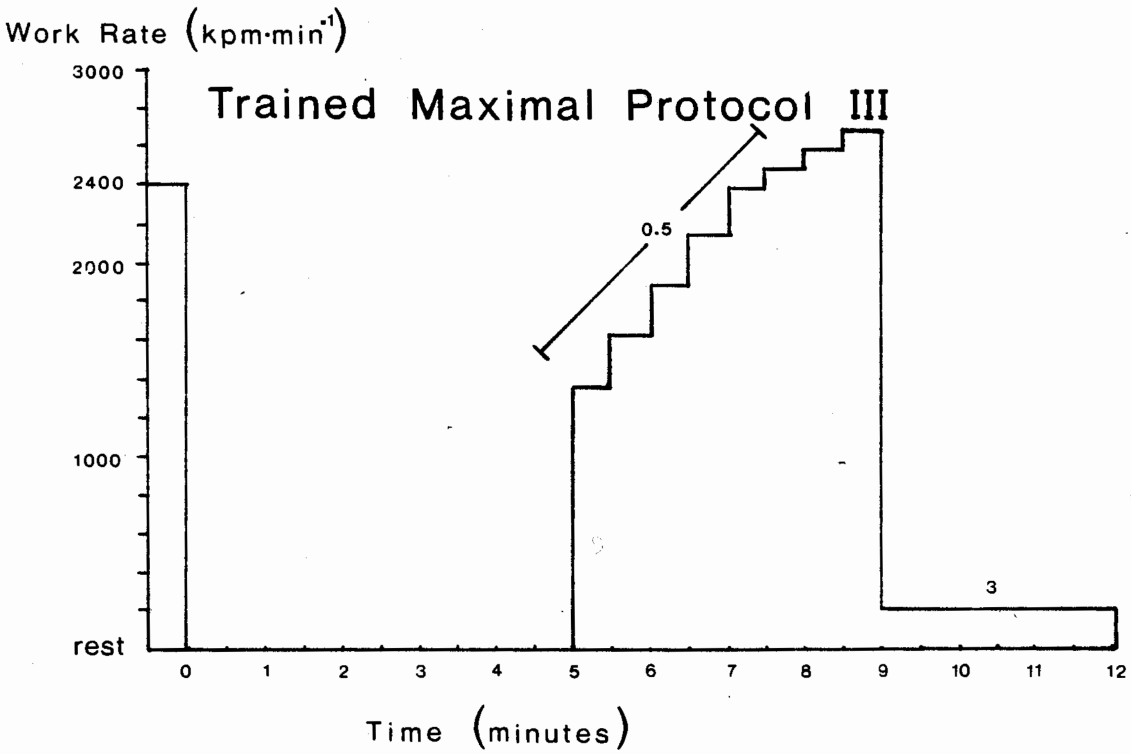

Figure 3: Maximum Protocol III for trained subjects shown as a work-time profile.

3.3.5 Criteria for Attainment of Maximum Oxygen Uptake

The end point of a maximal test was defined as the point when the subject could no longer maintain a pedal rate of 75 rpm. Other criteria were whether the subject attained his maximal age-predicted heart rate, and whether a plateau of oxygen uptake with increasing work rate was achieved. The true course of oxygen uptake continuously plotted on a Hewlett Packard 85 computer made this latter criterion easy to identify, although the plateau was slight due to the nature of the ramp work test. If subjects were able to ride for more than two minutes at the highest work rate, a plateauing in oxygen uptake was observed.

To confirm whether maximal performance was being achieved by this protocol, blood lactate concentration was determined in 10 of the 20 trained subjects and 10 of the untrained subjects, from a blood sample drawn from an antecubital vein five minutes after the cessation of maximal exercise. Although the time for the development of peak blood lactate has been shown by various investigators to vary from three to nine minutes following the cessation of maximal exercise, a time interval of five minutes was chosen as a suitable standard time for measurement. Samples were immediately deproteinized with ice-cold perchloric acid for subsequent analysis of lactate concentrations using enzymatic techniques (modified from Gutman and Wahlefeld, 1974).

3.3.6 Astrand-Ryhming Submaximum Exercise Test

A traditional Astrand-Ryhming submaximal six minute test was performed by all untrained subjects and half of the trained group. Untrained subjects began by performing for 6 minutes at 300 $kpm \cdot min^{-1}$, as suggested by Astrand for untrained individiuals. If the heart rate did not attain a value of 130 $b \cdot min^{-1}$ after the first workrate, the workrate was increased by 300 $kpm \cdot min^{-1}$ for an additional 6 minutes.

This protocol was continued until a heart rate of approximately 150 $b \cdot min^{-1}$ was attained. The working time of 5 to 6 minutes was deemed to be of sufficient a period to allow the pulse rate to equilibrate with the task being performed. The mean value of the pulse rate at the fifth and sixth minute was designated the working pulse for the work in question. If the difference exceeded 5 $b \cdot min^{-1}$, the work time was prolonged.

Trained subjects began, as suggested by Astrand, at 900 $kpm \cdot min^{-1}$, and increased the workrate to 1200 and 1500 $kpm \cdot min^{-1}$ if the heart rate was still less than 130 $b \cdot min^{-1}$. All subjects performed the Astrand-Ryhming test at a pedal rate of 50 rpm. The Astrand-Ryhming test was performed only once. This was on the same day as one of the maximal testing sessions in order to compare directly measured and maximal oxygen uptake predicted from the existing Astrand-Ryhming nomogram.

3.4 Techniques and Equipment

Oxygen uptake was measured continuously during all phases of the experiment, including rest, warm-up, submaximal and maximal exercise and recovery. All subjects breathed through a low-resistance two-way breathing valve that directed the expirate to a mixing box. A sample of mixed expired gas was then drawn from the mixing box and analyzed for carbon dioxide and oxygen content. The assembly connections are shown diagramatically in Figure 4.

Ventilatory volume was obtained by integrating the flow rate of inspired gas obtained from a respiratory flow transducer (HP 47304A) over a ten second period and conditioning the signal with a HP 17401A DC Preamplifier connected to an HP 7404A oscillographic recorder. Mixed expired gas was analysed for oxygen and carbon dioxide content with an S-3A Applied Electrochemical oxygen analyser and a CD-3A Applied Electrochemical carbon dioxide analyser, respectively.

Outputs from the gas analysers, electrocardiograph and carrier preamplifier were sampled at ten second intervals by an HP 3497A Data Acquisition Unit, controlled by a desktop computer(HP 85). Rectal temperature was recorded by a tele-thermometer with a general purpose probe (Yellow Springs Instrument Co. Inc.).

A BASIC program, written specifically for the metabolic analyser, controlled the sampling rate of the HP 3497A and computed ten second values for oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}ECO_2$), ventilation ($\dot{V}E$), and respiratory exchange ratio ($\dot{R}$). Minute values were computed by averaging six ten second samples for that particular minute.

The ECG was displayed continuously on a Physio-Control heart rate monitor and this enabled recognition of any heart conduction abnormalities. The ECG was also recorded during the final 10 seconds of each minute of warm-up, exercise and recovery on an electrocardiograph (HP 1500A).

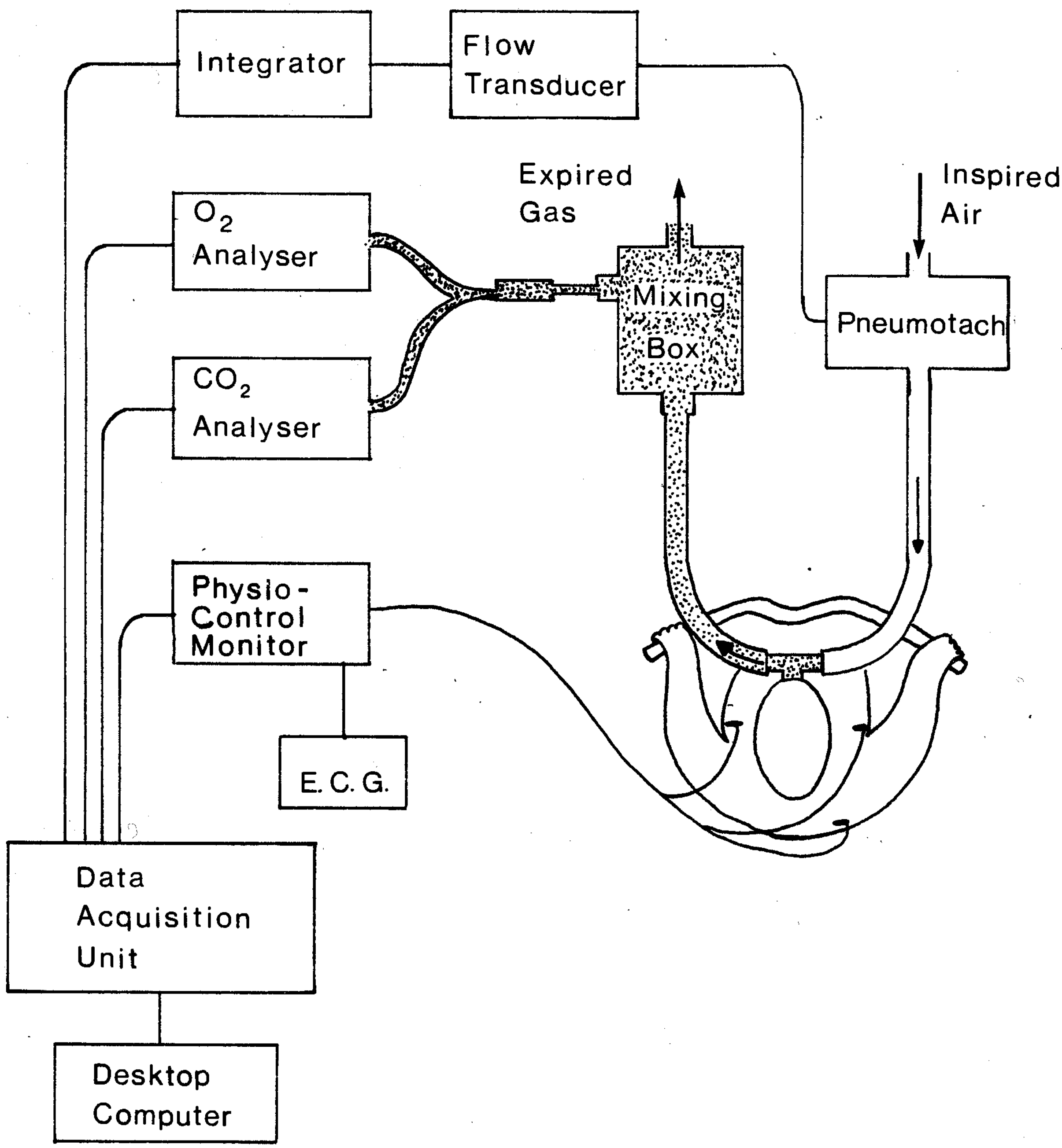

Figure 4: Diagrammatic Representation of the Experimental Equipment.

3.4.1 Calibration of Instruments

Gas Analyser and Pneumotachograph Calibration

Calibration of the oxygen and carbon dioxide gas analysers, pneumotachograph and electrocardiograph was performed during the specifically designed calibration section of the BASIC computer program. This procedure was completed prior to testing each subject. Gas analysers were calibrated with standard gases and known flow rates, respectively. Standard gases for calibration purposes were chosen to fall within the physiological range to be measured. Standard gas concentrations were themselves previously analysed by the micro-Scholander technique (1945). Correction factors for water vapour pressure and breathing valve dead space were applied to the respiratory variables by the program software.

Validation of Respiratory Gas Exchange Movement

Validation of the computed values of ventilation and oxygen uptake was performed by comparing computer calculated values with those measured using the traditional method of one minute expired gas samples collected in meteorological balloons at various intensities of bicycle ergometer work. The collected mixed expired gas was analyzed for oxygen and carbon dioxide concentrations. Ventilatory volumes were converted to standard temperature and pressure dry (STPD) and oxygen uptake was calculated. Simultaneous determinations of ventilation and oxygen uptake for 20 subjects during submaximal and maximal exercise are shown in Figures 5 and 6. Regression equations, correlation coefficients and the line of identity are shown. No significant differences existed between the computer calculated ventilations or oxygen uptakes and the directly measured values. The response characteristics and accuracy of the respiratory gas equipment used in this study compared very favourably with published data on other similar systems in the literature (Beaver _et al_., 1973; Wilmore _et al_., 1978). The computer calculated oxygen uptake was, therefore, assessed as accurate.

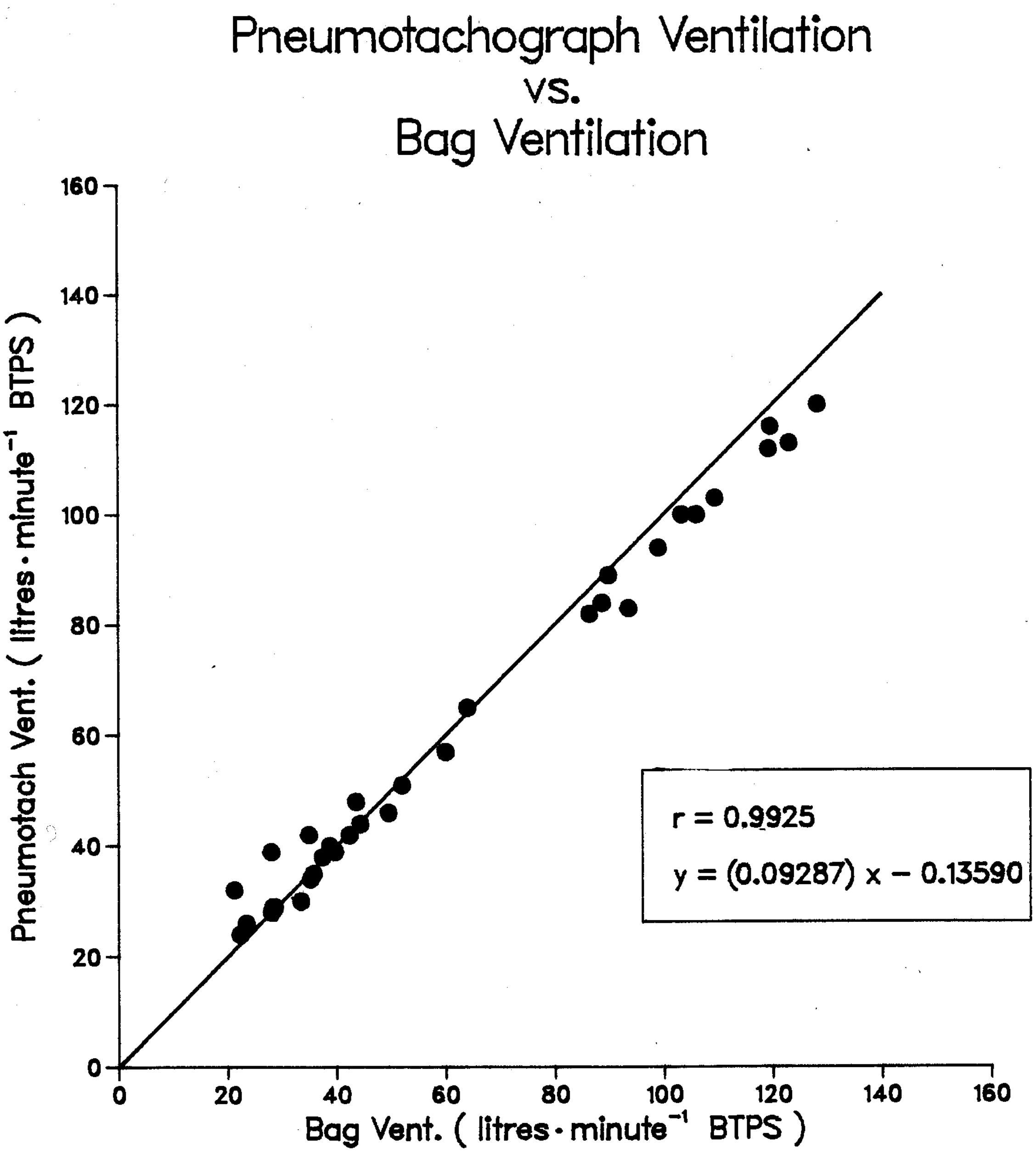

Figure 5: Comparison of respiratory gas volumes determined from bag collections simultaneously with pneumotachograph determinations. Solid line indicates the line of identity.

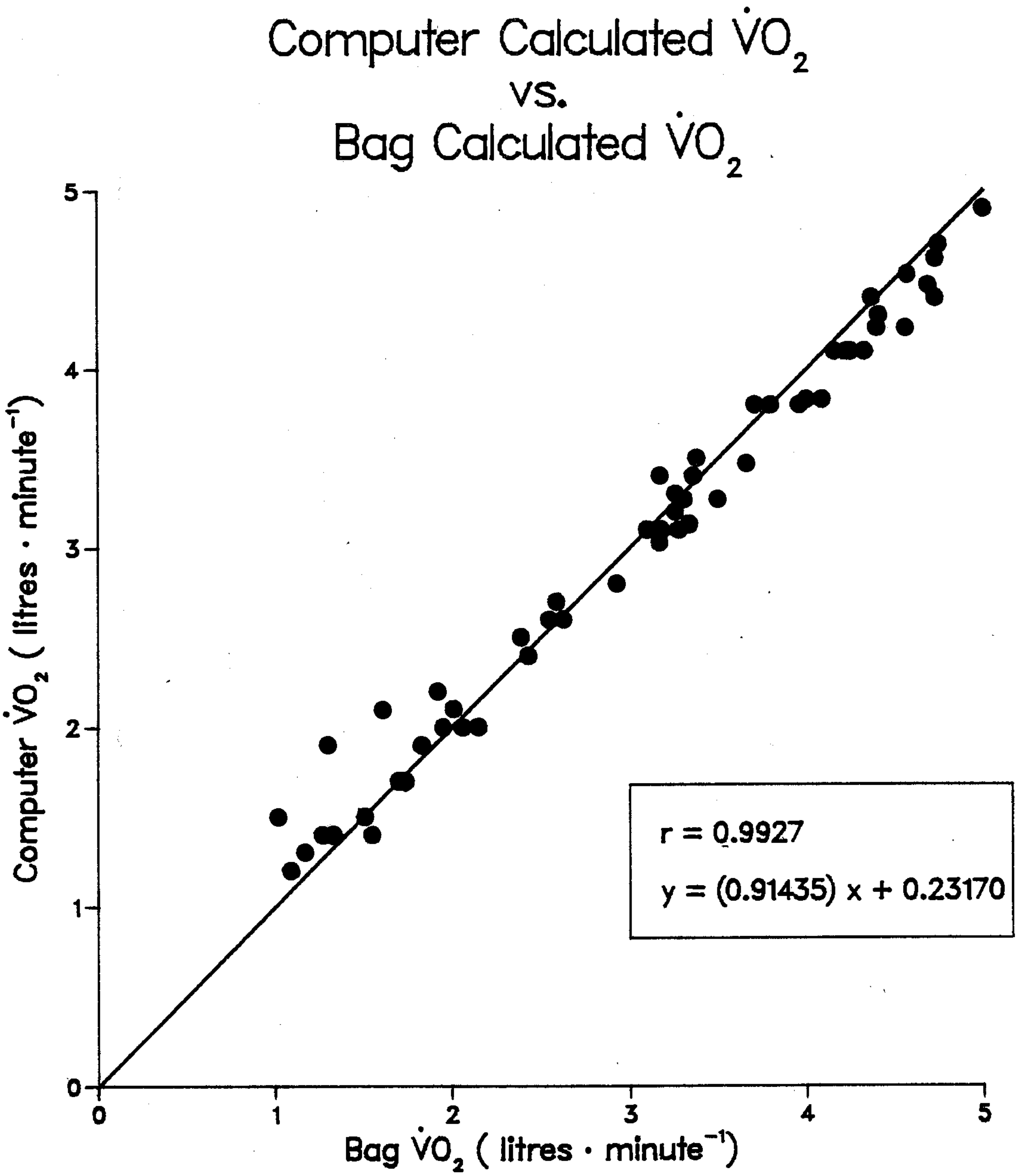

Figure 6: Showing a comparison of oxygen uptake measurements determined from on-line computer calculations and separate analysis of collected respired gases in minute bags. Solid line indicates the line of identity.

Bicycle Ergometer Calibration

Precise measurement of the work rates and power outputs demand precise calibration of the ergometer. Electronic ergometers are designed so that work varies directly as resistance multiplied by rate of work (rpm). The generator's resistance is designed to decrease as the rate increases, thus maintaining the work load at a constant value.

The QI-845 bicycle ergometer used in the experiments was calibrated at the Quinton Manufacturing Company in Seattle, Washington prior to the start of the experiments.

3.5 Definition of Variables

The variables studied in this investigation were oxygen uptake, heart rate and work rate. These variables, in particular heart rate and work rate, were manipulated to provide greater insight into the existing relationships between work rate, heart rate and oxygen uptake. A definition of derived variables and an explanation of the treatment of the variables is described below.

3.5.1 Unloaded Pedalling

Unloaded pedalling is actually a misnomer, although the term was used here, since it did not actually represent zero work rate, but involved the work of moving the legs. During the first five minutes of each submaximal protocol (Protocol I), unloaded pedalling was performed by all subjects. At any defined pedalling rate it was the minimum work rate possible on the bicycle ergometer and provided a relatively stable baseline value of oxygen uptake and heart rate for each subject. It was valuable in reducing fluctuations in heart rate during the initial phase of testing. In this study unloaded pedalling was assigned a work rate of 200 $kpm \cdot min^{-1}$ based on the mean oxygen uptake measured on 39 subjects during this activity. In this evaluation, oxygen uptake during the fifth minute of unloaded pedalling was taken as the cost of the exercise and the mean corresponding heart rate determined concomitantly was regarded as a representative mean group heart rate for unloaded pedalling.

3.5.2 Delta Heart Rate

For an individual, delta heart rate (ΔHR) was defined as the difference between all determined exercise heart rates and the heart rate measured during the fifth minute of unloaded pedalling. Unloaded pedalling heart rate was chosen to provide a more accurate starting point in the extrapolation procedure for predicting maximal oxygen uptake. It replaced the resting heart rate value previously used but for which it was very difficult to define a standard condition under which it could be measured accurately and consistently. The use of the delta heart rate value discriminated better the heart rate span (exercise heart rate minus unloaded pedalling heart rate) increase with exercise between groups of different age, sex and degree of training. A salient observation of training in an individual is the training bradycardia developed for any given work rate. Thus assuming a similar maximum heart rate for two individuals within the same age group, the trained individual would have a greater delta heart rate than the untrained individual due to the lower heart rate attained during the standard performance of unloaded pedalling. Using maximum heart rate alone in any heart rate based predictive procedure would ensure no such discrimination between trained and untrained subjects.

The use of delta heart rate may also help to resolve the obscuring effect of the age related decline in maximum heart rate predictions made from heart rate measurements. Thus in a 55 year old male, despite an age related decline in maximum heart rate, a decrease in unloaded pedalling heart rate accompanying training bradycardia would maintain a high span heart rate (delta heart rate) in predictive work. An unfit 35 year old, on the other hand, despite having a higher maximum heart rate, might indeed have a markedly less span heart rate because of an accompanying high unloaded pedalling heart rate.

Delta heart rate values from the maximal exercise protocol were calculated by subtracting unloaded pedalling heart rate measured during the fifth minute of the unloaded pedalling portion of the submaximal protocol from all maximal protocol heart rate measures. This procedure was performed in an attempt to account for the influence of the previous performance of a submaximal test on the following maximal test. In effect it attempted to remove any remaining influence of increased body core temperature (indicated by rectal temperature) on heart rate. Although in the majority of cases the unloaded pedalling heart rate recorded during the maximal protocol was almost indentical to that measured during the submaximal test, the procedure was followed as an aid in standardizing the overall methodology.

3.5.3 Delta Work Rate

The work of unloaded pedalling was calculated from oxygen uptake measurements to be equivalent to a 200 $kpm \cdot min^{-1}$. This value has been used to express every other work rate as a delta work rate (ΔWR) value by subtracting 200 $kpm \cdot min^{-1}$ from the recorded test work rate performed (i.e. a work rate of 300 $kpm \cdot min^{-1}$ becomes a delta work rate of 100 $kpm \cdot min^{-1}$). This procedure proved useful in describing the relationship between delta heart rate and delta work rate. By definition, both variables become zero during unloaded pedalling and define the origin of the exponential curve,

$$y = a\,(1 - e^{-kx})$$ (Equation 6)

where a = a constant,

k = a rate constant,

y = delta heart rate, and

x = delta work rate.

3.6 Data Reduction and Analysis

3.6.1 Individual Data Treatment

Subjects performed submaximal and maximal bicycle ergometer rides at separate times. Oxygen uptake, heart rate and work rate variables were recorded during the final minute of unloaded pedalling and during the third minute of 300, 600, 900 $kpm \cdot min^{-1}$ work rates for untrained individuals during submaximal tests. Data for trained individuals was collected similarly and also at two higher work rates of 1200 and 1500 $kpm \cdot min^{-1}$.

During maximal ramp tests to exhaustion, the mean minute value from the continuous record was chosen as representative of the work. Both the complete submaximal and maximal set of oxygen uptake and heart rate values as derived above, were plotted against time. Due to the nature of the maximal protocol work rate increases, heart rate and oxygen uptake were not steady state values for the particular work rates performed. This is in contrast to the submaximal work rates performed. However, the submaximal oxygen uptake/delta heart rate curve intersected the maximal oxygen uptake/delta heart rate curve at approximately 900 and 1500 kpm$\cdot$min^{-1} for the untrained and trained group, respectively. All individual submaximal oxygen uptake/delta heart rate data and maximal data above this intersection point for each group was combined and treated as one complete set of $\dot{V}O_2$/delta HR data for the remainder of the analysis. Figure 7 illustrates the process of combining individual submaximum and maximum oxygen uptake and delta heart rate data.

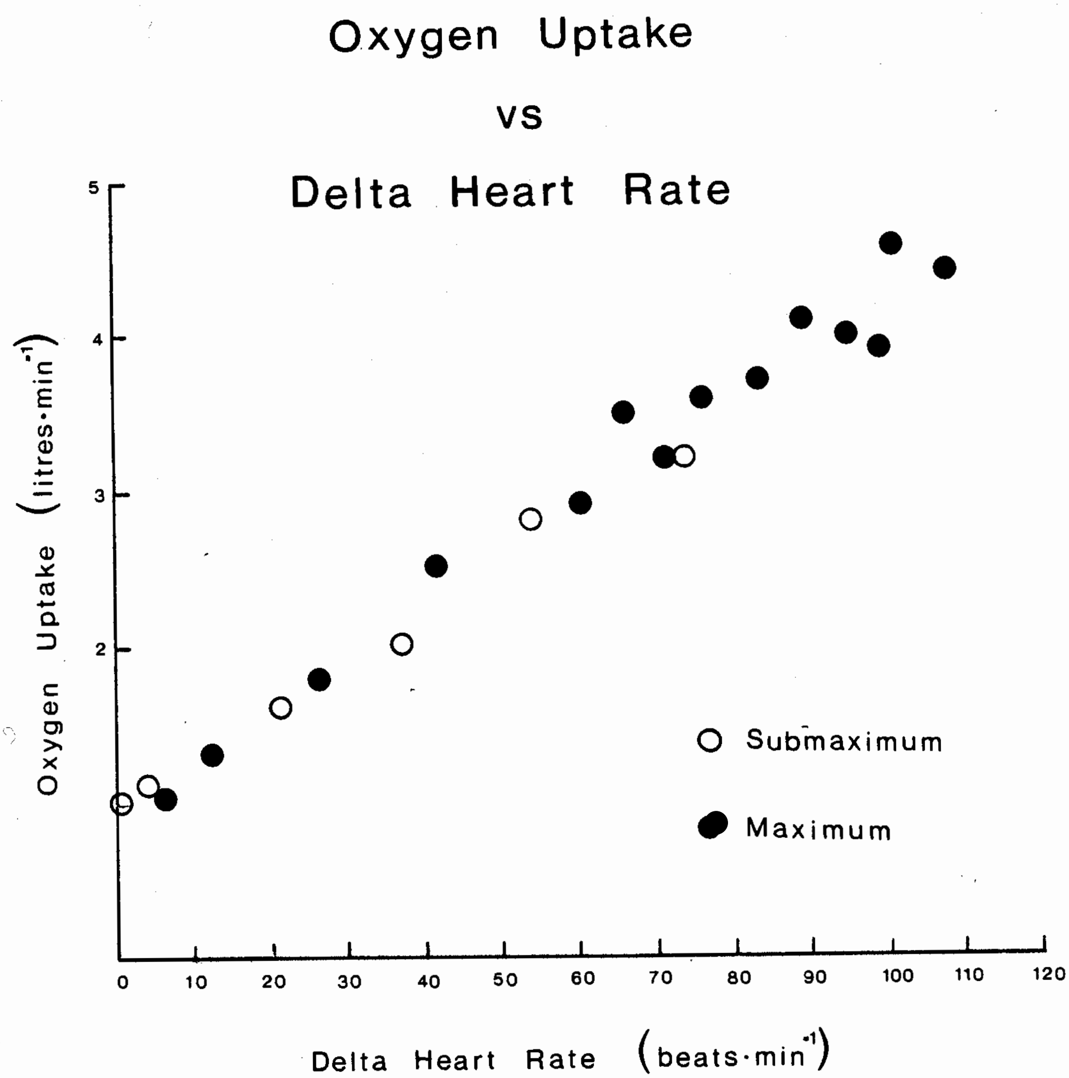

Figure 7: Showing Submaximum and Maximum $\dot{V}O_2$ and Δ HR Relationship for a Trained Male.

3.6.2 Test-Retest Reliability

Individuals within the trained group performed three complete submaximal and maximal protocols, while those in the untrained group completed two sets. Trained individuals were tested during their off-season, therefore three sets of tests were conducted to check for variations in maximum oxygen uptake as a result of training or detraining. A one-way analysis of variance tested for significant differences between trials. The level of significance was set at $p<0.05$.

3.6.3 Group Data

Groups were termed core or validation according to their later role in the construction and validation of a nomogram for predicting maximal oxygen uptake. The slopes of the regression lines between oxygen uptake and delta heart rate for the trained and untrained core groups, respectively, were tested for significant difference by a one-way ANOVA ($p<0.05$). A small sample t-test for parallelism, as outlined by Kleinbaum and Kupper (1978), was performed. This provided the basis for continuing the categorization of groups into T and UNT.

Mean maximum oxygen uptake, maximum heart rate, maximum delta heart rate and other measured variables for trained and untrained groups were checked for statistically significant differences ($p<0.05$). Core and validity group data within the T and UNT groups were not compared since any statistically significant differences would only reflect differences due to the random assignment of individuals within the main trained or untrained group to core or validity groups. Any such determined significant differences between core and validity groups may also be representative of the smaller number of subjects in the validity groups compared to the core groups.

3.7 Treatment of Data

The hypothesized relationship between oxygen uptake and delta heart, following step changes in external work rate, was a simple exponential function (Wyndham *et al.*, 1959; Rowell *et al.*, 1964; Davies, 1968). The following first order function was therefore fitted to the recorded responses;

$$y(x) = a \cdot e^{kx} \qquad \text{(Equation 8)}$$

where $y(x)$ is oxygen uptake, x is delta heart rate generated from a step change in work rate, k is a rate constant and a is a constant. This equation described a similar exponential function as that initially proposed by Wyndham et al. (1959), but with a positive exponent due to the reversal of the x and y axes.

Linear regression and non-linear exponential and quadratic regression analyses were conducted in an attempt to interpret the relationship between the oxygen uptake and delta heart rate variables in a statistical sense and to help quantify the strength of the relationship. BMDP linear and non-linear curve fitting computer programs were used for statistical analyses.

The computation of the best fitting function was made using a least squares method i.e. the line of best fit is that which minimizes the sum of the squared differences between the predicted dependent values and the response values actually recorded.

In order to compare the fit by respective linear and non-linear exponential and quadratic functions, the mean square residual (MSR) was used. This term was used rather than residual sum of squares. The mean square residual is equal to the variance about the fitted line deduced from:

$$\text{MS residual} = \frac{\text{SS residual}}{\text{df residual}} = \frac{\text{SS residual}}{(n-p)} \quad \text{(Equation 8)}$$

where p is the number of parameters. For a linear function, p represents the slope and the intercept. For an exponential function, p represents the parameter, a, and rate constant, k. While the residual sum of squares has been reported in other studies (Hughson, 1982), the MSR was determined to be a more suitable statistic since it takes into account the number of cases (df) and enables comparisons to be made between the fits of various functions to reality.

Oxygen uptake and delta heart rate data were also analysed for trends of non-linearity in separate submaximum and maximum sections of the relationship.

3.7.1 Examination of Residuals

All equations fitted to those data described above were further analyzed by assessing the residuals. A graphical analysis of residuals vs. predicted oxygen uptake was performed to check for any violation of specific assumptions associated with ANOVA. These include independence, normality and homogeneity of variance. Figure 8 illustrates the normal situation as well as three common trends. A horizontal band of points should be obtained normally, as shown in Figure 8a, with no hint of the presence of any systematic trends, as in 8b, c and d. Transformation of data was conducted if analysis of residuals revealed systematic trends.

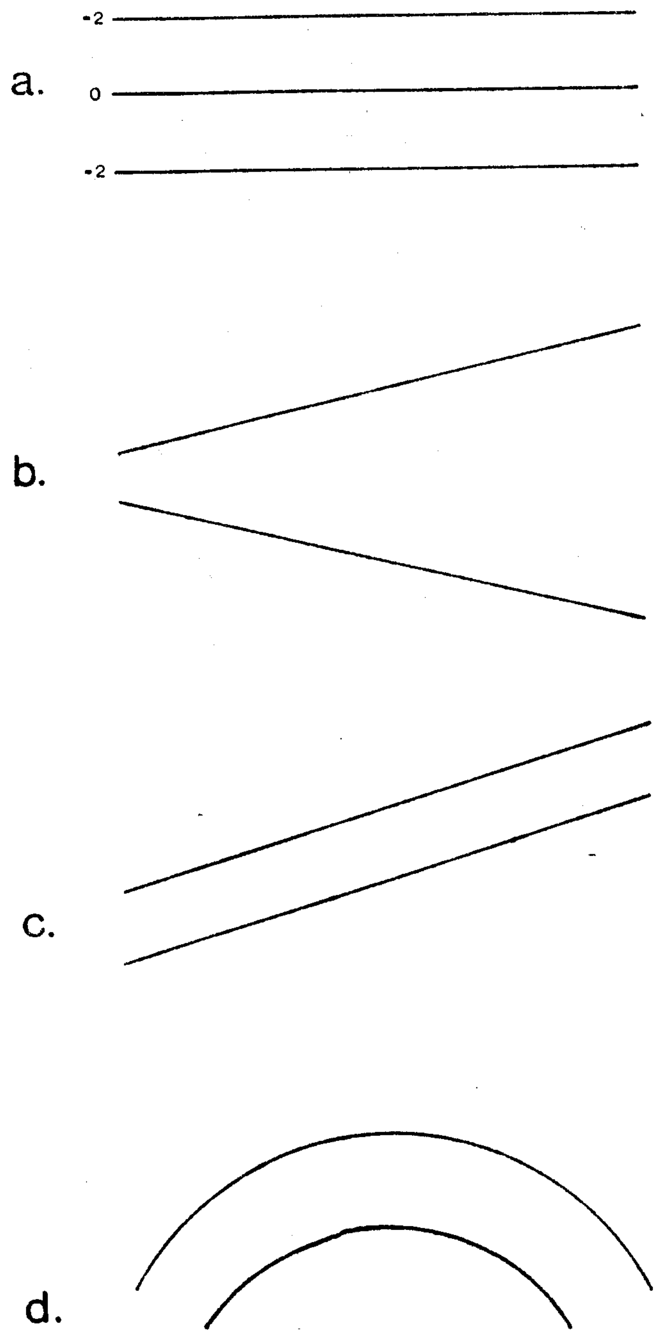

Figure 8: Examination of Residuals derived from predicted oxygen uptake and actual oxygen uptake. Normal situation is shown in 8a.

3.8 Method of Constructing Nomogram

3.8.1 Construction of Astrand-Ryhming Nomogram

The Astrand-Ryhming nomogram was originally constructed from the oxygen uptake and heart rate responses to single submaximal work rates performed for approximately 5 to 10 minutes by 86 male and female physical education students. Subjects completed a variety of light and heavy submaximum work tasks on several occasions on the last of which a maximum effort was also attempted. Oxygen uptake and heart rate were measured on each subject under every condition. At the highest work rates, the work period was only 2 to 3 minutes. The values used for oxygen uptake and heart rate referred to the last minutes of work at each level and were mean values obtained either from determinations on two or more occasions, or from two or more successive determinations on the same day. Oxygen uptake and heart rate were measured for bicycle ergometery, treadmill running and bench stepping.

The detailed construction of the Astrand-Ryhming nomogram predicting maximum oxygen uptake is outlined below. Oxygen uptake values for each subject were expressed as a percentage of an individual's maximum oxygen uptake (% $\dot{V}O_2max$). Oxygen uptake was plotted against heart rate and a regression equation calculated. From the determined regression equation, Astrand found that a work rate which produced an average heart rate of 128 $b \cdot min^{-1}$ required 50% of maximum oxygen uptake, and a work rate producing 154 $b \cdot min^{-1}$ required 70% of maximal oxygen uptake. The regression equation describing the % $\dot{V}O_2max$/HR relationship applied for all individuals within an age group. It followed, therefore, that individuals within such a group would have a smaller range of maximal values than individuals within another group varying in age, sex or state of training. Expression of oxygen uptake as a percentage of maximum allowed this variation in maximal oxygen uptake between individuals within a group and between groups to be defined better than merely comparison of absolute values of oxygen uptake.

Using the regression equation of % $\dot{V}O_2max$ against HR, a heart rate appropriate to a defined work rate was substituted into the regression equation and the percentage of $\dot{V}O_2max$ at which this heart rate occurred was calculated. For example, if the regression equation describing the relationship was of the form $y = mx + b$, where y represents the percentage of maximum oxygen uptake, x the heart rate, b the y-intercept, and m the slope of the line, and the actual equation was:

$$\% \dot{V}O_2max = (0.8)\ HR - 30 \qquad \text{(Equation 9)}$$

a heart rate of 100 would require 50% of maximum oxygen uptake. In order to calculate predicted $\dot{V}O_2max$, one merely needs to multiply the reciprocal of the derived % $\dot{V}O_2max$ by the theoretically calculated oxygen cost of the work rate. For example, the theoretical oxygen cost of performing a work rate of 600 $kpm \cdot min^{-1}$ is 1.5 liters $O_2 \cdot min^{-1}$. If the heart rate required to perform this work rate was 100 $b \cdot min^{-1}$ and, as determined previously, the % $\dot{V}O_2max$ at which this heart rate occurred was 50, the predicted $\dot{V}O_2max$ would be double (the reciprocal of 50/100) the calculated oxygen cost value, or 3.0 $l \cdot min^{-1}$.

$$\dot{V}O_2max = \frac{1}{\% \dot{V}O_2max} \times O_2cost \times 100 \qquad \text{(Equation 10)}$$

$$= \frac{1}{50\% \dot{V}O_2max} \times 1.5 \ l \ O_2 \cdot min^{-1} \times 100$$

$$= 3.0 \ l \ O_2 \cdot min^{-1}$$

If the heart rate attained by the same individual at a work rate of 1200 $kpm \cdot min^{-1}$ was 150 $b \cdot min^{-1}$, the percentage $\dot{V}O_2max$, using Equation 9 which describes the appropriate % $\dot{V}O_2max$/HR relationship, would be 90. If the theoretically determined O_2 cost of performing 1200 $kpm \cdot min^{-1}$ was 2.8 $l \cdot min^{-1}$, the predicted $\dot{V}O_2max$ would be equal to 3.1 $l \cdot min^{-1}$ as determined from Equation 10.

$$\dot{V}O_2max = \frac{1}{90\% \ \dot{V}O_2max} \times 2.8 \ l \ O_2 \cdot min^{-1} \times 100 \quad \text{(Equation 10)}$$

$$= 3.1 \ l \ O_2 \cdot min^{-1}$$

In this fashion, the predicted $\dot{V}O_2max$ for every heart rate and every work rate could be calculated.

To reiterate; the necessary prerequisites for construction of a nomogram for predicting $\dot{V}O_2max$ for a group of homogeneous individuals are:

1. expression of each individual $\dot{V}O_2$ as a percentage of maximum oxygen uptake,

2. determination of the regression equation describing the relationship between % $\dot{V}O_2max$ and the corresponding heart rates,

3. determination of the heart rate at a defined work rate and calculate from the $\dot{V}O_2$ vs. HR regression the % $\dot{V}O_2max$ that this heart rate elicits,

4. theoretical determination, from basic energetic relationships (Appendix C), of the oxygen cost of the submaximal work rate eliciting the specific heart rate and corresponding % $\dot{V}O_2max$ at which the heart rate occurs, and

5. use of the relationship dscribed by Equation 10 to predict $\dot{V}O_2max$.

3.8.2 Construction of Present Nomogram and O_2 Cost Calculation

Individuals in the present study performed bicycle ergometer exercise only. The work rate protocol was of a continuous nature with increments every 3 minutes during the submaximal portion. Mean oxygen uptake values were determined to assess whether this was adequate time for adjustment of the circulation and ventilation to the level of exericse. These values were compared to the oxygen cost determined from relevant work rates according to the theoretical considerations shown in Appendix C. Thermodynamic calculations usually assume a constant efficiency of 25% for bicycling humans (Whipp and Wasserman, 1969; Astrand and Rodahl, 1977). Although it may be argued that the group of trained cyclists had a higher efficiency than the untrained group, balancing this was the fact that the bicycle ergometer used in this investigation was very different in terms of the required body position of the rider from that required on the cyclist's normal training bicycle. Astrand and Rodahl (1977) also determined that a non-significant difference existed between Olympic cyclists and untrained individuals with regard to the efficiency of cycling. It was concluded that an efficiency of 25% would be used in the theoretical calculation of O_2 cost from the relevent work rate value.

The first step in the analysis of these data attempted to reconstruct the original Astrand-Ryhming nomogram. This was a plausible aim due to the similarity in age and general activity level of the core group of males with the subjects assessed in Astrand's original study (1952).

The same procedure for constructing a nomogram as outlined above for Astrand's original work was followed. This procedure was performed separately on data from both the trained and untrained core groups. For the sake of simplicity, description of the process will be confined here to the trained group.

Individual $\dot{V}O_2$ values obtained during the submaximal and maximal tests were expressed as a percentage of the individual's directly determined maximal oxygen uptake. The regression equation describing the group relationship between the percentage $\dot{V}O_2max$ values and the corresponding heart rates for all individuals within the group was then determined. In order to construct a table to predict $\dot{V}O_2max$ at any heart rate and any given submaximal work rate, every heart rate was substituted into the determined linear regression equation,

$$y = mx + b \qquad \text{(Equation 11)}$$

where y is the percent of maximum oxygen uptake and x is the corresponding heart rate, given the determined values of slope, m, and y-intercept, b.

This procedure determined the % $\dot{V}O_2max$ at which each heart rate occurred according to the empirically determined regression equation for the group data. It was evident that the regression equation was dependent upon the $\dot{V}O_2$ and heart rate determined during the standard submaximal work protocol. Therefore it was of utmost importance that the $\dot{V}O_2$ and HR values used were steady state values. The accuracy of this was determined by comparison of the mean $\dot{V}O_2$ values determined empirically with the oxygen cost of the work rates calculated according to theoretical considerations.

The heart rate of interest, the corresponding % $\dot{V}O_2max$ value (determined from the regression equation) and the work rate eliciting the response were then used to predict $\dot{V}O_2max$ using Equation 10, as previously outlined. Each predicted $\dot{V}O_2max$ was then entered into an appropriate cell in the table of corresponding heart rates, % $\dot{V}O_2max$ values (from regression) and actual oxygen cost of the work rate (from calculation).

Maximum oxygen uptake predictive tables were then constructed from trained core group data (n=15), untrained core group data (n=10), as well as a third table which combined data from both core groups (n=25).

3.9 Construction of Line Nomogram

A nomogram to predict $\dot{V}O_2max$ from submaximal heart rate and oxygen uptakes during submaximal bicycle ergometer work may be constructed with a heart rate (or delta heart rate) scale on the left side and a O_2 cost or $\dot{V}O_2$/work rate scale on the right. A middle scale shows predicted $\dot{V}O_2max$ values. The heart rate response to a given submaximal work rate is located on the heart rate scale (left) and aligned with the corresponding work rate scale (right) and the predicted $\dot{V}O_2max$ read from the middle scale.

These scales are aligned by locating identical predicted $\dot{V}O_2max$ values in the related predictive tables drawn up previously and identifying the coordinates of its position in terms of HR and WR. At least three identical predicted $\dot{V}O_2max$ values should be located within the table and pairs of HR and WR coordinates (HR,WR) located. Each pair of coordinates are connected on the appropriate scales. The intersection of the three lines is then marked and given the value of the corresponding predicted $\dot{V}O_2max$. In this way, the orientation of the predictive $\dot{V}O_2max$ line may be determined.

This method was used to construct nomograms using either heart rate or delta heart rate/$\dot{V}O_2$ relationships, respectively.

3.10 Performance of Submaximal Protocol to Predict $\dot{V}O_2max$

During the performance of a submaximal bicycle ergometer test, the only measures recorded are heart rate responses to particular submaximal work rates. Oxygen uptake is not measured. It is of utmost importance, therefore, that the work rate protocol performed during the submaximal test is identical to that from which the data used to construct the predictive nomogram and associated table were obtained. In the present test, work was performed at a pedal rate of 90 rpm. The work protocol began with 5 minutes of unloaded pedalling and was continuously incremented every 3 minutes by 300 $kpm \cdot min^{-1}$ until a heart rate of 150 to 160 $b \cdot min^{-1}$ was attained. The final work rate which elicited this heart rate was recorded and the test completed with 3 minutes of unloaded pedalling to allow for recovery.

The heart rate identified as the unloaded pedalling heart rate was the value recorded during the fifth minute of the unloaded pedalling period. This heart rate was subtracted from the heart rate during the third minute of the final work period to give a delta heart rate value. The delta heart rate and related work rate were then located in the appropriate age, sex and fitness grouped predictive tables and an estimate of $\dot{V}O_2max$ made. If the line nomogram was used, the delta heart rate and $\dot{V}O_2$ or O_2 cost/WR were located and a line drawn to connect the two points. The point at which this line intersected the central line was the predicted $\dot{V}O_2max$.

3.11 Submaximal Test Response

Heart rate responses to submaximal work rates provided the basis for distinguishing between untrained and trained individuals. For a given submaximal work rate, a trained individual will have a consistently lower heart rate response than an untrained individual. The delta heart rate will also be lower for the same submaximal work rate.

The difference in HR/WR relationship between trained and untrained individuals enabled new individuals to be separated into trained or untrained categories following completion of the specific submaximal protocol. The delta heart rate/delta work rate relationship was determined from core data and a master graph constructed. During performance of the well-defined submaximal predictive work protocol, heart rate responses to submaximal bicycle work rate were plotted on the graph and the resulting regression line found to be closer to either the trained or untrained regression lines. From this process, the appropriate table and related nomogram was selected and the $\dot{V}O_2max$ predicted.

3.12 Prediction of Maximal Oxygen Uptake

3.12.1 Cross-Validation

Maximal oxygen uptake was predicted from the appropriate tables for untrained (n=5) and trained (n=5) individuals within the validity groups and compared to directly measured maximal oxygen uptake values. Predictions of $\dot{V}O_2max$ were also made for each validity group member using the nomogram constructed from all core data (n=25). Heart rate values were those measured at 900 and 1500 $kpm \cdot min^{-1}$ for untrained and trained subjects, respectively. Maximal oxygen uptake was also predicted for the moderate group (n=4) using the trained predictive nomogram. Regression correlation coefficients were calculated for observed $\dot{V}O_2max$ vs. predicted $\dot{V}O_2max$. Predicted $\dot{V}O_2max$ from the Astrand-Ryhming nomogram was also compared to observed maximal oxygen uptake. The two correlation coefficients were then compared for a significant difference using Fisher's Z statistic as described by Kleinbaum and Kupper (1978).

3.13 Kinetics

In order to understand the relationship between oxygen uptake and heart rate, three underlying relationships must be clearly understood. These include the relationships between work rate and time, oxygen uptake and time, and heart rate and time. A systems analysis approach, as outlined by Wolf (1979), helped to clarify these relationships. The system under study was the cardiovascular system, the input was the work rate and the output was any cardiovascular measure, in this case either oxygen uptake or heart rate. If work rate, which acted as a forcing function, was made to vary as a step function, oxygen uptake and heart rate responded in a manner as shown in Figure 9a. If, on the other hand, work rate increased continuously as a ramp function, oxygen uptake and heart rate responded differently as shown in Figure 9b. In each case, the time constant, τ, represented the time required for the cardiovascular variable to achieve approximately two-thirds of its maximum value.

Hypothesized relationships between oxygen uptake and heart rate resulting from ramp and step work rate forcing functions are shown in Figure 10. Work rate has been replaced by time in this figure. When both oxygen uptake and heart rate respond in a non-linear fashion with similar time constants, the resulting oxygen uptake/heart rate relationship would be linear, as shown in Figure 10a. If either oxygen uptake or heart rate responded in a linear manner, the resulting relationship would be non-linear, as shown in Figure 10b. If the time constants for the relationships between oxygen uptake and time and heart rate and time were significantly different, the resulting oxygen uptake and heart rate relationship was hypothesized to be non-linear as shown in Figure 10c. A non-linear, exponential relationship between oxygen uptake and heart rate may, therefore, arise from two different types of oxygen uptake/heart rate responses.

The kinetics of the oxygen uptake/work rate relationship during the performance of the maximum ramp protocols were examined qualitatively and the general shape of the curves were described for two trained subjects and one untrained subject. The relationships between delta heart rate and work rate for the same subjects were examined in a similar fashion.

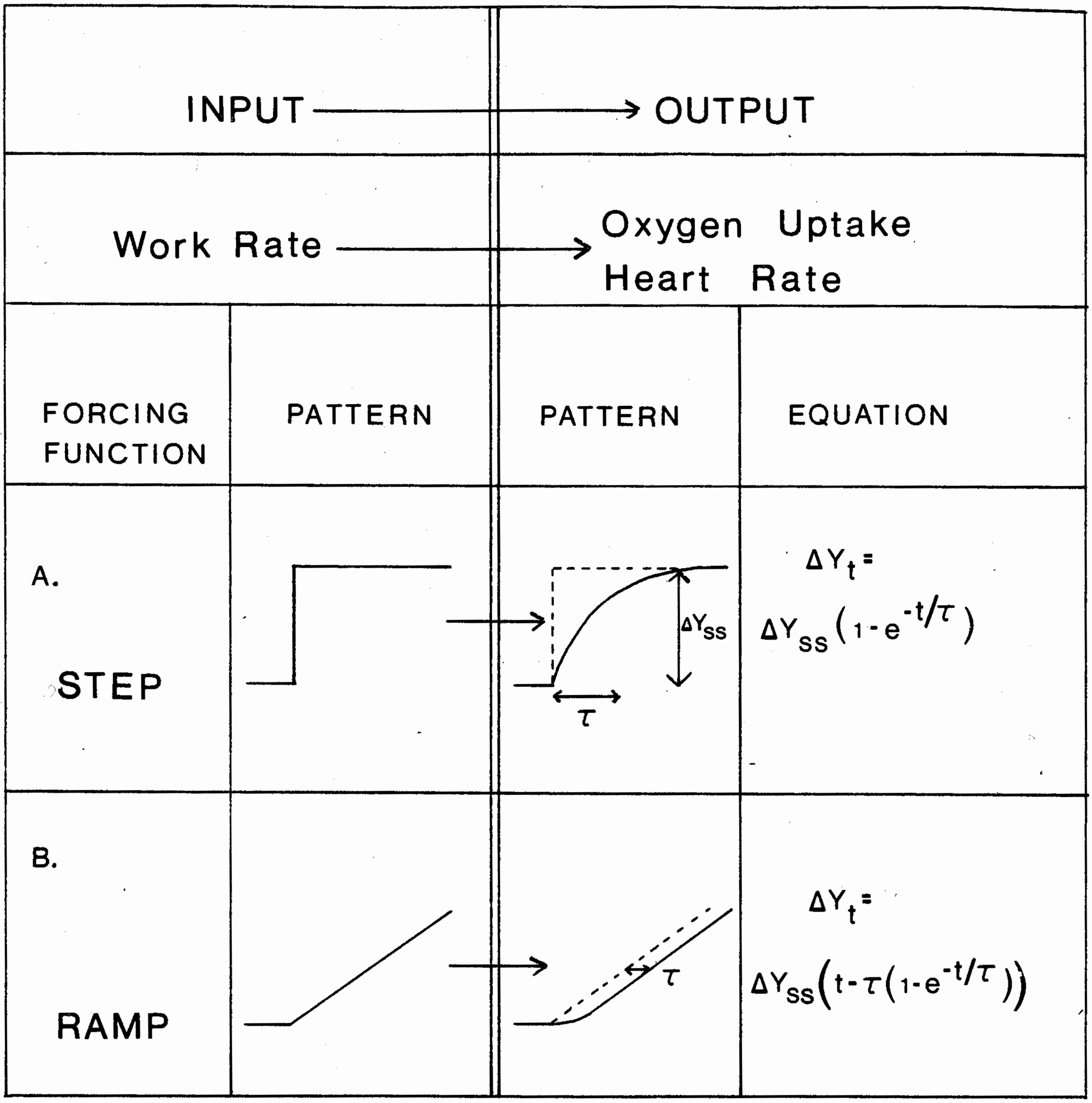

Figure 9: Relationship between oxygen uptake and time with step or ramp increases in work rate.

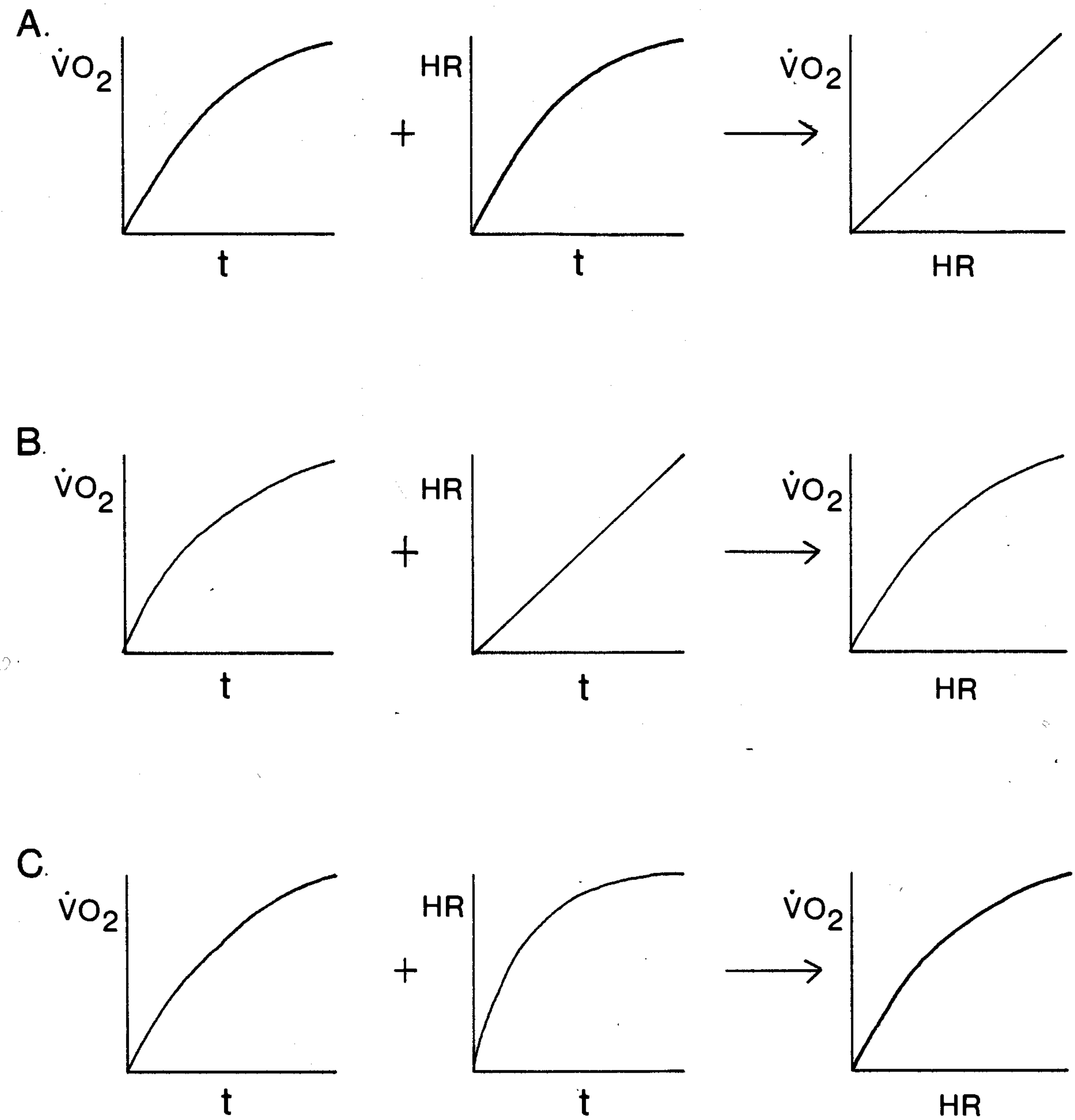

Figure 10: Variations in the relationships between oxygen uptake and heart rate with variations in work rate.

3.13.1 Calculation of Time Constants

Time constants for the relationships between oxygen uptake and time, and delta heart rate and time, were calculated for both the untrained and trained groups at the same absolute work rate of 600 $kpm \cdot min^{-1}$. The time constants of the same relationships were also calculated from work rates requiring the same percentage of maximum oxygen uptake, in this case approximately 45% of $\dot{V}O_2max$ for trained and untrained group data. The analysis of time constants was conducted to assess whether a non-linear relationship between oxygen uptake and delta heart rate was the result of different time constants for oxygen uptake and time and heart rate and time, or due to the effects of differences in the form of the applied work rate.

4. Results

4.1 Group Data

4.1.1 Peak Values

Maximal values determined in this study were maximal only in terms of the apparatus upon which the work was performed, in this case the bicycle ergometer. It has been determined, as described previously, that oxygen uptake values measured on a treadmill were 4 to 18% higher than those determined on a bicycle ergometer. Therefore, the highest values measured in this investigation were more correctly referred to as "peak" values. The terms "peak" and "maximal" were, therefore, used interchangeably.

Mean values of age and weight, and peak mean values of oxygen uptake ($\dot{V}O_2max$, STPD), heart rate (HR), delta heart rate (ΔHR), minute ventilation ($\dot{V}E$, BTPS), work rate (WR) and blood lactate concentration (mM) are presented in Table IV. Peak work rate values for trained individuals are expressed in minutes completed at a work rate of 2400 $kpm \cdot min^{-1}$. For example, 2400(4) means that the subject completed four minutes at 2400

$kpm \cdot min^{-1}$. Standard deviations are recorded in minutes at 2400 $kpm \cdot min^{-1}$. Peak work rates for untrained individuals are expressed as the highest work rate in $kpm \cdot min^{-1}$ completed for 0.5 minutes.

Peak values of maximum oxygen uptake, ventilation and lactate concentration recorded for trained individuals agreed well with those published for competitive cyclists (Burke et al., 1977; Hagberg et al., 1978; Burke et al., 1981; Verstappen et al., 1982).

Statistically significant differences ($p<0.05$) were found between trained and untrained core groups for mean maximal oxygen uptake and mean maximum delta heart rate values. As expected, the $\dot{V}O_2max$ ($l \cdot min^{-1}$) was higher in the trained core group 5.01 ± 0.38 (SD) compared to the untrained core group value of 3.42 ± 0.29 (SD). Mean delta heart rates were 109.0 ± 10.0 (SD) and 91.0 ± 8.0 (SD) for the trained and untrained groups, respectively. Significant differences were also recorded for maximum ventilation and maximum work rate completed.

Table IV: Physical Characteristics and Peak Cardiorespiratory Variables for Trained (T) and Untrained (UNT) Core and Validation (valid) Groups.

	Trained		Untrained	
Measure	Core (n=15)	Valid (n=5)	Core (n=10)	Valid (n=5)
Age (years)	23.0 ±3.1	22.4 ±2.2	22.4 ±1.7	24.8 ±1.9
Weight (kg)	70.5 ±4.9	72.1 ±5.8	70.9 ±8.5	70.2 ±13.9
$\dot{V}O_2$ max ($l \cdot min^{-1}$)	5.01 ±0.38	4.86 ±0.06	3.42* ±0.29	2.94 ±0.45
$\dot{V}O_2$max ($ml \cdot kg \cdot m^{-1}$)	71.1 ±4.1	67.8 ±4.9	48.8* ±6.7	42.7 ±7.8
HRmax ($b \cdot min^{-1}$)	190.0 ±7.0	196.0 ±9.0	188.0 ±9.0	185.0 ±7.0
HRmax ($b \cdot min^{-1}$)	109.0 ±10.0	111.0 ±13.0	91.0* ±8.0	84.0 ±10.0
VEmax ($l \cdot min^{-1}$)	134.9 ±20.2	131.8 ±10.0	100.9* ±12.3	83.0 ±9.7
WRmax	2400(3.4) ±1.7	2400(3.4) ±2.0	1810.0* ±152.4	1600.0 ±255.0
Lactate (mM)	13.60 ±1.67	13.50 ±1.60	13.32 ±2.76	13.50 ±2.11

Values are means ± standard deviations of the mean (SD).

* Significant difference between Tcore and UNTcore, ($p < 0.05$).

4.1.2 Submaximal oxygen uptake and delta heart rate

Mean values of oxygen uptake and delta heart rate obtained during completion of submaximal work Protocols IA and IB for untrained and trained core and validity groups are presented in Table V. A significant difference ($p<0.05$) was determined between untrained and trained group mean delta heart rate data at the submaximal work rates of 300, 600 and 900 $kpm \cdot min^{-1}$.

Table V: Mean values of oxygen uptake ($\dot{V}O_2$) and delta heart rate (ΔHR) for trained and untrained groups for all submaximal work rates completed. $\dot{V}O_2$ values are in units of $l \cdot min^{-1}$, ΔHR values are in $b \cdot min^{-1}$ and WR in $kpm \cdot min^{-1}$.

Work Rate ($kpm \cdot min^{-1}$)		Trained Core	Trained Valid	Untrained Core	Untrained Valid
		n=36	n=15	n=20	n=9
0	$\dot{V}O_2$ ($l \cdot min^{-1}$)	1.01 ±0.09	0.97 ±0.11	1.06 ±0.14	0.85 ±0.05
	ΔHR ($b \cdot min^{-1}$)	0.0	0.0	0.0	0.0
300		n=37	n=14	n=19	n=9
	$\dot{V}O_2$	1.13 ±0.11	1.14 ±0.15	1.23* ±0.16	1.07 ±0.07
	ΔHR	5.0 ±3.0	6.0 ±3.0	8.0* ±4.0	8.0 ±3.0
600		n=38	n=15	n=20	n=9
	$\dot{V}O_2$	1.65 ±0.13	1.61 ±0.14	1.68 ±0.16	1.52 ±0.04
	ΔHR	20.0 ±5.3	22.0 ±4.4	30.0* ±10.0	32.0 ±9.0
900		n=38	n=15	n=19	n=9
	$\dot{V}O_2$	2.16 ±0.13	2.15 ±0.16	2.16 ±0.16	2.04 ±0.10
	ΔHR	36.0 ±7.0	40.0 ±7.0	50.0* ±11.0	54.0 ±11.0

...cont'd

Table V (cont'd)

Work Rate		Trained Core	Trained Valid	Untrained Core	Untrained Valid
1200	$\dot{V}O_2$	2.75 ±0.17	2.73 ±0.19		
	ΔHR	53.0 ±8.0	60.0 ±9.0		
1500	$\dot{V}O_2$	3.27 ±0.19	3.23 ±0.22		
	ΔHR	68.0 ±10.0	75.0 ±9.0		

Values are means ± standard deviations (SD).

* Significant difference between Tcore and UNTcore ($p<0.05$).

4.2 Resting and Unloaded Pedalling Heart Rate Values

Mean resting heart rate and mean unloaded pedalling heart rate values for the trained and untrained groups are presented in Table VI.

Table VI: Mean Resting and Unloaded Pedalling Heart Rate Values for Trained and Untrained Group Data.

	Mean Resting Heart Rate ($b \cdot min^{-1}$)	Mean Unloaded Pedalling Heart Rate ($b \cdot min^{-1}$)
Trained (n=20)	71.0 ±11.0	84.0 ±10.0
Untrained (n=15)	78.0 ±11.0	99.0 ±10.0

Values are means ± standard deviations (SD)

4.3 Oxygen Uptake and Delta Heart Rate Relationship

4.3.1 Group Oxygen uptake and delta heart rate data

The relationship between oxygen uptake and delta heart rate for the trained core group (n=15) is shown in Figure 11. Figure 12 shows the relationship between oxygen uptake and heart rate for the untrained core group (n=10). Visual inspection of both sets of core group data revealed a linear relationship between oxygen uptake and delta heart rate.

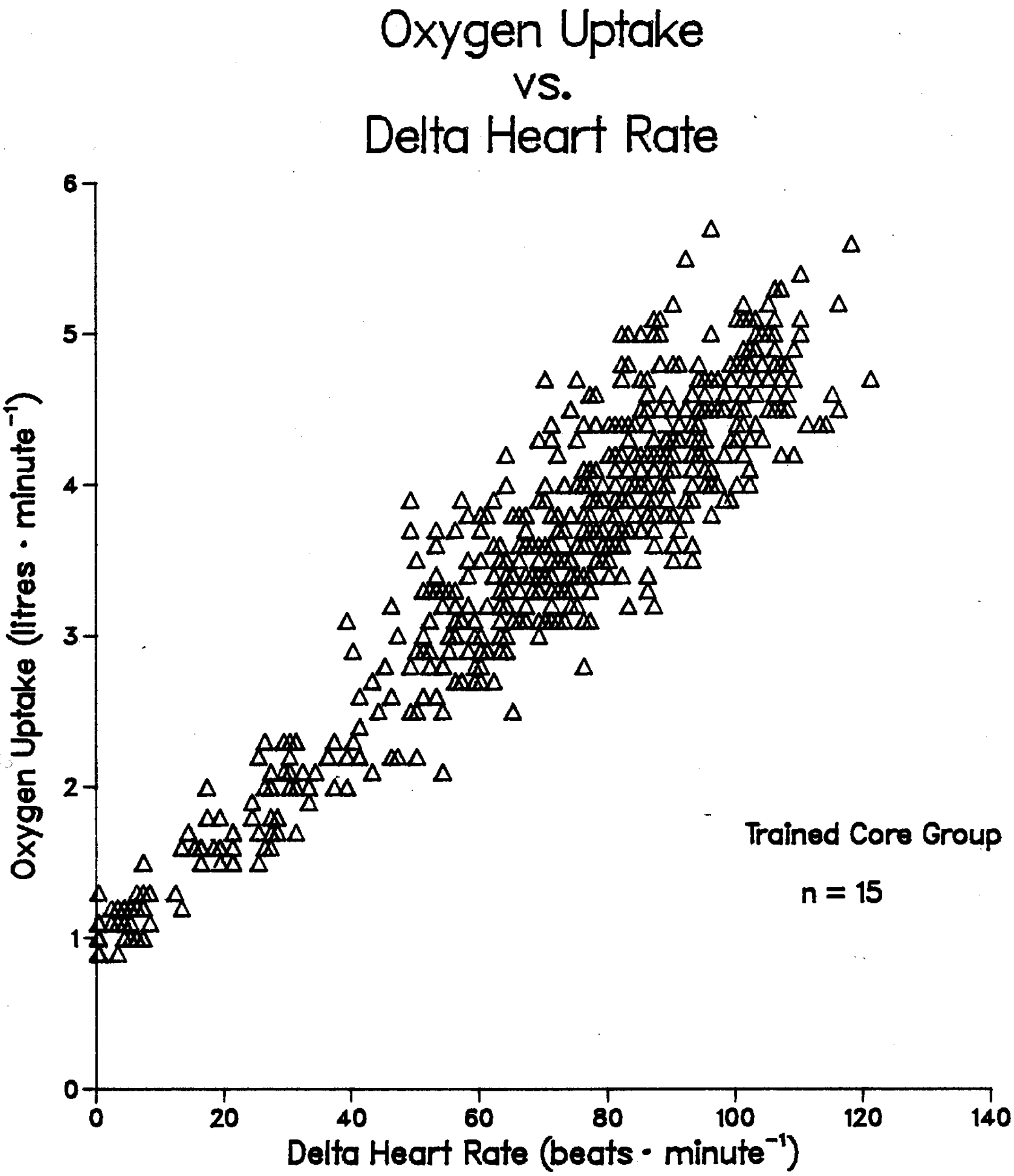

Figure 11: Showing the relationship between mean oxygen uptake (ordinate) and mean delta heart rate (abscissa) for trained males 20 to 29 years (n=15).

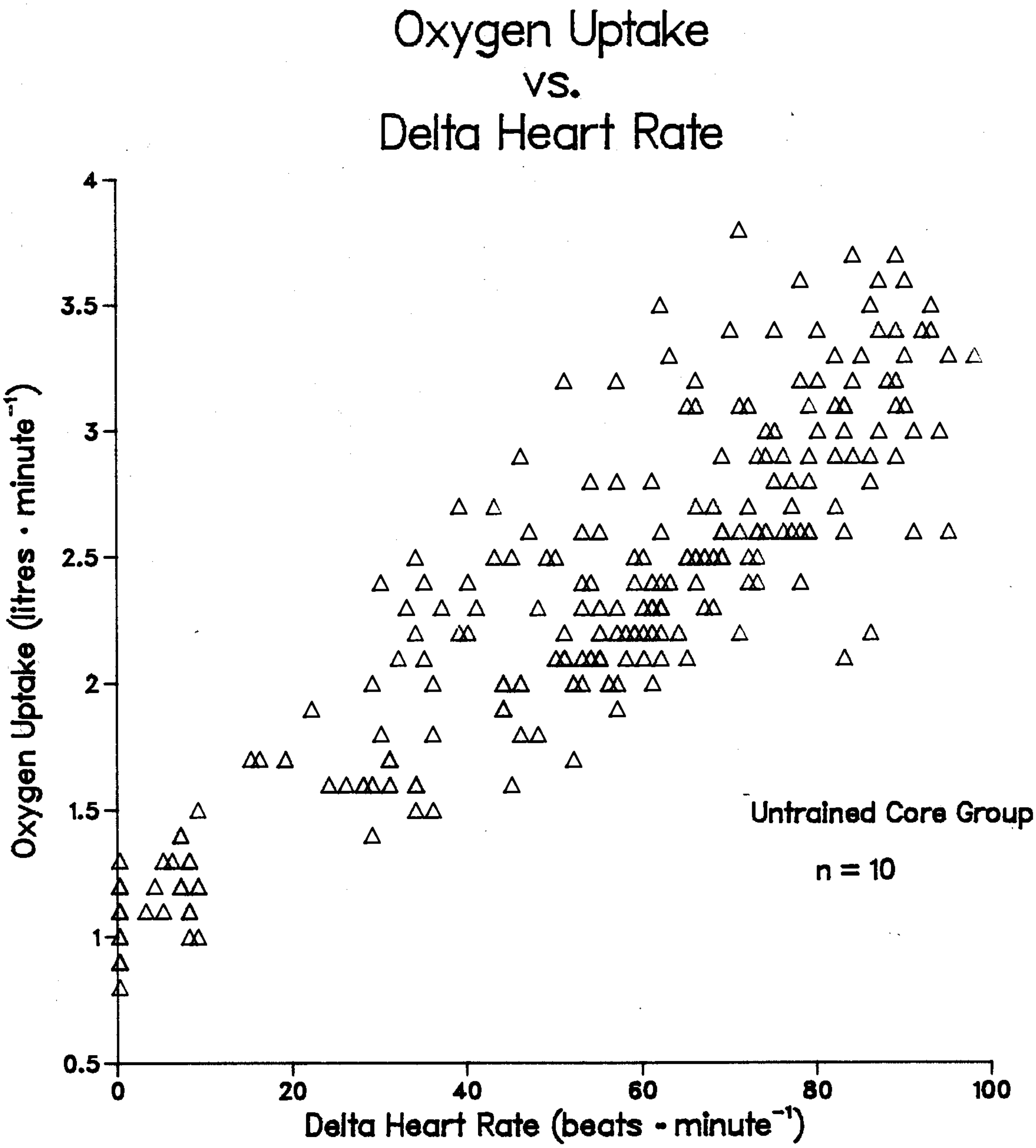

Figure 12: Showing the relationship between mean oxygen uptake (ordinate) and mean delta heart rate (abscissa) for untrained males 20 to 29 years (n=10).

Oxygen uptake and delta heart rate data for the trained and untrained groups were analysed statistically to determine which of the three chosen functions described the relationship best. The three functions fitted to the data were a linear, an exponential and a quadratic function. The specific exponential function fitted was that described by Equation 1 as follows;

$$f(x) = a \cdot e^{kx} \qquad \text{(Equation 1)}$$

where $f(x)$ = oxygen uptake,

x = delta heart rate,

a = a constant, and

k = a rate constant.

Table VII lists the mean square residual (MSR) values determined from linear, exponential and quadratic function fitting.

Table VII: Mean Square Residuals determined by curve fitting with linear, exponential and quadratic functions.

	Linear MSR	Exponen MSR	Quadratic MSR
Group	$y=mx+b$	$y=a \cdot e^{kx}$	$y=a+bx+cx^2$
Tcore (n=15)	0.1297	0.1846	0.1290
Tvalid (n=5)	0.1756	0.2437	0.1685
UNTcore (n=10)	0.1028	0.1118	0.1032
UNTvalid (n=5)	0.0765	0.0824	0.0770
MOD (n=4)	0.0727	0.0842	0.0730

4.3.2 Examination of Residuals

Residual values, or the differences between the observed and predicted oxygen uptake measures, were examined to check for any violation of the assumptions associated with analysis of variance as outlined previously. Figures 13 and 14 show the residual values plotted against the predicted oxygen uptake values as determined by the linear regression equation describing the relationship between oxygen uptake and delta heart rate for trained and untrained group mean data, respectively. Figures 15 and 16 illustrate the residuals determined when the exponential equation was fitted to the same trained and untrained data. Visual inspection of the residuals failed to reveal any systematic trends in the data.

Examination of the MSR showed that both the linear and quadratic functions resulted in consistently smaller mean square residual values, and therefore provided a better fit, than the exponential function. A linear function was chosen to describe the relationship between oxygen uptake and delta heart rate. The original exponential hypothesis was abandoned. Table VIII lists the linear regressions determined to describe the oxygen uptake/delta heart rate relationships best.

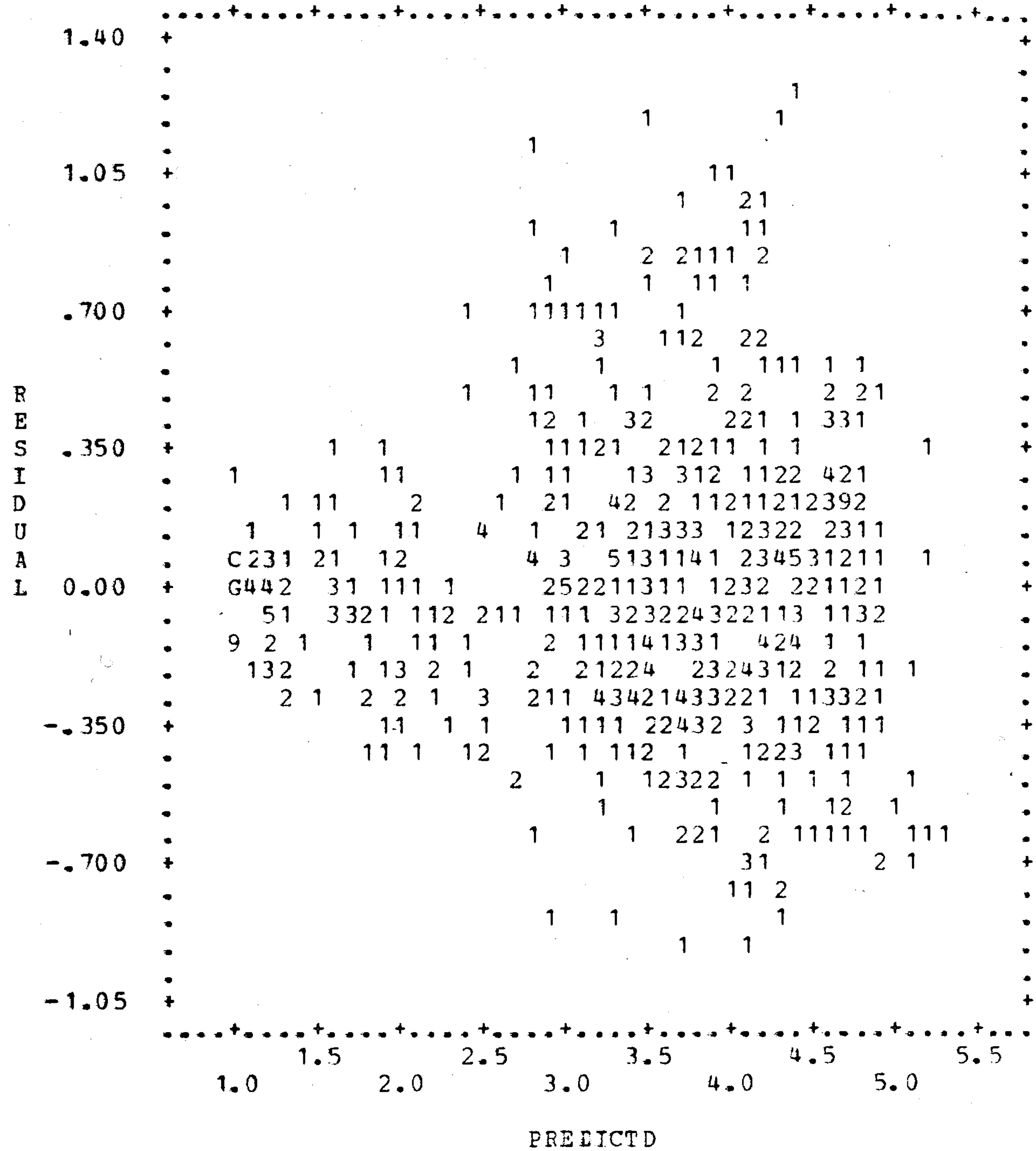

Figure 13: Examination of residuals between actual values of oxygen uptake and those predicted from the linear plot of oxygen uptake against delta heart rate for trained subjects 20 to 29 years (n=15).

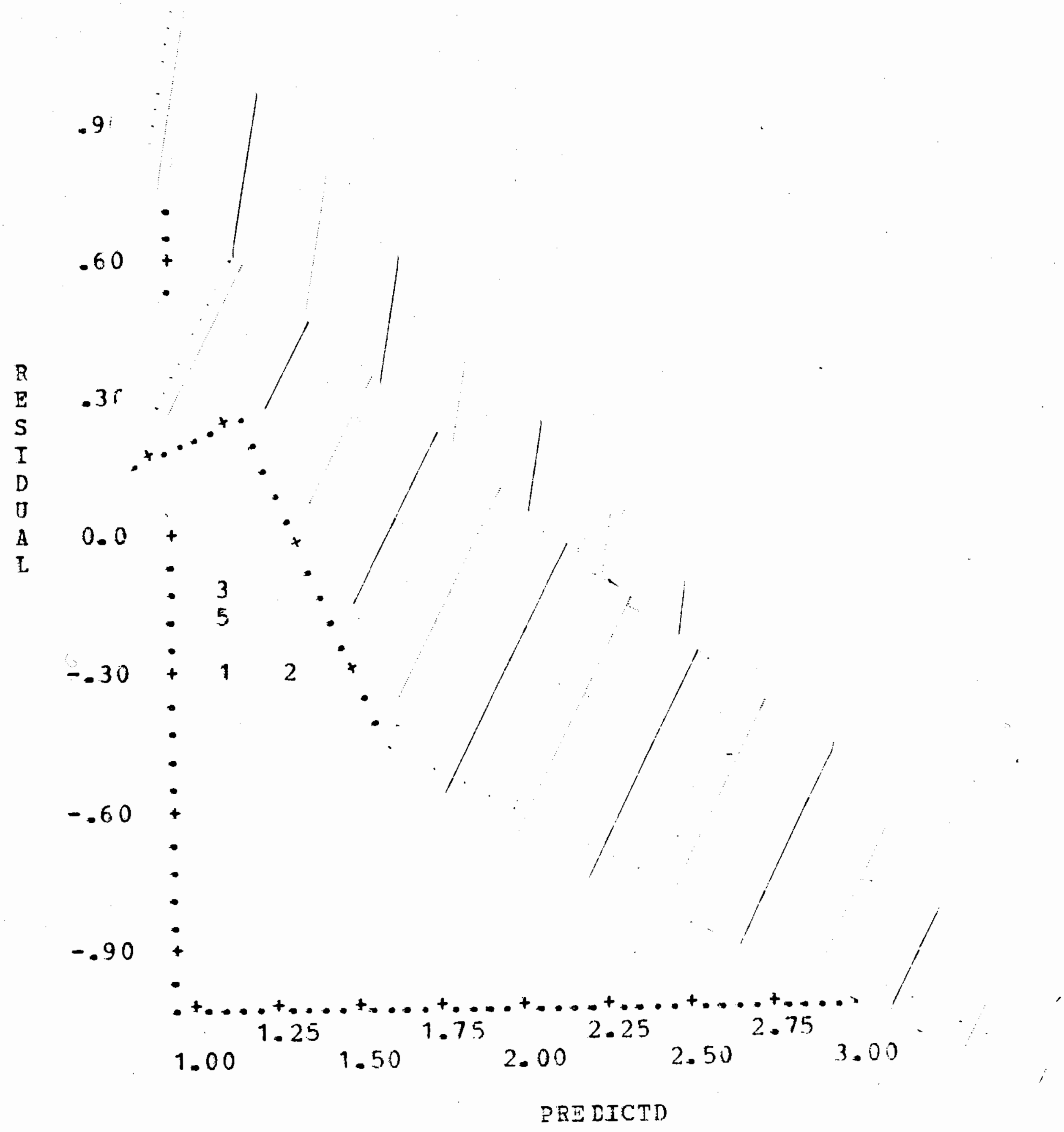

Figure 14: Examination of residuals between actual values of oxygen uptake and those predicted from the linear plot of oxygen uptake against delta heart rate for untrained subjects 20 to 29 years (n=10).

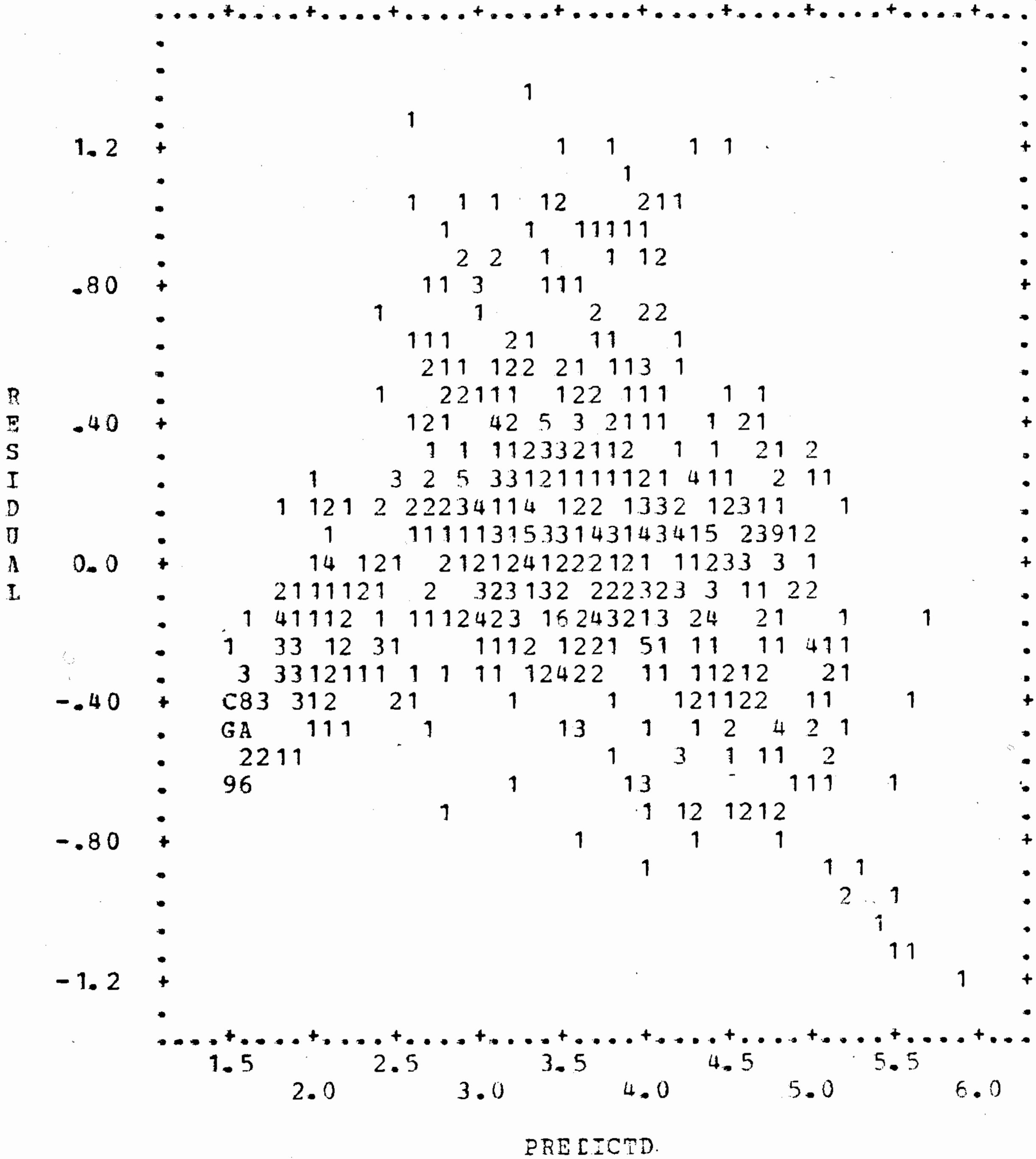

Figure 15: Examination of residuals between actual values of oxygen uptake and those predicted from the exponential plot of oxygen uptake against delta heart rate for trained subjects 20 to 29 years (n=15).

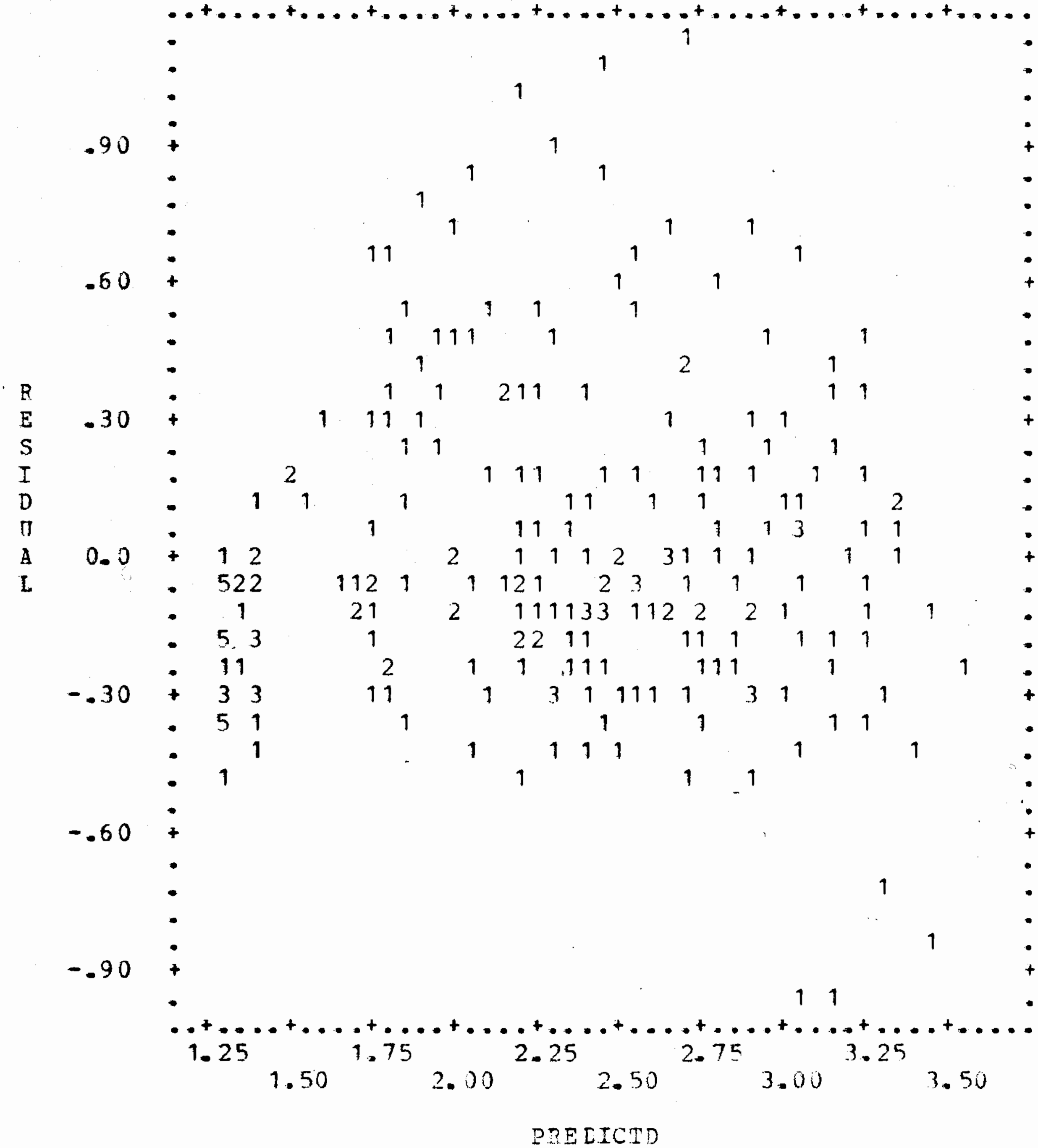

Figure 16: Examination of residuals between actual values of oxygen uptake and those predicted from the exponential plot of oxygen uptake against delta heart rate for untrained subjects 20 to 29 years (n=10).

Table VIII: Showing linear regression equations for groups of trained (T), untrained (UNT) and moderately (MOD) trained males 20 to 29 years for the relation between oxygen uptake (ordinate) and delta heart rate (abscissa).

Group	Linear regression Equation
Tcore (n=15)	Y=(0.03577)X + 1.010
Tvalid (n=5)	Y=(0.03178)X + 1.024
UNTcore (n=10)	Y=(0.02292)X + 1.093
UNTvalid (n=5)	Y=(0.02324)X + 0.877
MOD (n=4)	Y=(0.02450)X + 0.948

Figure 17 shows both the trained and untrained linear relationships determined to exist between oxygen uptake and delta heart rate. The appropriate regression equations are also included. Slopes of oxygen uptake vs. delta heart rate between untrained and trained core groups differed significantly ($p<0.05$) as determined by a small sample t-test.

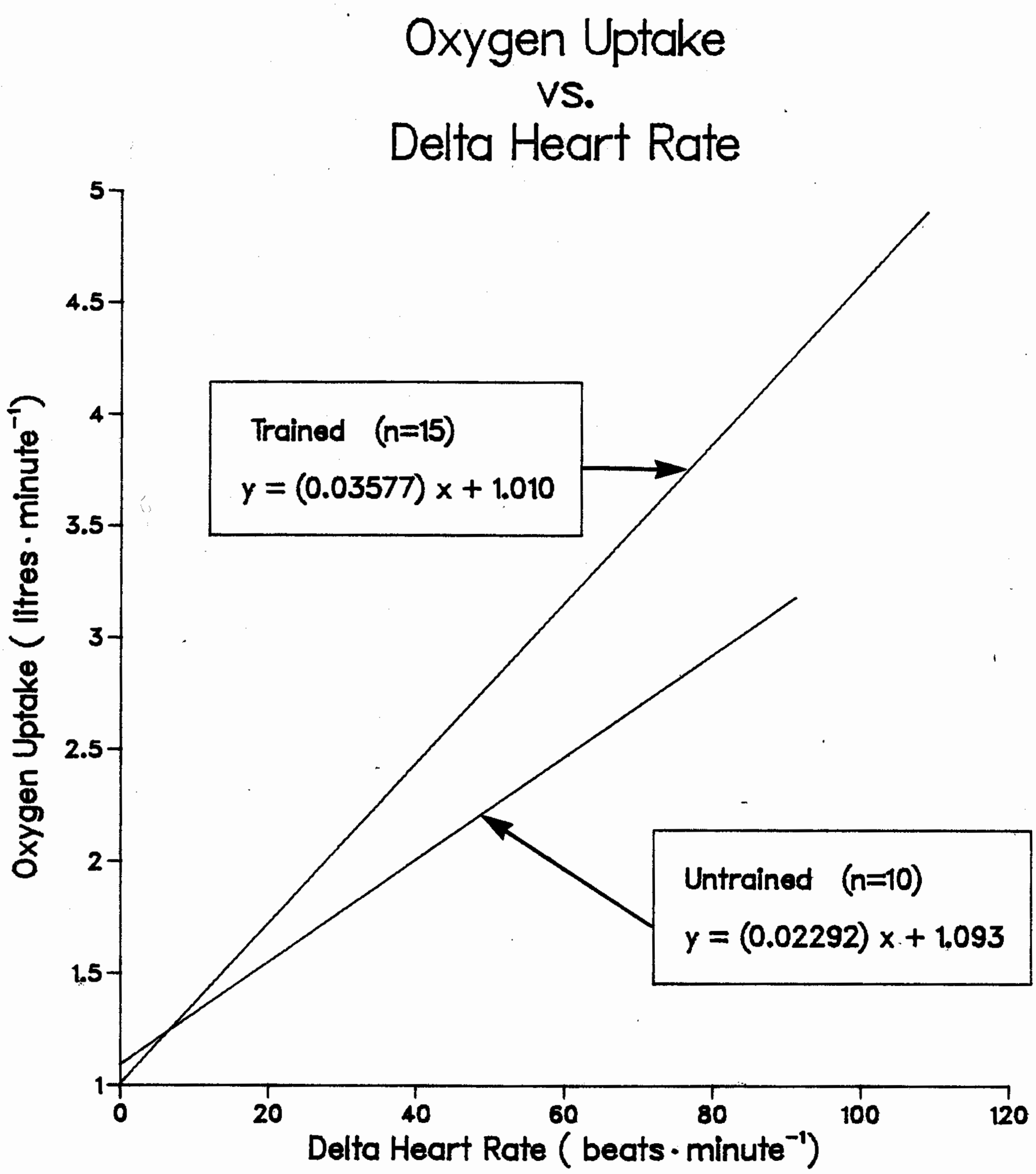

Figure 17: Linear regression of the relationship between oxygen uptake and delta heart rate for trained and untrained core groups.

4.3.3 Test-Retest Reliability

Examination of the slopes of the linear regression equations describing the oxygen uptake/delta heart rate relationship for each trial revealed no significant difference ($p<0.05$). Table IX shows the related F ratios and probability (p) values.

Table IX: Test-Retest Reliability

Group	F ratio	p value
Tcore (n=15)	2.8674	0.0575
Tvalid (n=5)	2.4336	0.0897
UNTcore (n=10)	0.5158	0.4734
UNTvalid (n=5)	0.4934	0.4842

4.3.4 Individual $\dot{V}O_2$/delta HR relationships

While the relationship between oxygen uptake and delta heart rate for both trained and untrained group mean data was determined to be linear, a few individuals within each group exhibited the hypothesized exponential relationship. Figures 18 and 19 show the relationships between oxygen uptake and delta heart rate for a trained and an untrained individual and the non-linear trend at near maximum rates of work.

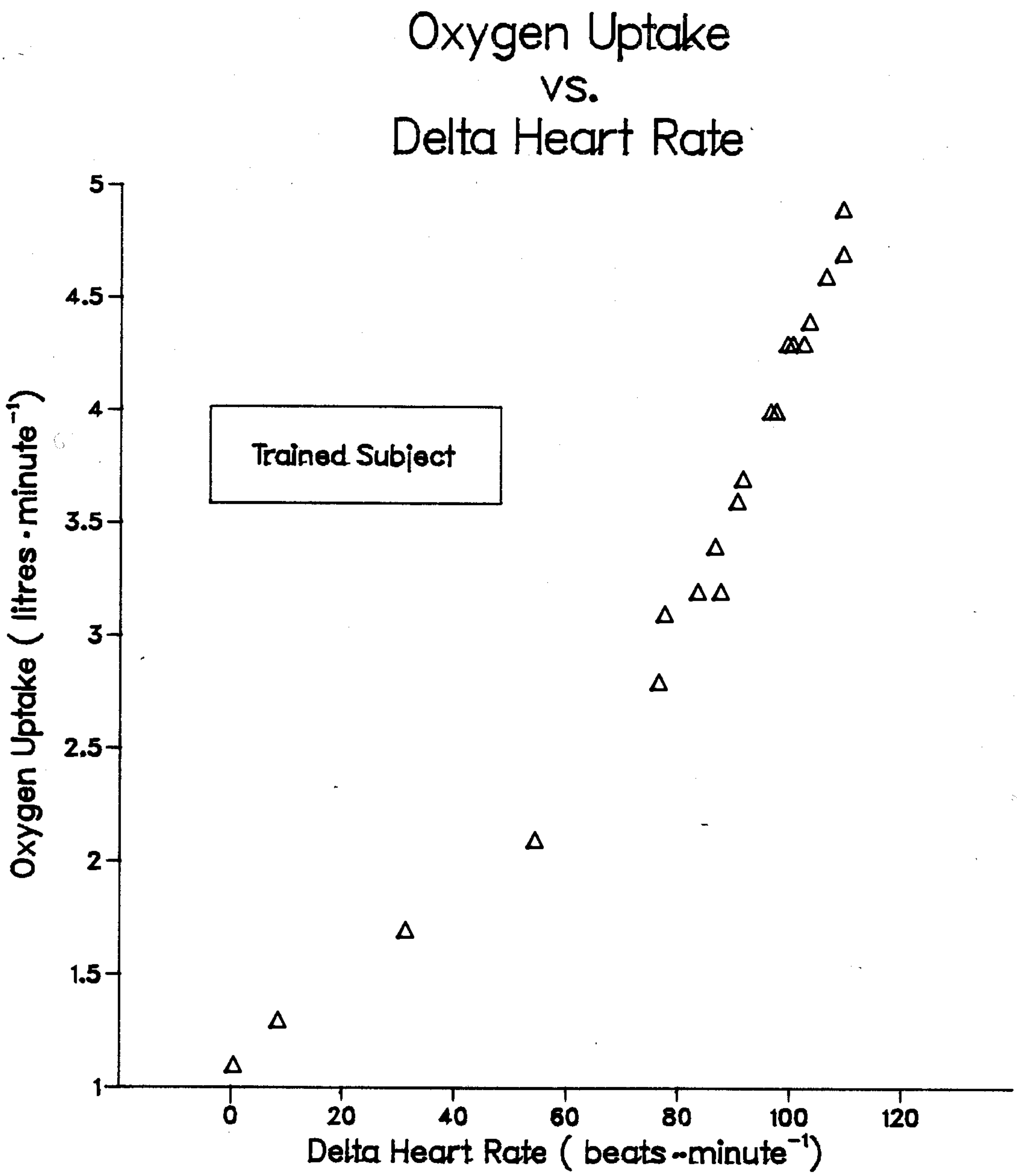

Figure 18: Showing the hypothesized exponential relationship between oxygen uptake and delta heart rate for an individual trained male subject.

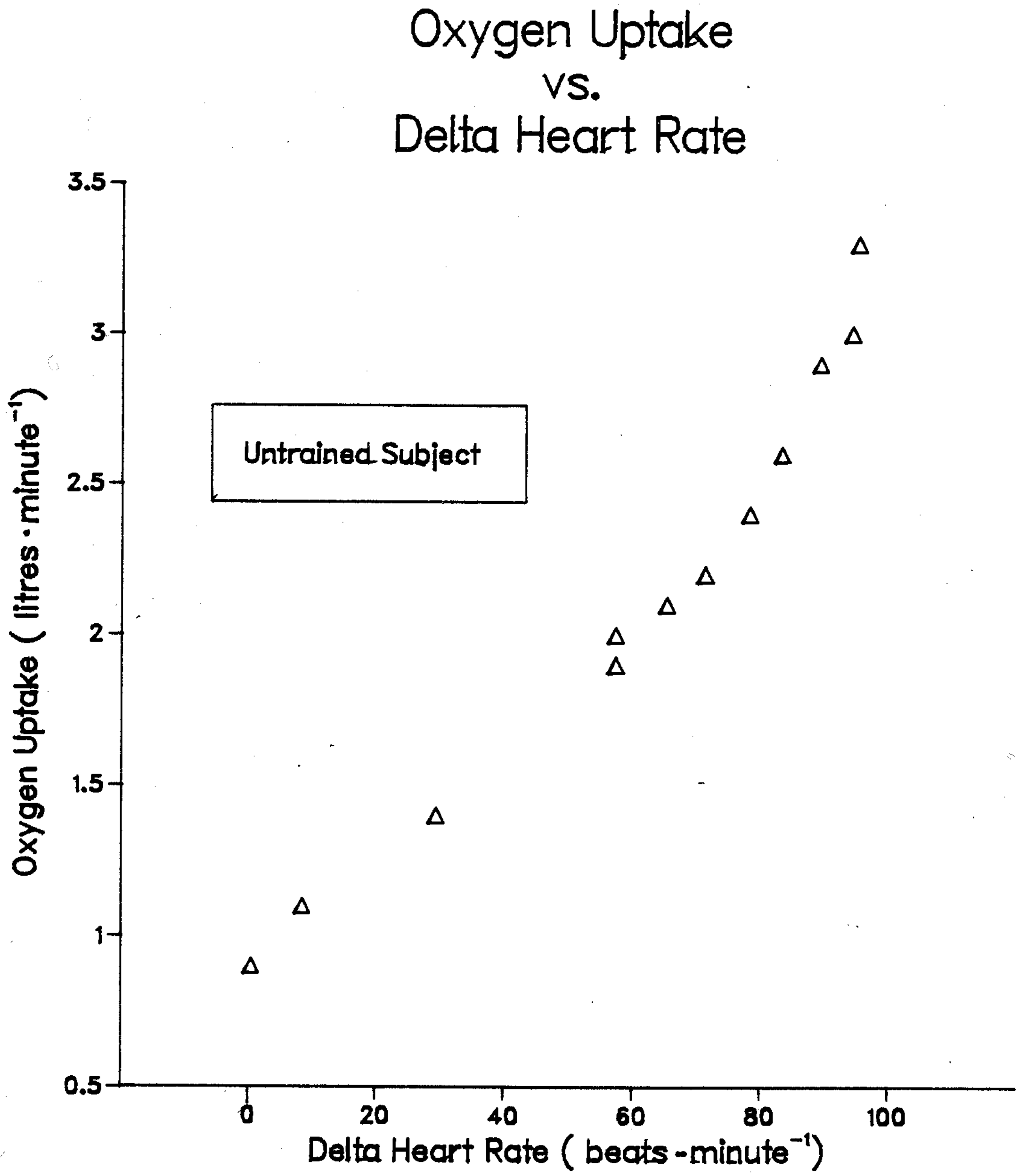

Figure 19: Showing the hypothesized exponential relationship between oxygen uptake and delta heart rate for an individual untrained male subject.

4.4 Relationship between Percent Maximum Oxygen Uptake and Heart Rate

4.4.1 Reconstruction of Astrand-Ryhming Nomogram

In this investigation, the relationship between mean oxygen uptake and mean delta heart rate was found to be expressed most accurately by a linear relationship. The subjects examined in the study were similar in age and general activity level as those examined by Astrand (1952). For these reasons, a nomogram was constructed using the same method as that used by Astrand and Ryhming in their nomogram (1954). This involved expressing each individual oxygen uptake value as a percentage of the individual's maximum oxygen uptake (% $\dot{V}O_2max$). Data were then plotted as percent of maximum oxygen uptake versus heart rate.

The oxygen cost of each submaximal work rate was determined and found to approximate closely the oxygen cost of work determined theoretically as shown in Table X. The theoretical calculation of oxygen cost is shown in Appendix C. Oxygen uptakes achieved were, therefore, considered to be steady state values. No significant difference was found to exist between the oxygen uptake measured for trained and untrained groups and the theoretical cost of performing the submaximum work rates of 600, 900, 1200 and 1500 $kpm \cdot min^{-1}$. A significant difference was found to exist at the submaximum work rate of 300 $kpm \cdot min^{-1}$. This may have been related to a decreased efficiency when pedalling at 90 rpm at a low work rate for both untrained and trained subjects. No significant difference existed, however, between the two groups of subjects in terms of the oxygen cost of 300 kpm·min^{-1}.

Table X: Showing the directly measured oxygen uptake and theoretically calculated oxygen cost of performing submaximum steady state work (liter O_2min).

Group	Work rate (kpm ·min^{-1}) 300	600	900	1200	1500
Trained core (n=15)	1.13 ±0.11	1.65 ±0.13	2.16 ±0.13	2.75 ±0.17	3.27 ±0.19
Untrained core (n=10)	1.23 ±0.16	1.68 ±0.16	2.16 ±0.16		
Theoretical value	0.90*	1.50	2.10	2.80	3.40

Values are means ± standard deviations of means (SD).

* Significant difference between theoretically calculated oxygen cost and directly measured oxygen uptake ($p<0.05$).

4.4.2 Data expressed as % $\dot{V}O_2max$/Heart Rate

Data was expressed as % $\dot{V}O_2max$ and heart rate rather than $\dot{V}O_2max$ and delta heart rate, in an attempt to duplicate Astrand's nomogram. Figures 20 and 21 show raw data plots of % $\dot{V}O_2max$ vs. heart rate for trained and untrained groups, respectively.

Figure 22 shows a graph of trained and untrained data plotted as % $\dot{V}O_2max$ vs. heart rate. In addition, this figure shows similar data from Astrand's 1952 study derived from his determination that heart rates of 128 $b \cdot min^{-1}$, 154 $b \cdot min^{-1}$ and 195 $b \cdot min^{-1}$ required oxygen uptakes representing 50, 70 and 100% $\dot{V}O_2max$, respectively. Trained and untrained group mean data was also combined into one larger group and referred to as Allcore data. A separate linear regression equation was also derived for Allcore data and shown in Figure 22.

Linear regression analysis of the data expressed as % $\dot{V}O_2max$ vs. heart rate revealed no significant difference at the 0.05 level of significance between regression equations in terms of slopes or intercepts. This is apparent by the almost complete overlap of regression equations derived for trained and untrained groups with Astrand's data (1952). Table XI shows the regression equations, correlation coefficients (r), mean square residuals (MSR) and standard errors of estimate (SE_{EST}) for trained and untrained data expressed as % $\dot{V}O_2max$ vs. heart rate compared to Astrand's original data.

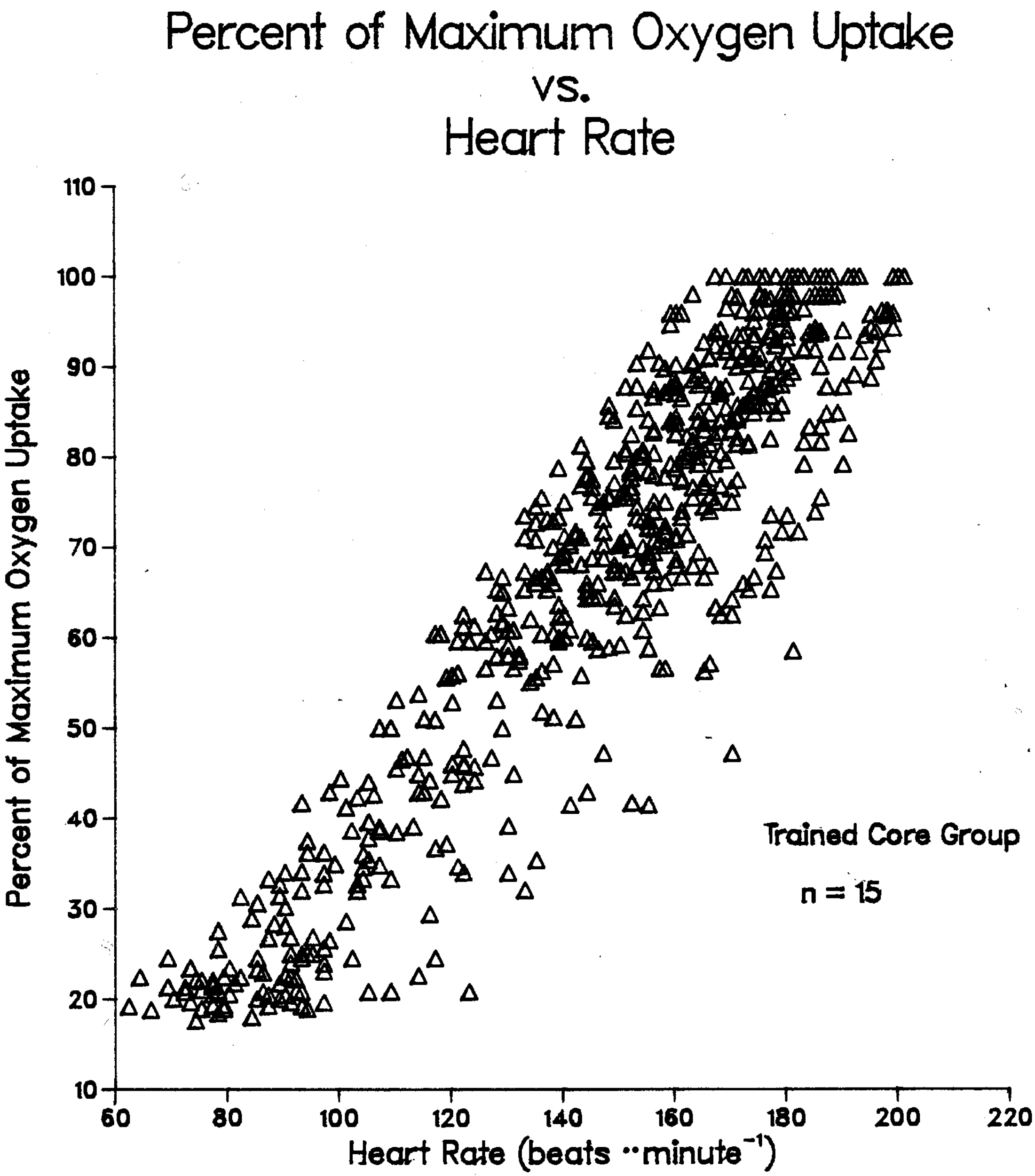

Figure 20: Showing the relationship between % $\dot{V}O_2max$ and heart rate for trained males 20 to 29 years (n=15).

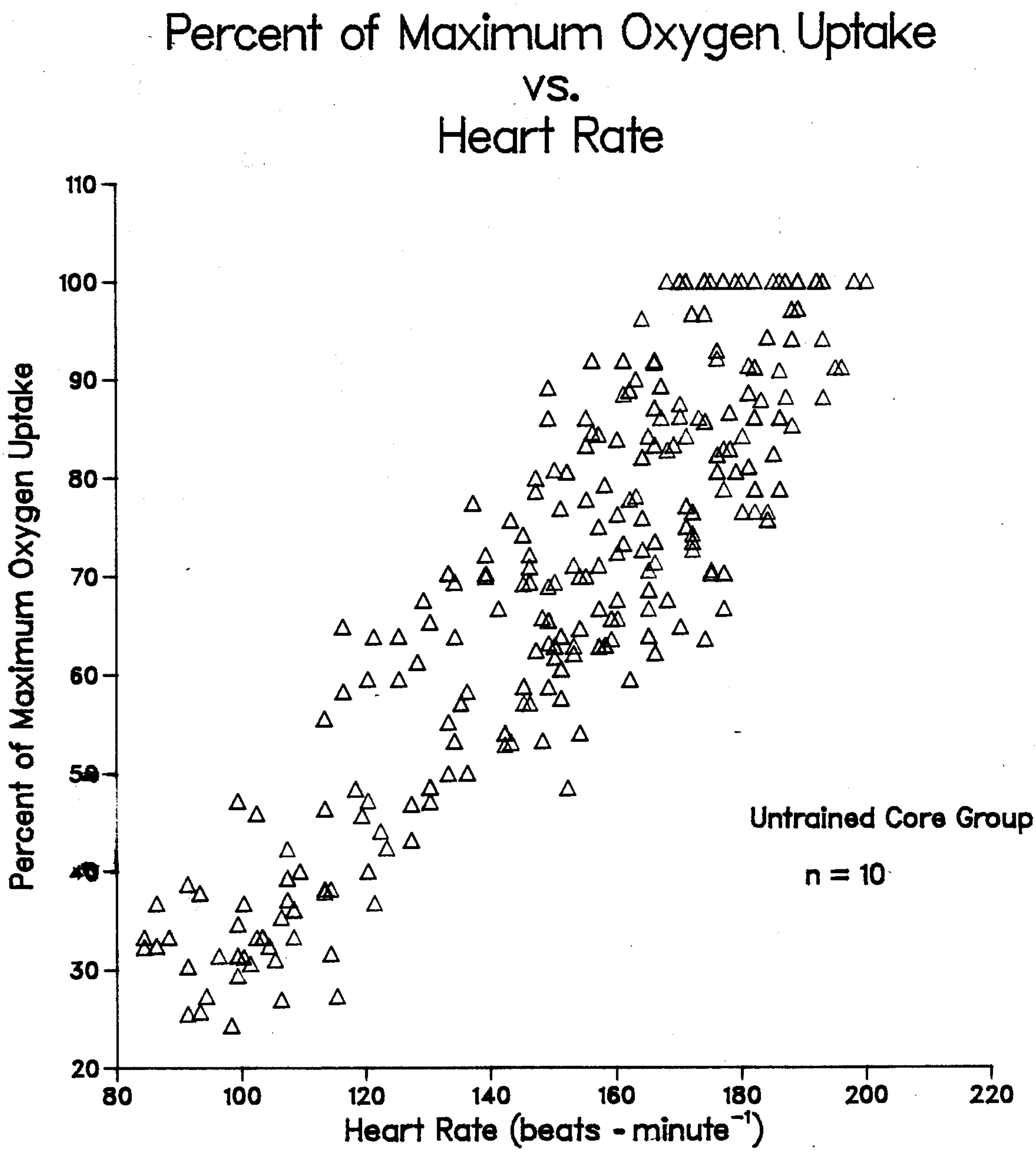

Figure 21: Showing the relationship between % $\dot{V}O_2$max and heart rate for untrained males 20 to 29 years (n=10).

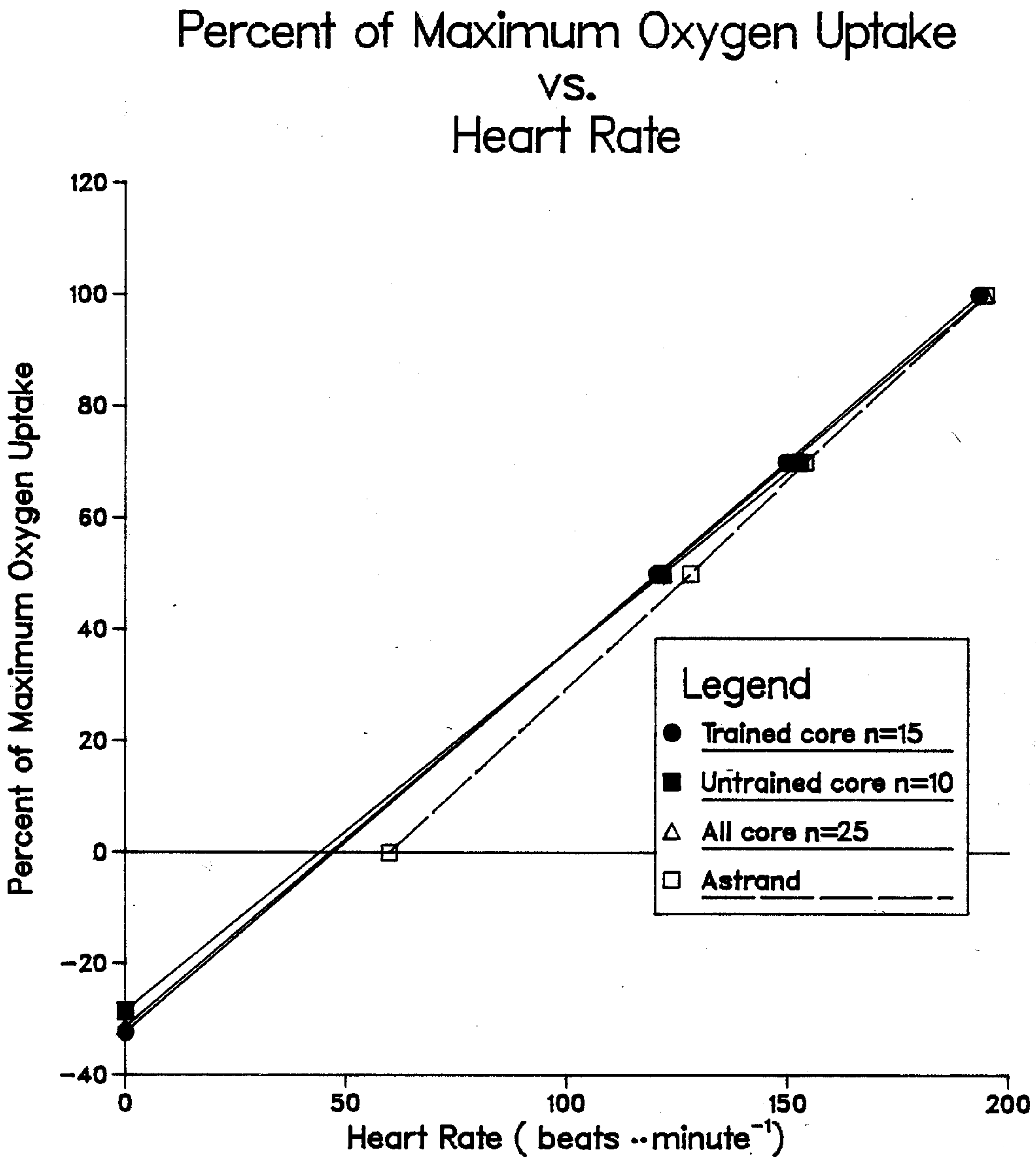

Figure 22: Data expressed as % $\dot{V}O_2$max vs. heart rate for trained and untrained group data. Astrand's original test group data is also included.

Table XI: Results of Linear Regression Analysis for Trained and Untrained Core and Validity Group Data Expressed as % $\dot{V}O_2max$ vs. Heart Rate.

Group	Regression Equation	r	MSR	SE_{EST}
Tcore (n=15)	y=(0.68398)x-32.302	0.9270	83.284	
Tvalid (n=5)	y=(0.69742)x-38.450	0.9456	62.428	7.9012
UNTcore (n=10)	y=(0.64471)x-28.453	0.8931	88.177	9.3903
UNTvalid (n=5)	y=(0.70635)x-35.607	0.9313	66.416	8.1496
All core (n=25)	y=(0.67355)x-31.332	0.9187	85.519	9.2476
Astrand	y=(0.74627)x-45.53			

Table XII lists the heart rates determined at 50% $\dot{V}O_2max$ 70% $\dot{V}O_2max$ and 100% $\dot{V}O_2max$ from Astrand (1952) and the present investigation. Heart rate values from the present study have been calculated from the appropriate regression equation and are shown without corresponding standard deviations. No significant differences ($p<0.05$) were determined to exist between heart rates at 50, 70 or 100% $\dot{V}O_2max$.

Table XII: Mean heart rate values ($b \cdot min^{-1}$) at 50, 70 and 100 percent of maximum oxygen uptake as determined by linear regression analysis.

	Astrand (n=86)	Tcore (n=15)	UNTcore (n=10)	T+UNT (n=25)
50%	128	122	120	121
70%	154	153	150	150
100%	195	199	193	195

Data were then used to construct maximum oxygen uptake predictive tables and corresponding nomograms using % $\dot{V}O_2max$ and heart rate from the present study in a method similar to that used by Astrand and Ryhming (1954).

4.5 Relationship between % $\dot{V}O_2max$ and Delta HR

4.5.1 Expression of data as % $\dot{V}O_2max$ vs. Delta Heart Rate

Data were expressed as % $\dot{V}O_2max$ and delta heart rate in an attempt to differentiate between trained and untrained groups. Figures 23 and 24 show raw data expressed as % $\dot{V}O_2max$ vs. delta heart rate and the relationship existing for trained and untrained individuals.

Group mean data and the regression equations providing the best fit are shown in Figure 25 for both trained and untrained groups. Analysis of variance revealed a significant difference ($p<0.05$) between intercepts of the regression equations for trained and untrained groups, respectively.

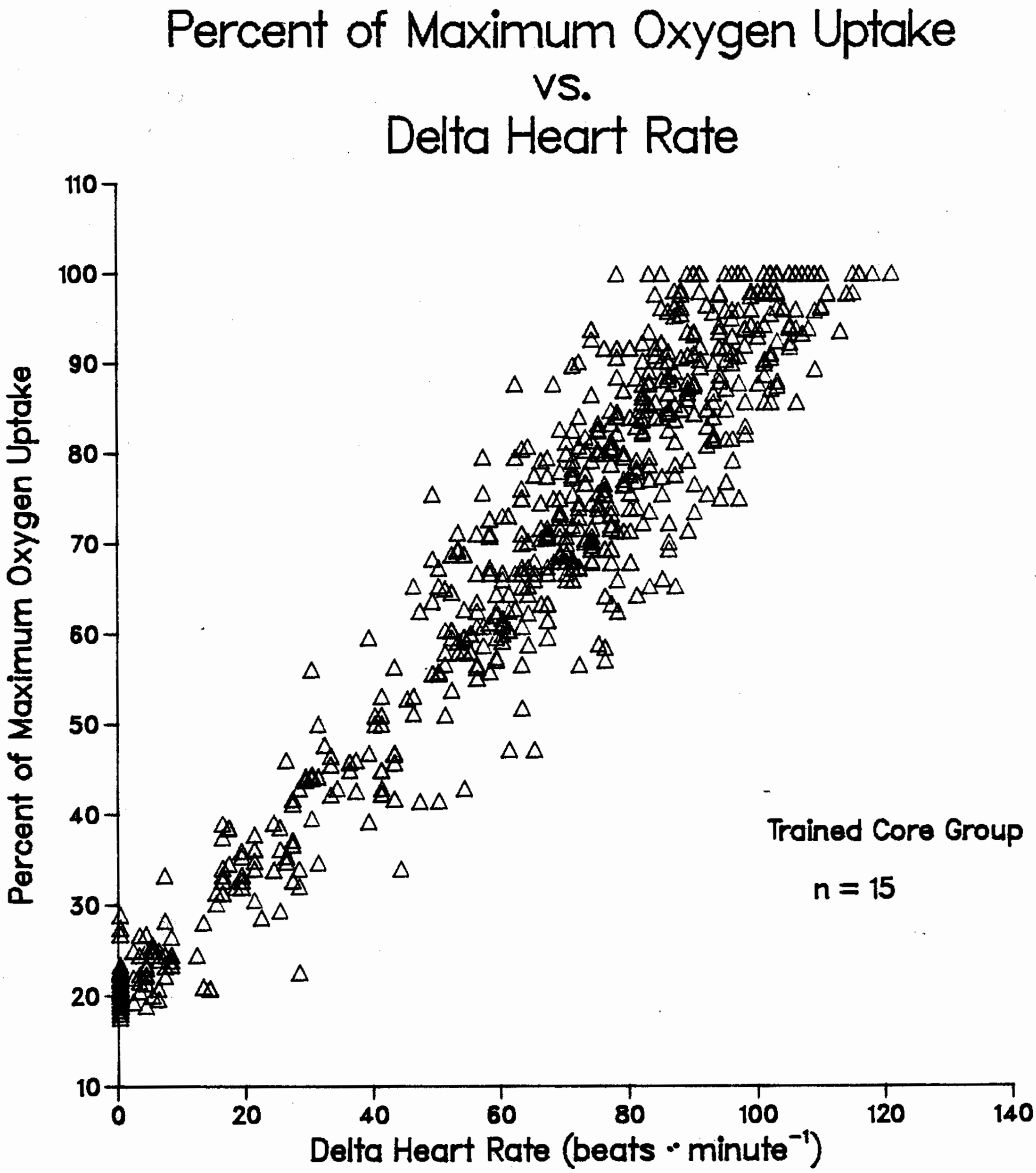

Figure 23: Showing the relationship between % $\dot{V}O_2max$ and delta heart rate for trained males 20 to 29 years (n=15).

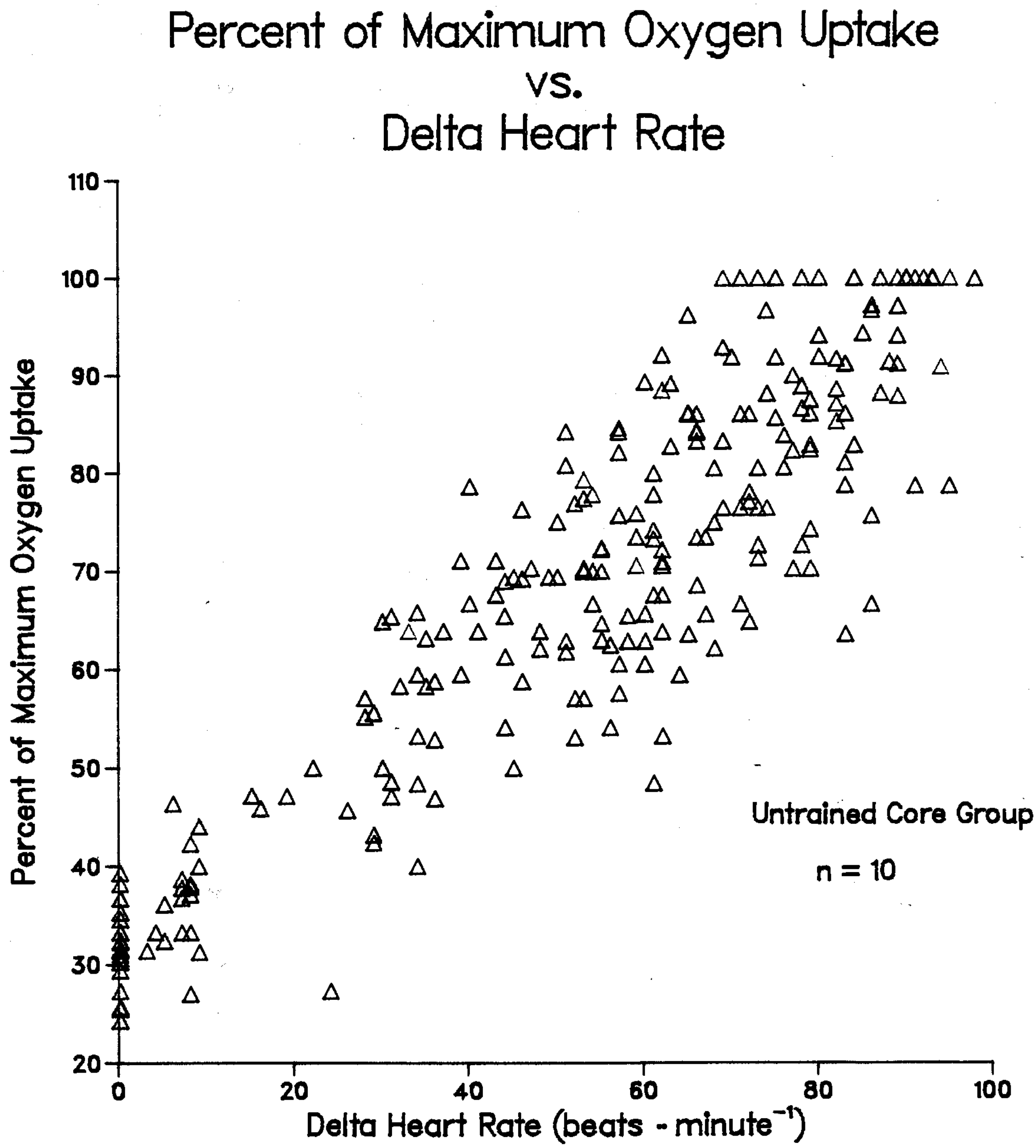

Figure 24: Showing the relationship between % $\dot{V}O_2$max and delta heart rate for untrained males 20 to 29 years (n=10).

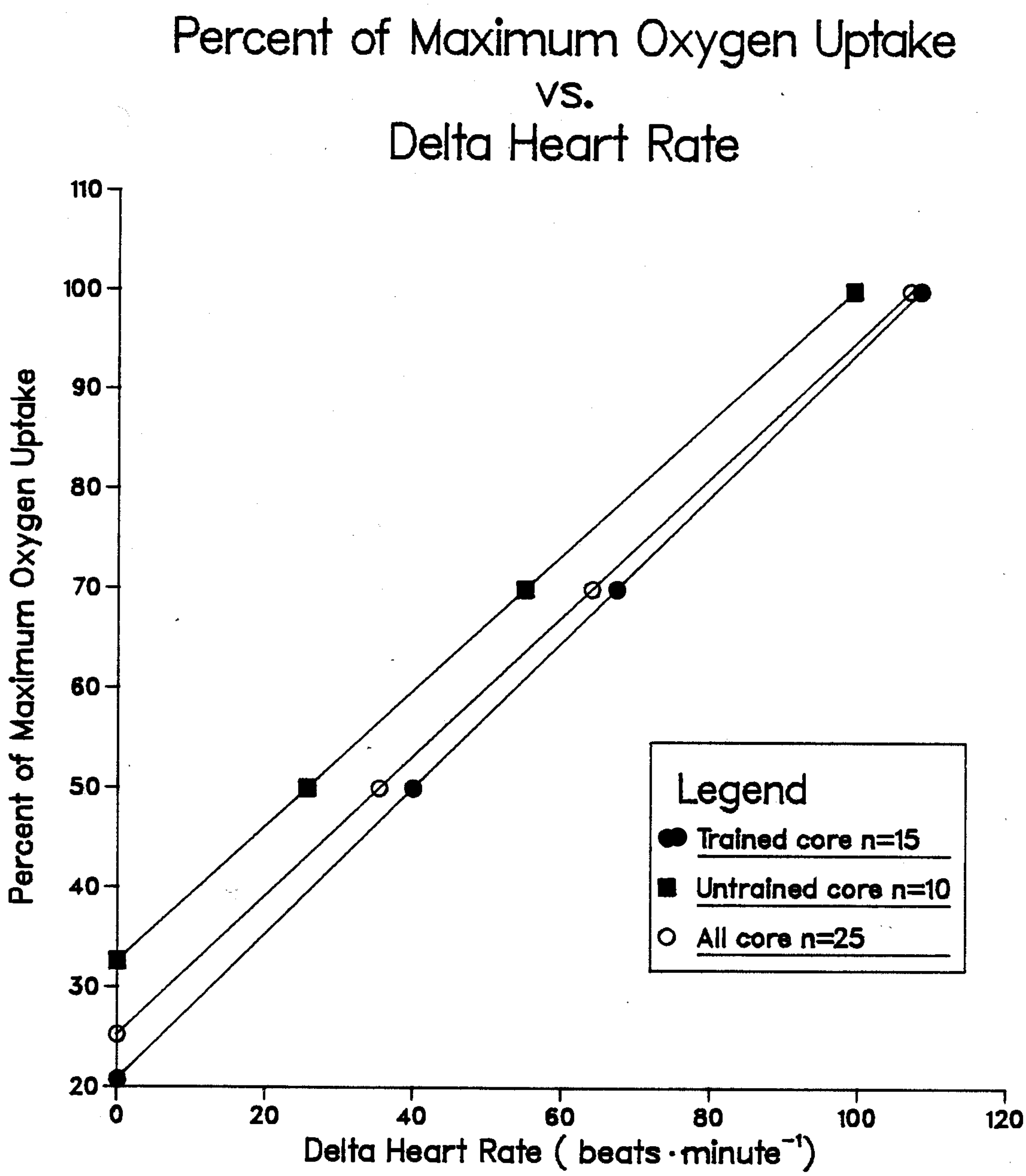

Figure 25: Showing regression equations and correlation coefficients for trained and untrained males.

Table XIII shows the delta heart rates at 50, 70 and 100% $\dot{V}O_2max$. A significant difference ($p<0.05$) was determined to exist between trained and untrained delta heart rates at 50, 70 and 100% $\dot{V}O_2max$. Maximum oxygen uptake predictive tables and corresponding nomograms were constructed.

Table XIII: Mean delta heart rates at 50, 70 and 100% $\dot{V}O_2max$ determined by linear regression analysis.

% $\dot{V}O_2max$	Trained Delta HR ($b \cdot min^{-1}$)	UNTrained Delta HR ($b \cdot min^{-1}$)
50%	40	26
70%	67	55
100%	108	99

4.6 Prediction of Maximum Oxygen Uptake

Two separate maximum oxygen uptake predictive tables were constructed from the relationship between percent maximum oxygen uptake and delta heart rate for trained and untrained groups as outlined previously. Validity groups of trained (n=5) and untrained (n=5) subjects performed the appropriate submaximum work tests and maximum oxygen uptake was predicted from the corresponding nomogram.

The moderate group (n=4) of individuals was included with the trained and untrained validity groups in the assessment of the accuracy of the newly devised predictive nomograms. Characteristic moderate group mean data is presented in Table XIV. Significant differences were determined between moderate and untrained groups for $\dot{V}O_2max$, maximum delta heart rate and maximum work rate. Moderate and trained groups also showed significant differences for $\dot{V}O_2max$ and maximum work rate. Maximum delta heart rate was determined to be the deciding variable in terms of the specific choice of trained or untrained nomogram from which to predict maximum oxygen uptake. Due to the significant difference between moderate and untrained group mean maximum delta heart rates and the non-significant difference between moderate and trained maximum delta heart rates, predictions of maximum oxygen uptake for the moderate group were made from the newly constructed trained predictive nomogram.

Table XIV: Physical characteristics and peak cardiorespiratory variables for moderately (MOD) males 20 to 29 years (n=4).

Age (years)	23.0 ±2.0
Weight (kg)	69.0 ±5.3
$\dot{V}O_2$ max ($l \cdot min^{-1}$)	3.80*# ±0.12
$\dot{V}O_2$ max ($ml \cdot kg^{-1} \cdot min^{-1}$)	55.4* ±5.5
HRmax ($b \cdot min^{-1}$)	198.0 ±2.0
HRmax ($b \cdot min^{-1}$)	111.0# ±8.0
$\dot{V}E$max ($l \cdot min^{-1}$)	111.8 ±11.2
WRmax ($kpm \cdot min^{-1}$)	2075.0*# ±95.7
Lactate (mM)	12.25 ±1.4

Values are means ± standard deviations of the mean (SD).

* Significant difference ($p<0.05$) between MOD and Tcore.
# Significant difference ($p<0.05$) between MOD and UNTcore.

Directly measured and predicted $\dot{V}O_2max$ values for trained, untrained and moderate validity group members (n=14) are shown in Table XV. Predicted maximum oxygen uptakes were made from the trained and untrained tables constructed from the % $\dot{V}O_2max$/heart rate relationship, designated PER, on the whole validity group (n=14). % $\dot{V}O_2max$ and heart rate data for trained and untrained core groups were combined and an All-PER table constructed and maximum oxygen uptake predicted.

Maximum oxygen uptake was also predicted from the trained and untrained predictive tables devised from the % $\dot{V}O_2max$/delta heart rate relationship, designated Banister-Legge (B-L) predictions on the fourteen validity group members. Predictions of maximum oxygen uptake were also made from a predictive table constructed from combined trained and untrained % $\dot{V}O_2max$ and delta heart rate data, designated All-Banister-Legge (All-B-L) predictions.

Table XV, therefore, includes the observed maximum oxygen uptake values as well as the predicted maximum oxygen uptakes using the Astrand-Ryhming nomogram and the four other predictive tables. The four predictive tables include predictions from the separate trained and untrained % $\dot{V}O_2max$/heart rate relationships and for the combined group relationship (n=25). Predictions made from separate trained and untrained % $\dot{V}O_2max$/ delta heart rate relationships, termed the Banister-Legge predictions, were recorded as well as the combined group data (n=25).

Table XV: Directly measured and Predicted $\dot{V}O$ max ($l \cdot min^{-1}$) values for Trained (T), Untrained (UNT) and Moderate (MOD) validity group members.

subject	OBS	Astrand	B-L	All-B-L	PER	All-PER
T1	4.7	4.1	4.68	4.54	4.74	4.79
T2	4.8	4.3	4.77	4.63	4.41	4.45
T3	4.8	3.7	4.77	4.63	4.15	4.19
T4	4.8	6.0	4.82	4.67	5.25	5.29
T5	4.3	4.0	3.86	3.80	4.02	4.06
UNT1	3.5	3.5	3.47	3.90	3.47	3.41
UNT2	2.7	2.4	2.76	3.00	2.61	2.55
UNT3	3.3	3.8	3.36	3.75	4.24	4.19
UNT4	2.8	2.7	3.12	3.45	2.91	2.85
UNT5	2.4	2.0	2.28	2.52	1.92	1.88
MOD1	3.6	2.8	3.62	3.45	2.79	2.72
MOD2	3.9	4.3	4.02	3.80	4.29	4.24
MOD3	3.5	3.7	3.32	3.19	3.43	3.37
MOD4	3.5	2.9	3.49	3.33	3.02	2.96

Each set of predicted maximum oxygen uptake values was regressed with directly measured maximum oxygen uptake measures and the calculated correlation coefficients compared. Standard errors of estimate were also calculated and recorded in Table XVI. Analysis for a significant difference between correlation coefficients determined from the Astrand-Ryhming nomogram, ($r=0.8043$), and the Banister-Legge nomogram, ($r=0.9791$), using Fisher's Z statistic, as outlined by Kleinbaum and Kupper (1978), revealed a statistically significant difference at the 0.05 level of significance. The standard error of estimate was smaller using the Banister-Legge nomogram, ($SE_{EST}=0.1738$), as compared to that determined using the Astrand-Ryhming nomogram,

(SE_{EST}=0.5082). Predictions of maximum oxygen uptake from the Banister-Legge nomogram, therefore, provided for an improved accuracy of prediction compared to the Astrand-Ryhming nomogram.

Table XVI: Comparison of directly measured and estimated $\dot{V}O_2max$ values with the help of linear regression equations.

Estimation Method Used	Number of Subjects	Correlation Coefficient	SE_{EST}	$\%SE_{EST}$
Astrand	14	0.8043	0.5082	14.2
PER	14	0.8622	0.4332	
All-PER	14	0.8733	0.4166	
B-L	14	0.9791	0.1738	4.65
All-B-L	14	0.9237	0.3276	8.72

Figures 26 and 27 show the relationship between observed and predicted maximum oxygen uptakes from the Astrand-Ryhming nomogram, and the Banister-Legge nomogram using separate trained and untrained predictive tables, respectively.

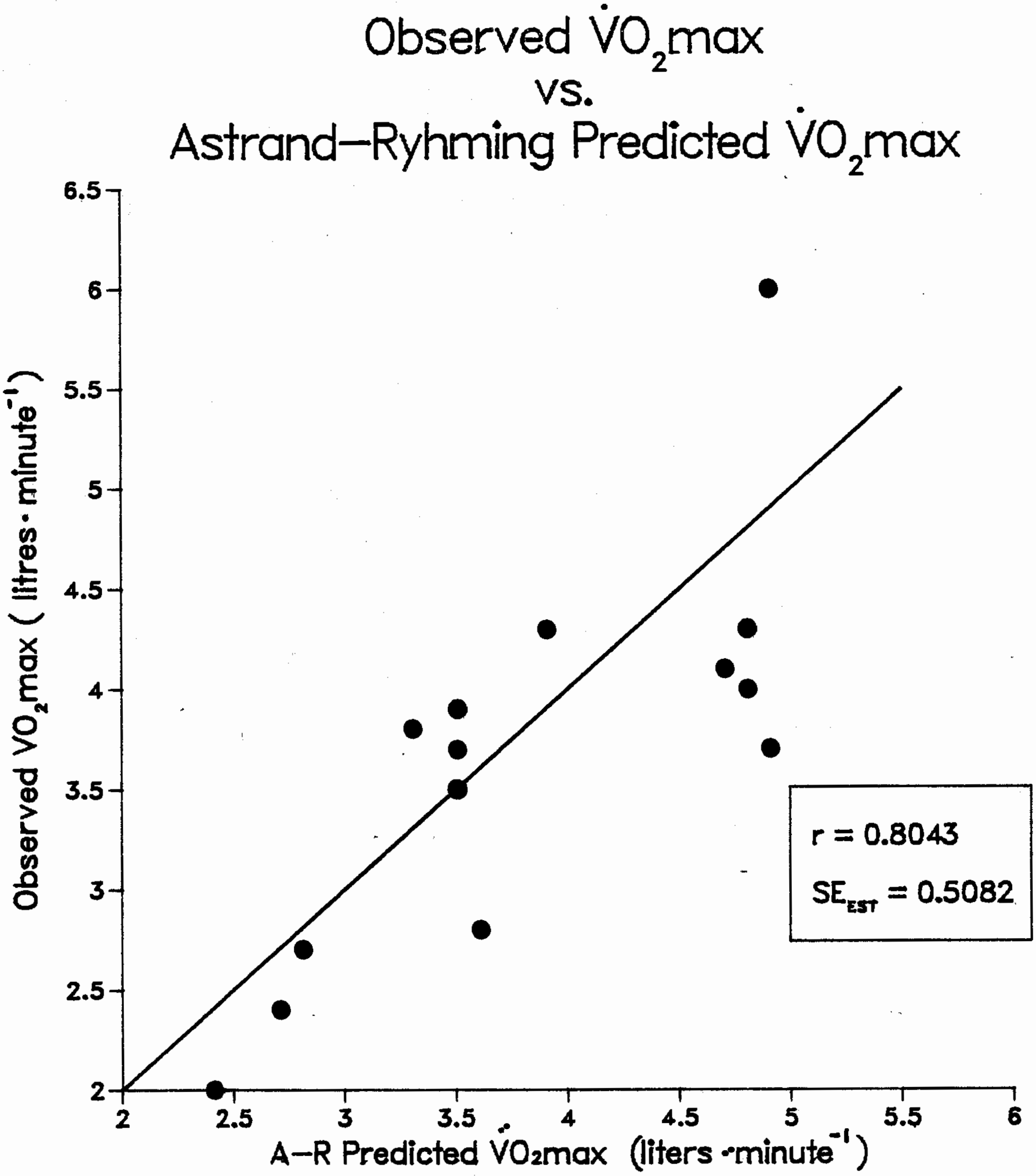

Figure 26: Showing the relationship between observed and predicted maximum oxygen uptake using the Astrand-Ryhming nomogram.

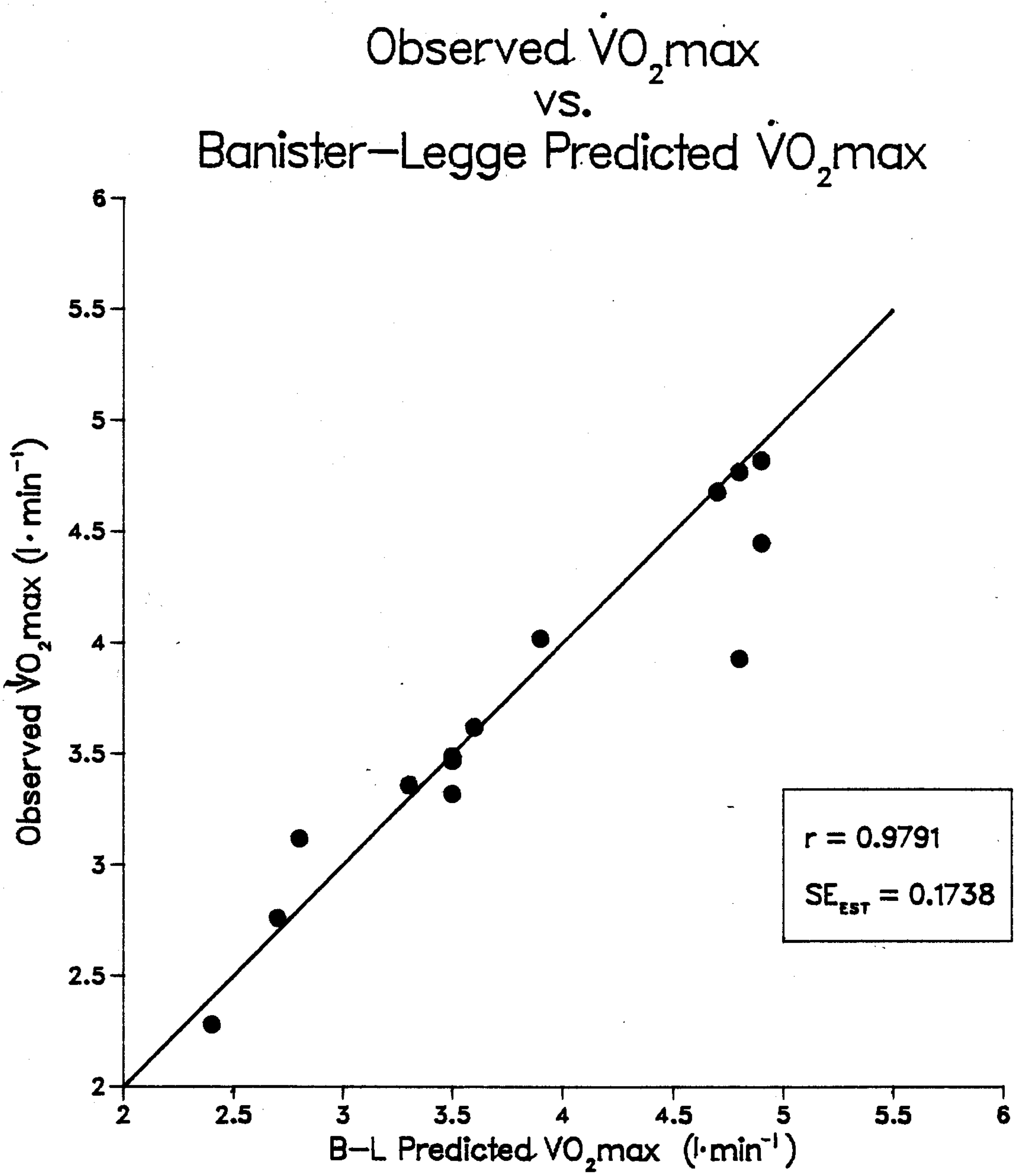

Figure 27: Showing the relationship between observed and predicted maximum oxygen uptake using the Banister-Legge nomogram.

4.7 Banister-Legge Nomogram

Since the validation groups were found to have their maximum oxygen uptakes predicted accurately by the newly constructed Banister-Legge nomogram providing separate predictive tables for trained and untrained individuals, the validation and core group data were combined to form two larger groups of trained (n=20) and untrained (n=15) individuals. The combining of core and validity group data was also undertaken to increase the statistical power of the predictive test by increasing the subject number. Using a small A significant difference ($p<0.05$) was determined between intercepts of the regression equations describing the relationship between % $\dot{V}O_2max$ and delta heart rate for trained and untrained group data using a small sample t-test for significant differences between common intercepts, as outlined by Kleinbaum and Kupper (1978). As expected, the slopes of these lines did not differ significantly. Figure 28 shows the regression equations and associated standard errors of estimate for the two regression equations for the trained (n=20) and untrained (n=15) groups.

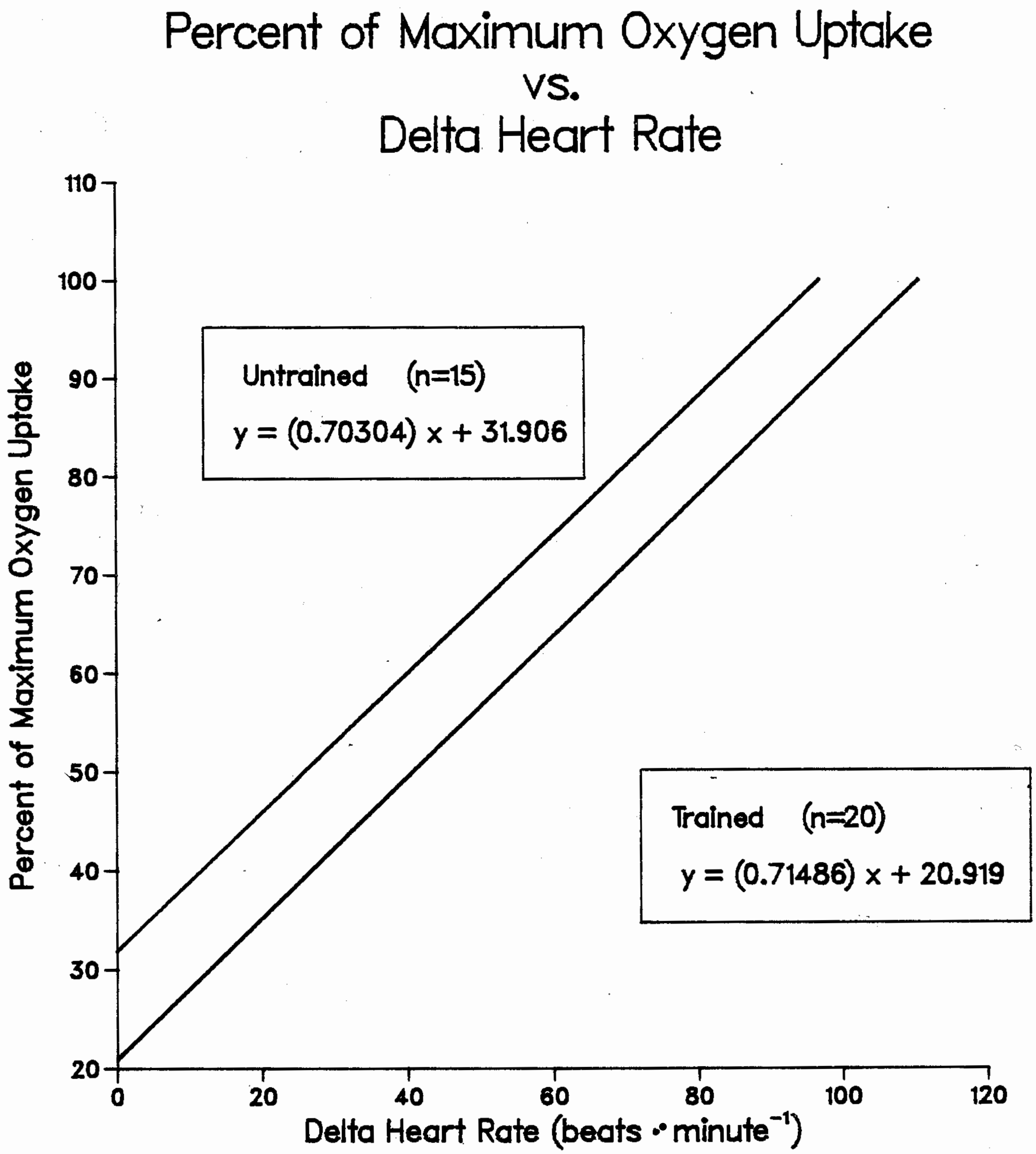

Figure 28: Showing the regression equations describing the relationship between % $\dot{V}O_2max$ and delta heart rate for trained (n=20) and untrained (n=15) males 20 to 29 years.

The Banister-Legge nomogram, constructed from data collected from 20 trained and 15 untrained subjects, is presented in its final form in Figure 29. The related tables for the prediction of maximum oxygen uptake from delta heart rate responses to submaximum bicycle ergometry for trained males aged 20 to 29 and for untrained males of the same age, are presented as Tables XVII and XVIII, respectively. Sample predictions of maximum oxygen uptake for both a hypothetical untrained and a trained individual having the same delta heart rate of 68 $b \cdot min^{-1}$ at different submaximum work rates, 900 $kpm \cdot min^{-1}$ and 1200 $kpm \cdot min^{-1}$, are shown in Figure 30. The predicted maximum oxygen uptake values for these hypothetical untrained and trained individuals are 2.66 and 4.00 $l \cdot min^{-1}$, respectively.

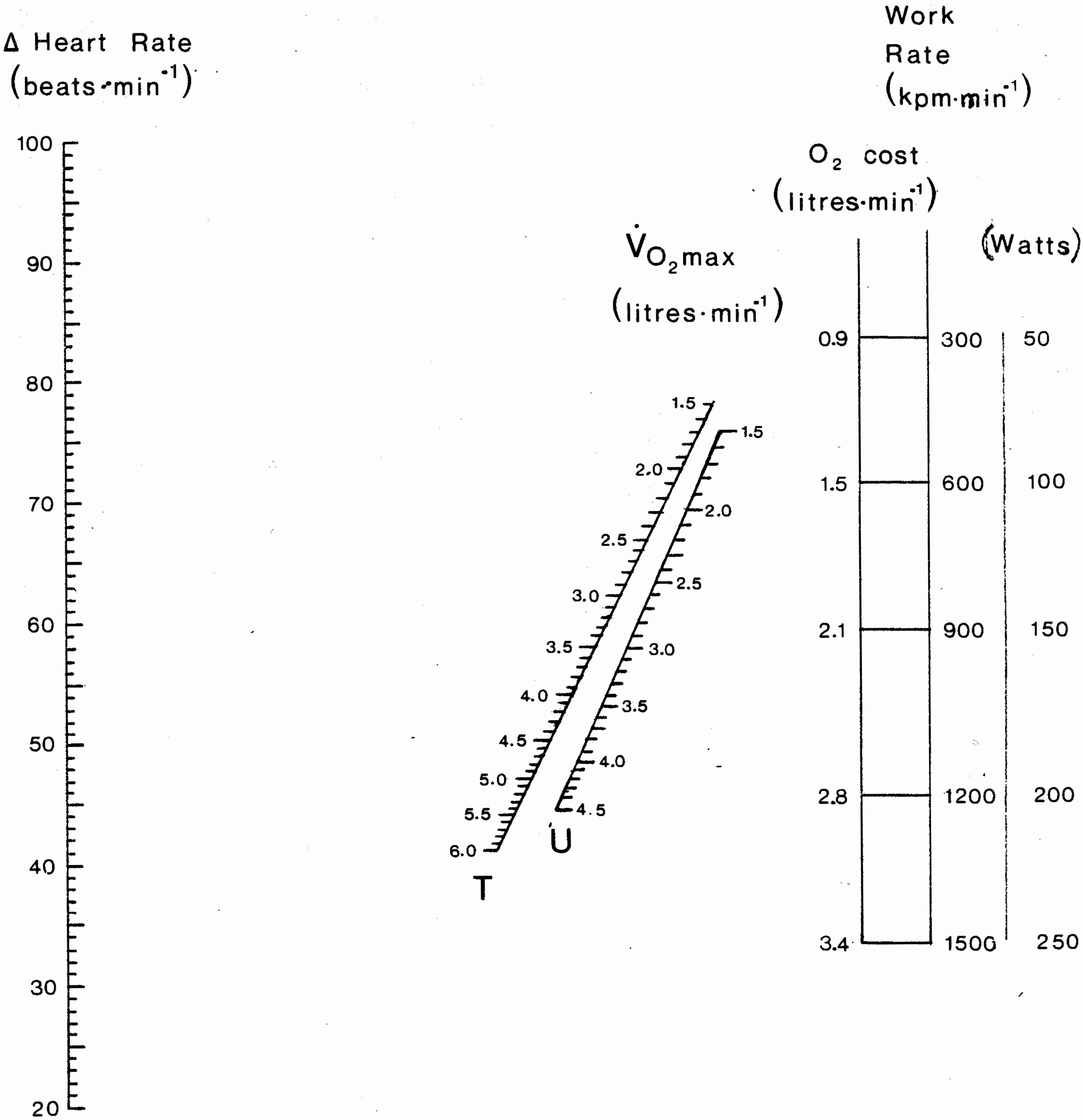

Figure 29: Banister-Legge nomogram for predicting $\dot{V}O_2max$ in litres·min^{-1} for Trained (T) and Untrained (U) males 20 to 29 years.

Table XVII: Banister-Legge Predictive Table for Trained Males (20-29 years)

TRAINED MAXIMAL OXYGEN UPTAKE (litres - min^{-1})					
Delta Heart Rate ($b \cdot m^{-1}$)	Work Rate ($kpm \cdot min^{-1}$) 300 (watts) 50	600 100	900 150	1200 200	1500 250
20	2.56	4.26	5.96		
21	2.50	4.17	5.84		
22	2.46	4.09	5.73		
23	2.41	4.01	5.62		
24	2.36	3.94	5.52		
25	2.32	3.87	5.41		
26	2.28	3.80	5.32		
27	2.24	3.73	5.22		
28	2.20	3.66	5.13		
29	2.16	3.60	5.04		
30	2.12	3.54	4.96		
31	2.09	3.48	4.87	6.50	
32	2.06	3.43	4.80	6.39	
33	2.02	3.37	4.72	6.29	
34	1.99	3.32	4.64	6.19	
35	1.96	3.27	4.57	6.10	
36	1.93	3.22	4.50	6.00	
37	1.90	3.17	4.43	5.91	
38	1.87	3.12	4.37	5.82	
39	1.84	3.07	4.30	5.74	
40	1.82	3.03	4.24	5.66	
41	1.79	2.99	4.18	5.57	
42	1.77	2.94	4.12	5.50	
43	1.74	2.90	4.07	5.42	
44	1.72	2.86	4.01	5.35	6.49
45	1.70	2.83	3.96	5.27	6.40
46	1.67	2.79	3.90	5.20	6.32
47	1.65	2.75	3.85	5.14	6.24
48	1.63	2.72	3.80	5.07	6.16
49	1.61	2.68	3.75	5.00	6.08
50	1.59	2.65	3.71	4.94	6.00
51	1.57	2.61	3.66	4.88	5.93
52	1.55	2.58	3.61	4.82	5.85
53	1.53	2.55	3.57	4.76	5.78
54	1.51	2.52	3.53	4.70	5.71
55	1.49	2.49	3.49	4.65	5.64

...cont'd

Delta Heart Rate	(kpm·min⁻¹) 300 (watts) 50	600 100	900 150	1200 200	1500 250
56	1.48	2.46	3.45	4.59	5.58
57	1.46	2.43	3.41	4.54	5.51
58	1.44	2.40	3.37	4.49	5.45
59	1.43	2.38	3.33	4.44	5.39
60	1.41	2.35	3.29	4.39	5.33
61	1.39	2.32	3.25	4.34	5.27
62	1.38	2.30	3.22	4.29	5.21
63	1.36	2.27	3.18	4.25	5.16
64	1.35	2.25	3.15	4.20	5.10
65	1.34	2.23	3.12	4.16	5.05
66	1.32	2.20	3.08	4.11	4.99
67	1.31	2.18	3.05	4.07	4.94
68	1.29	2.16	3.02	4.03	4.89
69	1.28	2.14	2.99	3.99	4.84
70	1.27	2.11	2.96	3.95	4.79
71	1.26	2.09	2.93	3.91	4.74
72	1.24	2.07	2.90	3.87	4.70
73	1.23	2.05	2.87	3.83	4.65
74	1.22	2.03	2.84	3.79	4.61
75	1.21	2.01	2.82	3.76	4.56
76	1.20	1.99	2.79	3.72	4.52
77	1.18	1.97	2.76	3.69	4.48
78	1.17	1.96	2.74	3.65	4.43
79	1.16	1.94	2.71	3.62	4.39
80	1.15	1.92	2.69	3.58	4.35
81	1.14	1.90	2.66	3.55	4.31
82	1.13	1.89	2.64	3.52	4.27
83	1.12	1.87	2.62	3.49	4.24
84	1.11	1.85	2.59	3.46	4.20
85	1.10	1.84	2.57	3.43	4.16
86		1.82	2.55	3.40	4.13
87		1.80	2.53	3.37	4.09
88		1.79	2.51	3.34	4.06
89		1.77	2.48	3.31	4.02
90		1.76	2.46	3.28	3.99
91		1.74	2.44	3.26	3.95
92		1.73	2.42	3.23	3.92
93		1.72	2.40	3.20	3.89
94		1.70	2.38	3.18	3.86
95		1.69	2.36	3.15	3.83
96		1.68	2.35	3.13	3.80
97		1.66	2.33	3.10	3.77
98		1.65	2.31	3.08	3.74
99		1.64	2.29	3.05	3.71
100		1.62	2.27	3.03	3.68

Table XVIII: Banister-Legge Predictive Table for Untrained Males (20-29 years)

UNTRAINED MAXIMAL OXYGEN UPTAKE (litres · min^{-1})					
Delta Heart Rate ($b \cdot min^{-1}$)	Work Rate ($kpm \cdot min^{-1}$) 300	600	900	1200	1500
	(watts) 50	100	150	200	250
20	1.96	3.26	4.57		
21	1.93	3.21	4.50		
22	1.90	3.17	4.43		
23	1.87	3.12	4.37		
24	1.85	3.08	4.31		
25	1.82	3.03	4.24		
26	1.79	2.99	4.18		
27	1.77	2.95	4.13	5.50	
28	1.74	2.91	4.07	5.43	
29	1.72	2.87	4.02	5.35	
30	1.70	2.83	3.96	5.28	
31	1.68	2.79	3.91	5.21	
32	1.65	2.76	3.86	5.15	
33	1.63	2.72	3.81	5.08	
34	1.61	2.69	3.76	5.02	
35	1.59	2.65	3.72	4.95	
36	1.57	2.62	3.67	4.89	
37	1.55	2.59	3.63	4.83	
38	1.54	2.56	3.58	4.78	
39	1.52	2.53	3.54	4.72	
40	1.50	2.50	3.50	4.66	
41	1.48	2.47	3.46	4.61	
42	1.46	2.44	3.42	4.56	5.53
43	1.45	2.41	3.38	4.51	5.47
44	1.43	2.39	3.34	4.46	5.41
45	1.42	2.36	3.30	4.41	5.35
46	1.40	2.33	3.27	4.36	5.29
47	1.39	2.31	3.23	4.31	5.23
48	1.37	2.28	3.20	4.26	5.18
49	1.36	2.26	3.16	4.22	5.12
50	1.34	2.24	3.13	4.18	5.07
51	1.33	2.21	3.10	4.13	5.02
52	1.31	2.19	3.07	4.09	4.97
53	1.30	2.17	3.04	4.05	4.92
54	1.29	2.15	3.01	4.01	4.87
55	1.28	2.13	2.98	3.97	4.82

....cont'd

Delta Heart Rate	(kpm·min⁻¹) 300 (watts) 50	600 100	900 150	1200 200	1500 250
56	1.26	2.10	2.95	3.93	4.77
57	1.25	2.08	2.92	3.89	4.72
58	1.24	2.06	2.89	3.85	4.68
59	1.23	2.04	2.86	3.82	4.63
60	1.21	2.02	2.83	3.78	4.59
61	1.20	2.01	2.81	3.74	4.55
62	1.19	1.99	2.78	3.71	4.50
63	1.18	1.97	2.76	3.67	4.46
64	1.17	1.95	2.73	3.64	4.42
65	1.16	1.93	2.71	3.61	4.38
66	1.15	1.92	2.68	3.58	4.34
67	1.14	1.90	2.66	3.54	4.30
68	1.13	1.88	2.63	3.51	4.27
69	1.12	1.87	2.61	3.48	4.23
70	1.11	1.85	2.59	3.45	4.19
71	1.10	1.83	2.57	3.42	4.16
72	1.09	1.82	2.54	3.39	4.12
73	1.08	1.80	2.52	3.36	4.09
74	1.07	1.79	2.50	3.34	4.05
75	1.06	1.77	2.48	3.31	4.02
76	1.05	1.76	2.46	3.28	3.98
77	1.05	1.74	2.44	3.25	3.95
78	1.04	1.73	2.42	3.23	3.92
79	1.03	1.72	2.40	3.20	3.89
80	1.02	1.70	2.38	3.18	3.86
81	1.01	1.69	2.36	3.15	3.83
82	1.00	1.67	2.34	3.13	3.80
83	1.00	1.66	2.33	3.10	3.77
84	0.99	1.65	2.31	3.08	3.74
85	0.98	1.64	2.29	3.05	3.71
86	0.97	1.62	2.27	3.03	3.68
87	0.97	1.61	2.26	3.01	3.65
88	0.96	1.60	2.24	2.99	3.63
89	0.95	1.59	2.22	2.96	3.60
90	0.95	1.58	2.21	2.94	3.57
91	0.94	1.56	2.19	2.92	3.55
92	0.93	1.55	2.17	2.90	3.52
93	0.93	1.54	2.16	2.88	3.49
94	0.92	1.53	2.14	2.86	3.47
95	0.91	1.52	2.13	2.84	3.44
96	0.91	1.51	2.11	2.82	3.42
97	0.90	1.50	2.10	2.80	3.40
98	0.89	1.49	2.08	2.78	3.37
99	0.89	1.48	2.07	2.76	3.35
100	0.88	1.47	2.05	2.74	3.33

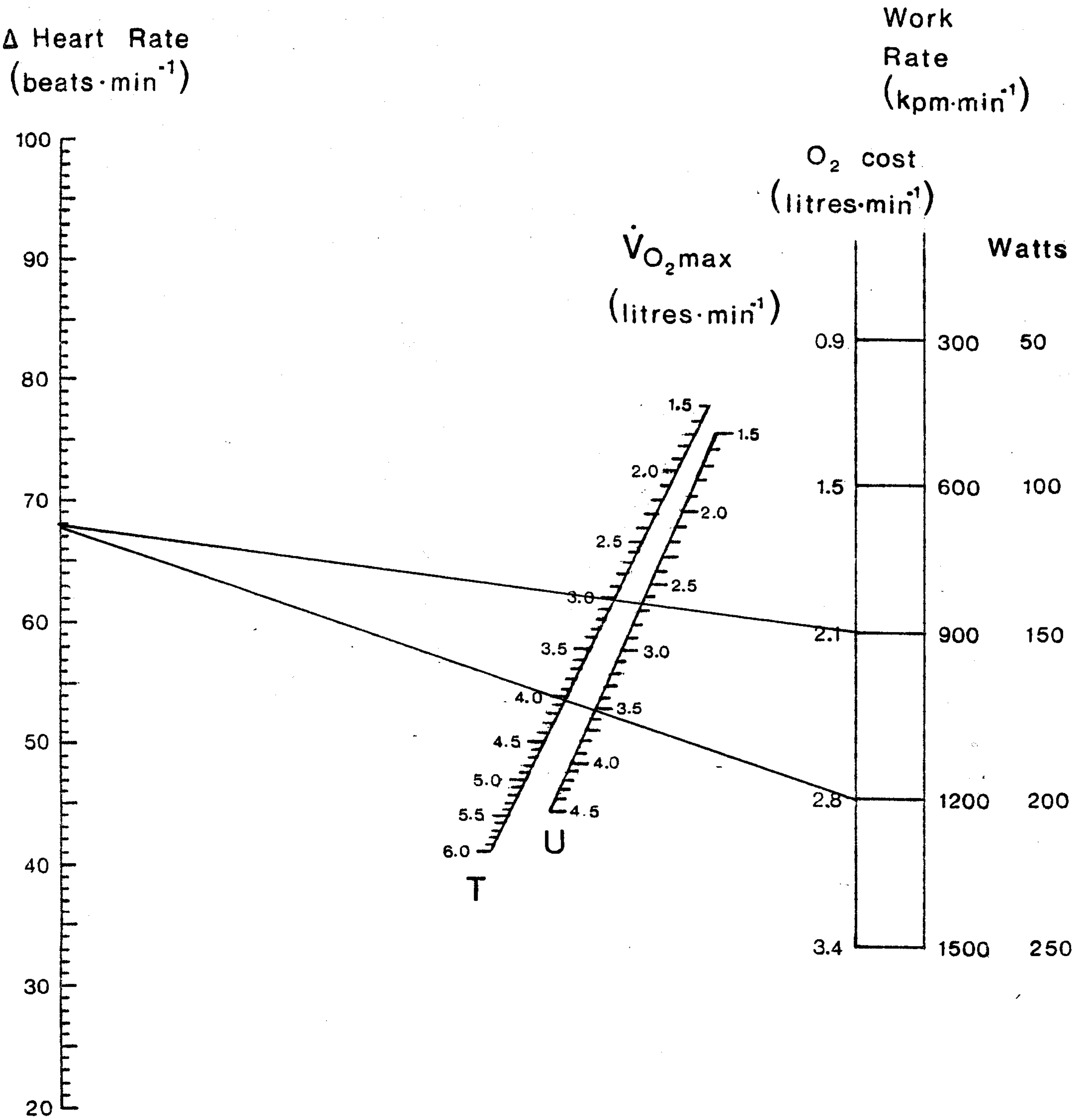

Figure 30: Sample calculations for predicting $\dot{V}O_2max$ using the Banister-Legge nomogram.

The regression equations determined to describe the % $\dot{V}O_2max$/delta heart rate relationship for trained and untrained group data are presented in Figures 31 and 32, respectively. Prediction intervals for 95% confidence were computed according to the method outlined in Kleinbaum and Kupper (1978) to provide an estimate of the variability associated with a maximum oxygen uptake prediction over the entire range of delta heart rate values. It is important to note that the minimum width predictive interval is always obtained when the delta heart rate used to predict maximum oxygen uptake is equal to the mean delta heart rate and thus the estimate of maximum oxygen uptake is better. Furthermore, the farther this value is away from the mean, the wider the predictive interval. This may explain the reason why more accurate predictions are obtained when delta heart rate values between 50 and 70 $b \cdot min^{-1}$ are used.

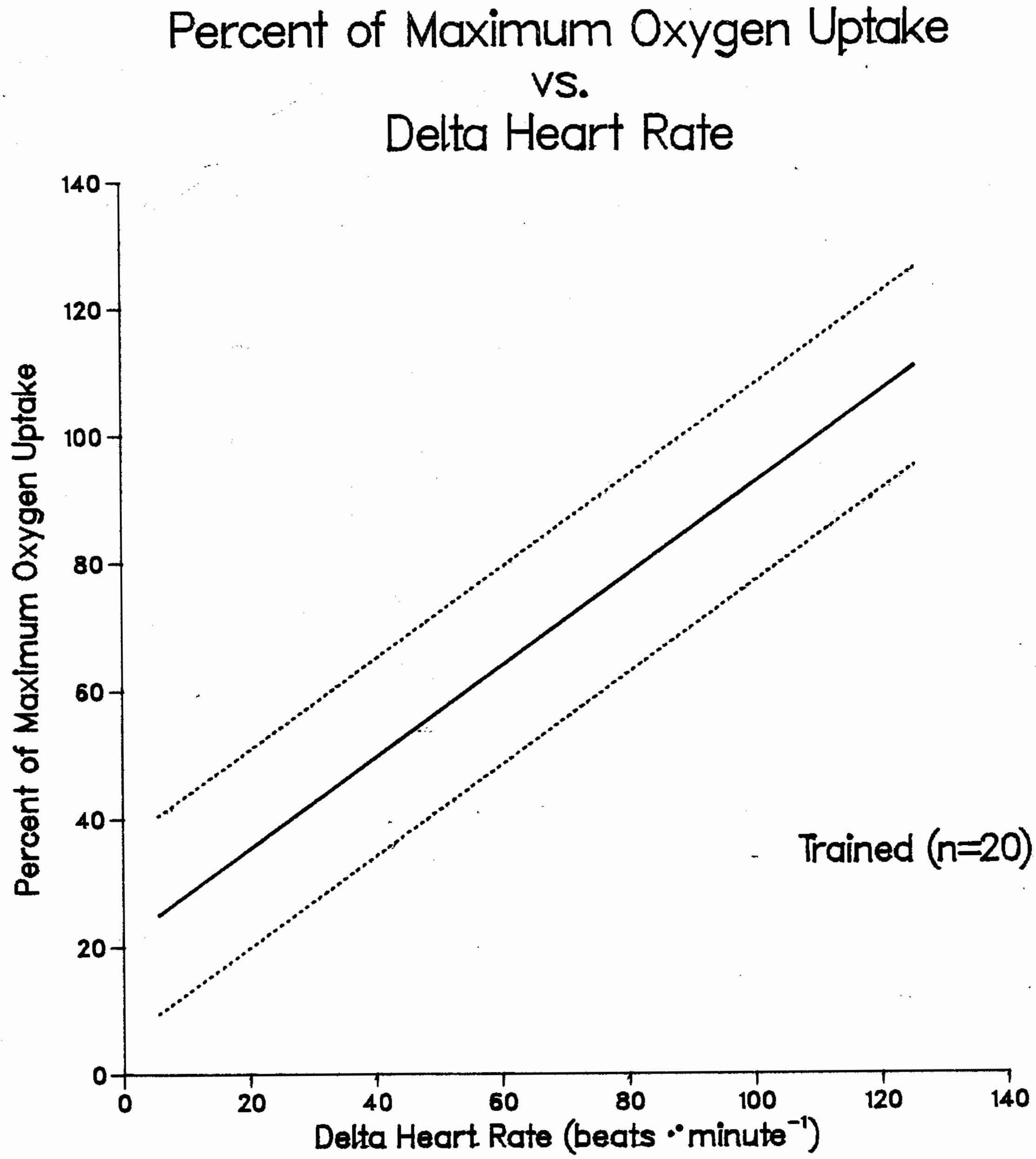

Figure 31: Showing the regression equation describing the relationship between % $\dot{V}O_2max$ and delta heart rate for trained males (n=20). Dotted lines represent predictive intervals.

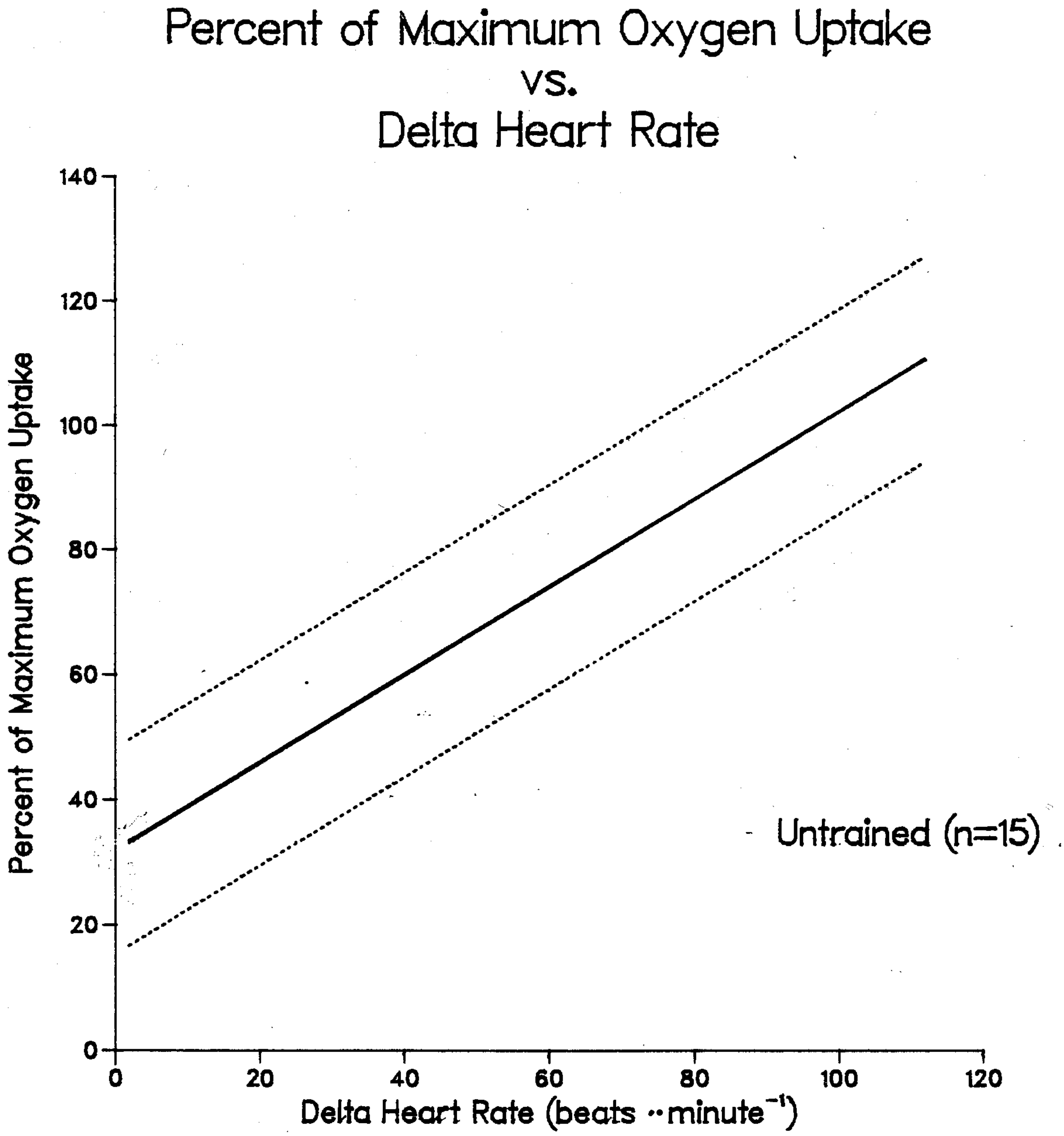

Figure 32: Showing the regression equation describing the relationship between % $\dot{V}O_2max$ and delta heart rate for untrained males (n=15). Dotted lines represent predictive intervals.

4.7.1 Submaximal Protocol Used to Predict $\dot{V}O_2max$ using the B-L Test

Prediction of $\dot{V}O_2max$ using the Banister-Legge nomogram requires only the delta heart response to the final completed submaximum work rate of the appropriate submaximum work rate protocol. Oxygen uptake is not measured in the submaximum predictive test. In order to select the appropriate nomogram for the most accurate prediction of maximum oxygen uptake, one must be able to distinguish between trained and untrained individuals on the basis of delta heart rate responses to submaximum work. The relationship between delta heart rate and delta work rate, therefore, was analyzed for trained and untrained groups, respectively, and a significant difference at the 0.05 level found to exist between the slopes of the corresponding regression equations.

Discrimination of the state of training of an individual as trained or untrained is based on the set of delta heart rate responses elicited from the well-defined submaximum exercise test. A graph of submaximal delta heart rates and related submaximum work rates is presented in Figure 33 to aid in the selection of the appropriate maximum oxygen uptake predictive table. A plot of delta heart rate vs. delta work rate would be made from the individual being tested and the similarity to either the trained or untrained response noted. Individual responses falling midway between the two regression lines for trained and untrained mean delta heart rate and delta work rate data, would rely on the experience of the investigator for a decision on the selection of an appropriate predictive table on which to position the subject for analysis.

4.8 Oxygen Uptake and Heart Rate Kinetics

4.8.1 Qualitative Oxygen Uptake Kinetics

The relationships between oxygen uptake versus time for the maximum work rate protocols were examined in a qualitative manner for representative trained and untrained subjects. Oxygen uptake data for two trained subjects were analyzed. One trained subject (A) was able to complete only one minute at 2400 kpm·min^{-1} while the other (B) was able to complete 5 minutes at this high rate of work. No attempt was made to determine time constants of the exercise response or other quantitative measurements from these particular relationships. The feature of interest in this examination was the general progression of oxygen uptake with increases in work rate over time. During the maximum ramp protocol, the progression of oxygen uptake from submaximum to maximum levels was focussed upon. It was of interest to note whether at near maximum levels of work the oxygen uptake reached an asymptote or continued to increase in a linear fashion to maximum levels.

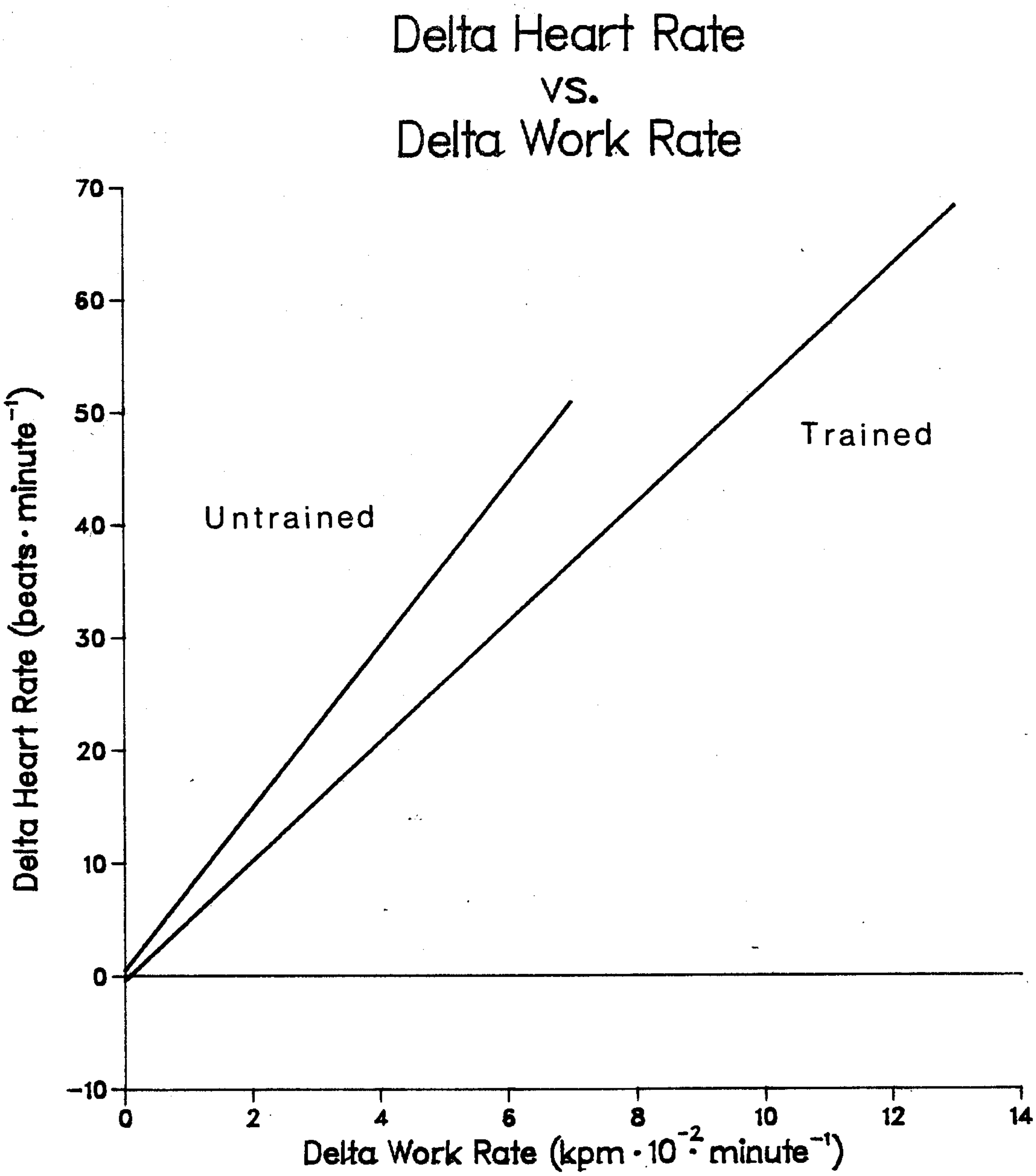

Figure 33: Showing Delta Heart Rate and Delta Work Rate Relationships for Trained and Untrained groups in a particular age range (20-29). This preliminary plot aids in delegating individuals to their appropriate classification table for $\dot{V}O_2max$ prediction.

Figures 34, A and B, and 35 show representative oxygen uptake versus work rate curves for two trained and one untrained individual, respectively. Trained subjects demonstrate a plateauing effect for oxygen uptake at near maximum levels of work, while the untrained subject exhibited a nearly linear progression up to maximum effort.

4.8.2 Qualitative Delta Heart Rate Kinetics

Delta heart rate values for the same two trained and one untrained individual described previously were plotted against time completed during the maximum ramp protocols. Plots of delta heart rate versus work rate for both the trained and untrained individuals exhibited a plateau at near maximum rates of work as shown in Figure 36 A and B and Figure 37.

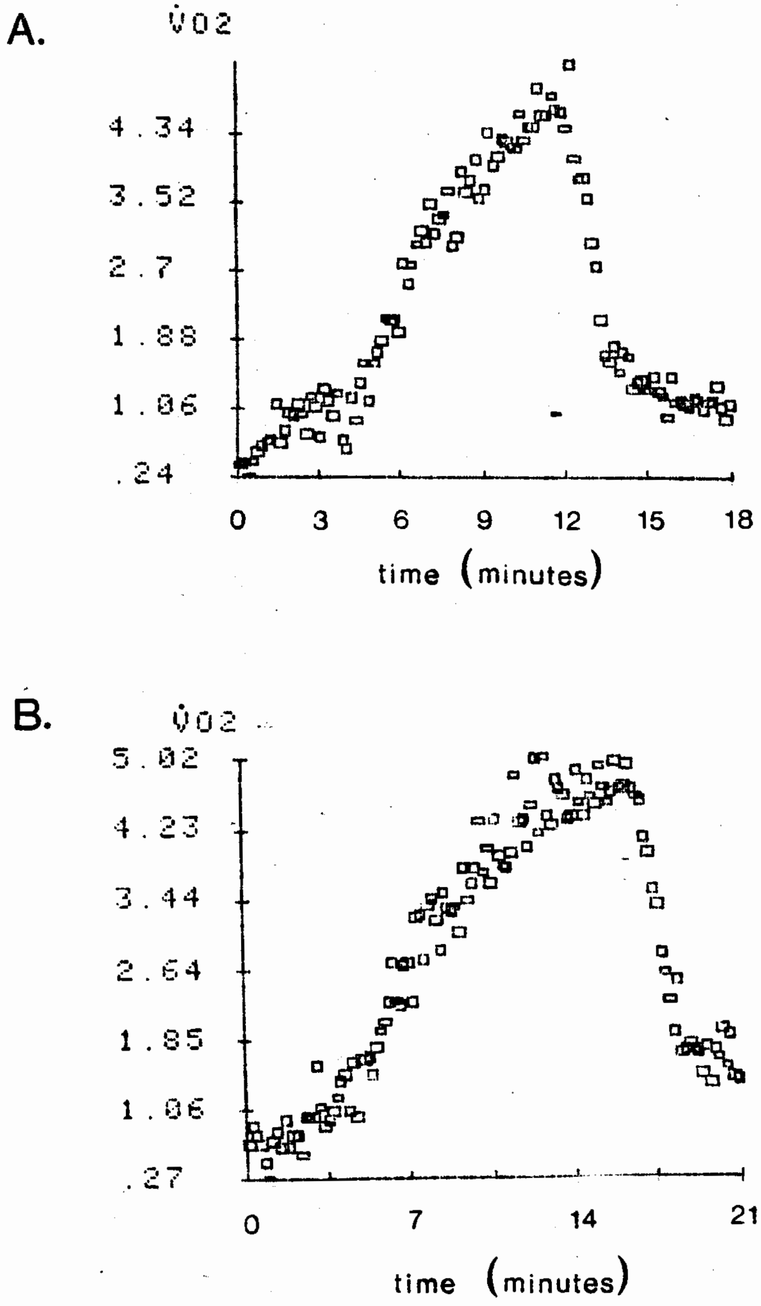

Figure 34: Showing the relationship between oxygen uptake and time during a maximum ramp protocol IIB for two trained subjects.

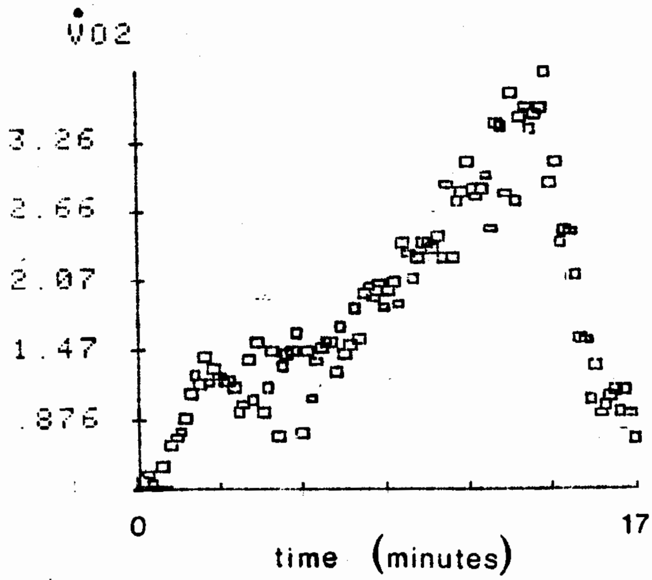

Figure 35: Showing the relationship between oxygen uptake and time during a maximum ramp protocol IIA for an untrained subject.

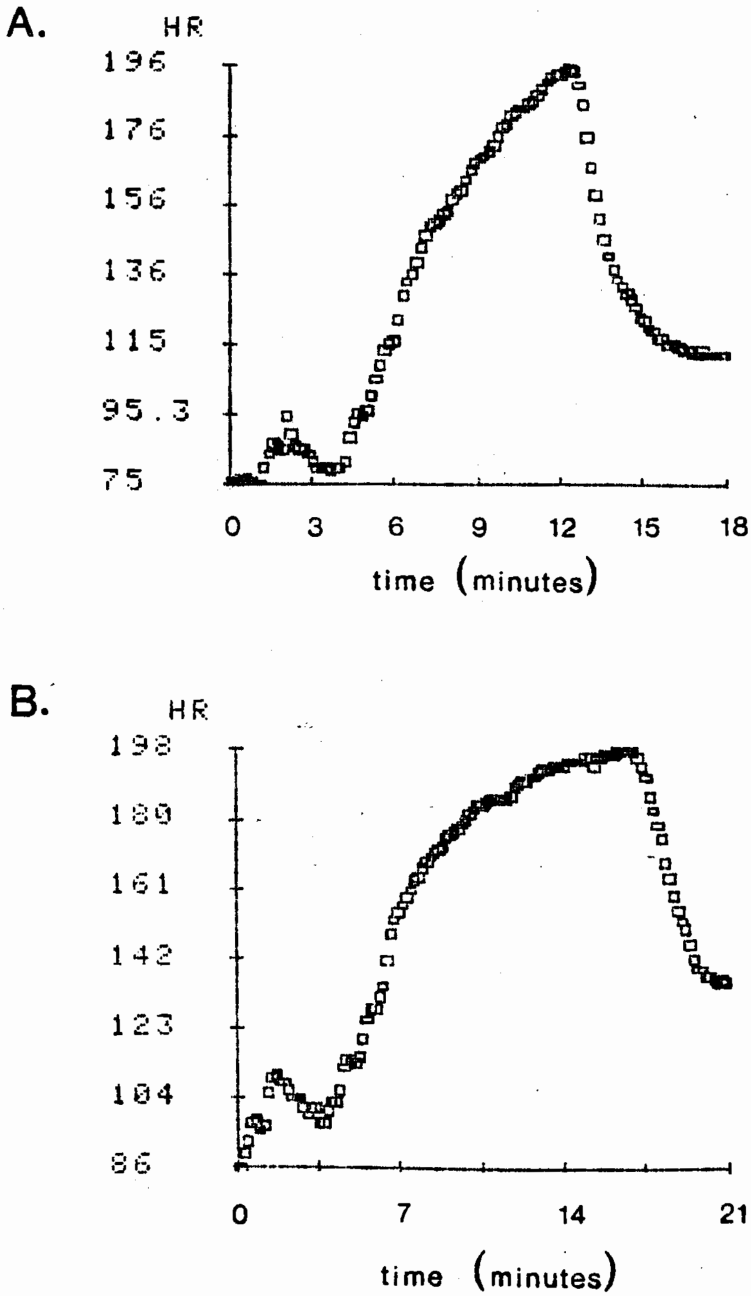

Figure 36: Showing the relationship between heart rate and time during a maximum ramp protocol IIB for two trained subjects.

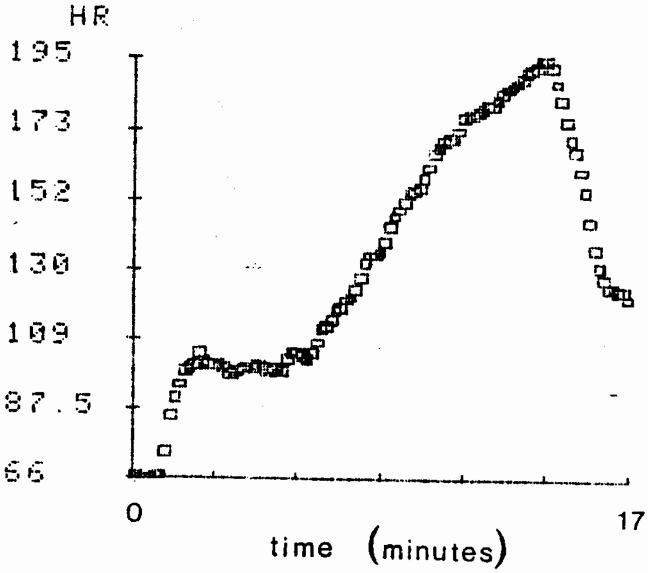

Figure 37: Showing the relationship between heart rate and time during a maximum ramp protocol IIA for an untrained subject.

4.8.3 Quantitative Oxygen Uptake Kinetics

The time constants, τ, of the relationships between oxygen uptake and time and heart rate and time during the completion of three minutes at a submaximum work rate of 600 $kpm \cdot min^{-1}$ for both trained and untrained core groups are shown in Table XIX. Also shown in Table XIX are the time constants of the relationships between oxygen uptake and time and heart rate and time during the completion of three minutes at a submaximum work rate demanding approximately 45% of maximum oxygen uptake. This corresponded to a submaximum work rate of 600 $kpm \cdot min^{-1}$ for untrained and 900 $kpm \cdot min^{-1}$ for trained groups, respectively. No significant differences were determined for any of the time constants for the oxygen uptake and time or heart rate and time relationships between trained and untrained groups.

Table XIX: Showing the time constants of the relationships between oxygen uptake and time ($\dot{V}O_2/t$) and between heart rate and time (HR/t) for untrained core subjects at 600 kpm min (UNT600) and trained core subjects at 600 kpm min (T600) and at 900 kpm min (T900). Time constants are in seconds (sec).

	UNT600	T600	T900
$\dot{V}O_2/t$	70 sec	66	57
HR/t	68	62	50

5. Discussion

5.1 Introduction

This study has examined the relationship between oxygen uptake and delta heart rate measured during submaximum and maximum bicycle ergometry for two groups of males, 20 to 29 years of age, varying in fitness level. It had originally been hypothesized that a non-linear, exponential relationship would describe the data best, however, a linear relationship proved to represent the data most effectively.

Examination of the oxygen uptake/delta heart rate relationship was deemed essential to an understanding of the inaccuracy of extrapolation procedures used to predict maximum oxygen uptake from heart rate responses to submaximal work. The inaccuracy was essentially an underestimation in maximum oxygen uptake when predicting $\dot{V}O_2max$ from a simple oxygen uptake/heart rate relationship. The specific predictive test examined which used the latter relation was the Astrand-Ryhming predictive test (1954) constructed on the premise that there was a linear relationship between heart rate and oxygen uptake.

The primary aim of the present investigation, therefore, was to assess the relationship between oxygen uptake and delta heart rate to determine its linearity or non-linearity. The effect of the state of training of an individual on this relationship was also assessed in order to gain insight into the basis for the consistent underestimation of maximum oxygen uptake determined by the Astrand-Ryhming predictive test. A subsidiary aim was to provide a simple method for predicting maximum oxygen uptake from heart rate responses to submaximum work rates which would improve upon the accuracy of prediction of the Astrand-Ryhming submaximum test.

A significant departure of the present study from previous investigations was the use of delta heart rate measures rather than absolute heart rates. Delta heart rate was defined as the difference between all determined exercise heart rates and the heart rate measured during the fifth minute of unloaded pedalling. Unloaded pedalling was the minimum work rate possible on the bicycle ergometer and provided relatively stable baseline heart rate and oxygen uptake measures. The use of delta heart rate provided a possible solution to the problem of the extreme variability of heart rate responses measured at variable states of "so called" rest, which have been a major source of error in all extrapolation procedures heretofore (Margaria, 1961; Rowell et al., 1964; Hughson and Morrissey, 1982). A delta heart rate of zero provided a well-defined lower end point for the oxygen uptake/heart rate relationship. The standard deviation associated with the mean unloaded pedalling heart rate values for both trained and untrained groups did not differ significantly from the variability related to the mean resting heart rates. This finding, however, was most likely the result of repeated exposure of the subjects to the testing procedures and laboratory environment. Use of unloaded pedalling and delta heart rate values are still expected to reduce the variability associated with the resting heart rates of new, inexperienced individuals during a single submaximum exercise test.

Expression of heart rate values as delta heart rates helped to identify the training status of an individual. This was due to the bradycardia associated with training where a trained individual worked at a reduced heart rate for a given submaximum work rate compared to an untrained individual.

Another significant departure of the present investigation from others was the examination of the oxygen uptake/delta heart rate relationship in contrast to the more usually defined heart rate/oxygen uptake relationship (i.e. ordinate and abscissa interchanged) which was originally examined by Astrand and Ryhming (1954). Predicted maximum oxygen uptake was assumed dependent upon delta heart rate, measured directly, and thus conventional assignment of the dependent variable to the ordinate was retained.

Justification of the basis for assignment of subjects into either trained or untrained core groups was provided by the significant difference in maximum oxygen uptake and maximum delta heart rate between these groups. Delta heart rate also differed significantly at each submaximum work rate between trained and untrained groups. No significant difference was determined between core and specific validity groups for either the trained or untrained group data. Nomogram construction was finally completed on two sets of pooled trained and untrained group data.

Prior attempts to assess the relationship between heart rate and oxygen uptake by Astrand (1952), Wyndham et al. (1959), Rowell et al. (1964) and Davies et al. (1968) required subjects to perform single submaximal work rates with rest periods separating each test protocol. In these tests, submaximal work rates were performed for 5 to 10 minutes in order to attain true steady state oxygen uptake and heart rate values. Maximum levels of work were performed for 1 to 2 minutes only.

The present study employed two separate work protocols, a submaximum and a maximum protocol, both of which required the completion of three or more continuously increasing work rates. The decision to perform several submaximum work rates rather than a single submaximum work rate was based on a systems analysis approach whereby characteristics of the system under study, the cardiorespiratory system, were more effectively identified. Input or stimuli to the system was work rate, and the output was either the heart rate or the corresponding oxygen uptake. While biological systems are basically continuous in nature, most experimental data measured to describe them are sampled and the continuous nature of the processes reconstructed from these sampled data (Wolf, 1979). Performance of a single submaximal work rate may be viewed as providing little aid in understanding the functional characteristics of the cardiorespiratory system. Astrand himself (1954) stated that the pulse rate at a single submaximum test revealed nothing about a subject's state of training due to the major role played by constitutional factors. More information may be gained by studying the dynamic or transient properties of the cardiorespiratory system (Margaria et al., 1965; Whipp and Wasserman, 1972; Whipp et al., 1981).

A transient response is composed of a natural response, excited by an input of energy to the system by any kind of stimulus which dies out with time as the energy of the system is dissipated, and a forced response which depends on the form of the input to the system (Able, 1979). A natural response is difficult to measure but alternatively a foreed response may be measured by forcing the system with a function that elicits the characteristic responses of the system. In the present study, the submaximum test employed a three minute step function to allow attainment of steady state values of oxygen uptake and heart rate at submaximum rates. In this case steady state values of oxygen uptake at each work rate were necessary so that they might be related to the theoretical cost of the work rate and thus provide a basis for construction of a predictive nomogram by the process used by Astrand and Ryhming described previously. The attainment of these steady states was verified by a lack of statistically significant difference between measured values and theoretically calculated oxygen uptake measures from work rate.

The specific forcing function chosen in the test of maximum oxygen uptake was one used commonly in current testing methodology, i.e. a ramp function in which work rate is increased continuously by small increments. The ramp used a one-half minute slope of 100 kpm·30 sec^{-1} in an attempt to elicit a rapid rise to maximum oxygen uptake. Maximum oxygen uptake has been shown to be readily discerned from a ramp exercise test protocol and also to be invariant over a wide range of ramp slopes provided the criterion is met that a perceptibly linear $\dot{V}O_2$ response to the ramp slope is obtained (Whipp _et al_., 1981; Davis _et al_., 1982).

Submaximal and maximal portions of the protocol were separated by a recovery period to prevent any increase in heart rate due to an increased body temperature as a result of prolonged exercise performance (Rowell, 1974), but unrelated to the actual cost of performing the work. Thus the current protocol included all the essential features determined from the most recent literature on exercise testing protocol and from personal experience, to be most compatible with minimizing test duration while achieving steady state during the submaximal phase.

Transition from the highest submaximal work rate completed to a maximum level was not composed of a series of steady states. Attainment of intermediate steady states was not required in maximum testing since the feature of interest in this phase was the attainment of a maximum oxygen uptake and maximum delta heart rate. Oxygen uptake and heart rate both depended upon the forcing function, work rate. They varied together over the range of work rates up to maximum and deviations from steady state were reflected in both oxygen uptake and heart rate and their linear dependence maintained. Steady state values were not required in this region of the relationship since the predictive nomogram was based only on work rates demanding an oxygen uptake of approximately 70% to 80% of maximum oxygen uptake.

Forcing the system with a ramp function helped identify the dynamic behaviour of an individual's cardiorespiratory system which in turn identified the training status of the individual undertaking the test. Trained individuals produced a lower heart rate than untrained individuals and therefore a lower delta heart rate in response to a given submaximum work rate.

The theoretical exponential mathematical model originally hypothesized in this study to provide the best fit for the heart rate/oxygen uptake data, was first proposed by Wyndham et al. (1959). It was proposed in response to the consistent underestimation in predicted maximum oxygen uptake using the A-R predictive nomogram. Wyndham et al. (1959) showed that heart rate/ oxygen uptake plots appeared asymptotic and suggested that oxygen uptake predictions could be improved if the relationship was fitted to an exponential funtion of the form

$$y = a (1 - e^{-kx}) \qquad \text{(Equation 12)}$$

where y = heart rate,

x = oxygen uptake,

a = a constant, and

k = a rate constant.

A major criticism by Wyndham et al. (1959) concerned the implied criterion of the Astrand-Ryhming predictive test, that the maximum levels of heart rate and oxygen uptake were attained coincidentally in time at approximately the same rate of work. In such cases, if heart rate were plotted against oxygen uptake, the relationship should be best represented by a straight line which would hold up to maximum heart rate. In fact, the oxygen uptake/heart rate relationship was determined to be linear only up to a point, after which the curve deviated sharply from coincidence at higher rates of work. After this point, higher oxygen uptake values were obtained than would be predicted by linear extrapolation to maximum heart rate values. Figure 40 illustrates the underprediction of maximum oxygen uptake as a result of the slower approach of the oxygen uptake/ work rate to asympotic values compared to the heart rate/work rate relationship leading to the non-linearity of the heart rate/

oxygen uptake relationship at high levels of work. Linear extrapolation to a maximum age-predicted heart rate would result in a predicted $\dot{V}O_2max$ of 3.75 $l \cdot min^{-1}$ as indicated by point A in Figure 40. Point B reveals a higher predicted $\dot{V}O_2max$ of 4.5 $l \cdot min^{-1}$ as a result of an asymptotic heart rate/oxygen uptake relationship.

Rowell et al. (1964) also identified the asymptotic nature of the heart rate/oxygen uptake relationship as the major limitation to the direct prediction of maximum oxygen uptake from submaximum heart rate and work rate measures. Both Rowell et al. (1964) and Wyndham et al. (1959) found gross underestimations in predicted maximum oxygen uptake compared to directly obtained measures. Later, Davies et al. (1968) confirmed the underprediction.

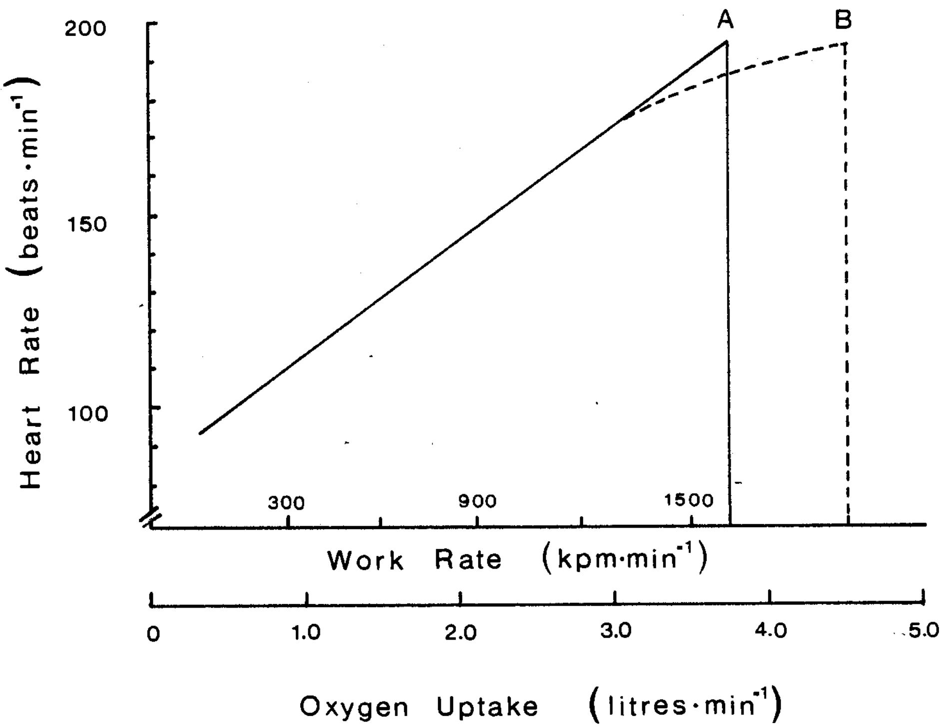

Figure 40: Showing the underprediction in $\dot{V}O_2max$ due to Asymptotic nature of Relationship between Heart Rate and Oxygen Uptake.

In this study, in an attempt to provide an increased understanding of the cardiorespiratory system, an exponential equation of the form

$$y = a \cdot e^{kx} \quad \text{(Equation 1)}$$

where y = oxygen uptake and

x = delta heart rate,

based on theoretical considerations, was chosen to fit the oxygen uptake/delta heart rate relationship. This equation is in contrast to that proposed by Wyndham *et al*. (1959) due to the reversal of the x and y axes. This equation, however, also describes a similar exponential relationship but with a positive exponent.

A clear distinction must be made between theoretical and empirical model equations at this point. Theoretical equations are those which have been derived from analytical considerations of the phenomenon or system studied. The items in the equation should have analogy to known system elements or processes. Empirical equations, on the other hand, are those which have neither a direct nor an implied theoretical origin. From a mathematical standpoint, theoretical equations and empirical equations are equally useful in describing the function of a system component (Spain, 1982).

It is generally true, however, that a modeler would prefer to employ equations having a theoretical origin, because they contribute more to the understanding of the system under study. Fitting empirical equations to experimental data is generally easier to accomplish than fitting such data to theoretical equations because there are none or few system constructs to consider. However, from a theoretical standpoint, polynomials and other empirical equations have little significance, and for this reason are used sparingly by knowledgable investigators. If a jump is made immediately to an empirical solution without at least cursory attempts to employ theoretical reasoning to justify the form of the equation, one may be missing an opportunity to understand system elements better. An analytical equation often provides greater insight into the process of interacting relationships within a system, therefore an analytical approach to the study of oxygen uptake/heart rate relationships in submaximum and maximum work was taken in this investigation.

The original hypothesis of this study was that the relationship between oxygen uptake and delta heart rate would be best expressed by a non-linear exponential relationship, even with heart rate expressed as delta heart rate. However, while apparent in individual cases, interindividual variation obscured this hypothesized non-linearity when group data were examined. Thus, ultimately, a linear relationship was found to exist between oxygen uptake and delta heart rate and the regression equations describing the data best are shown below, where oxygen uptake plots as the ordinate and delta heart rate as the abscissa,

Trained $y = (0.03577)\ x + 1.0100$ (Equation 13)

Untrained $y = (0.02292)\ x + 1.0930$ (Equation 14)

5.2 Reconstruction of the A-R Nomogram

It is likely that Astrand's (1952) original group of physical education students contained individuals with the same variety of fitness abilities as the combined group of trained and untrained subjects of the present study. To a degree this variability in fitness level would account for some of the inaccuracy of the original nomogram even within a homogeneous group of similar age and sex. Because of this similarity, the oxygen uptake data measured at each submaximum work rate on individuals of the whole mixed group of trained and untrained individuals were expressed as percentages of their individual $\dot{V}O_2max$ (% $\dot{V}O_2max$). The relationship between % $\dot{V}O_2max$ and heart rate was then manipulated in the manner described by Astrand and Ryhming to produce almost an exact copy of their published results.

The degree of coincidence between Astrand's original nomogram and that presently derived may be judged by the results of regression analysis which showed a non-significant difference between the correlation coefficients and standard error of estimates (assessed by Student's t-test) of the respective nomogram regression lines (% $\dot{V}O_2max$ vs. heart rate).

However, when trained and untrained % $\dot{V}O_2max$ and delta heart rate data were used in the same manner for subjects of the present study, two distinct regression equations of % $\dot{V}O_2$ max/delta heart rate emerged, one each for the trained and untrained groups. A statistically significant difference was found between the intercepts of these equations and was related to a significant difference in maximum oxygen uptake and maximum delta heart rate for the groups. A second nomogram was constructed in a manner similar to the A-R nomogram and maximum oxygen uptake predicted for the validity group. Predicted $\dot{V}O_2max$ was determined to be highly correlated with observed $\dot{V}O_2max$ values and the subgroups of trained and untrained individuals within the whole core group could be separately defined and assigned distinctly different nomogram $\dot{V}O_2max$ prediction lines, as illustrated in Figure 28. A correlation coefficient of 0.9791 was determined for the relationship between observed and predicted $\dot{V}O_2max$ for the whole validity group, including trained and untrained subjects.

Predictions of $\dot{V}O_2max$ made on subjects of the present study following the procedures of the original A-R submaximum test compared to $\dot{V}O_2max$ measured directly, yielded a correlation coefficient of only 0.8043. This value was in general agreement with the range of values, 0.60 to 0.83, determined in other studies outlined previously (Astrand and Ryhming, 1954; Astrand, 1960; Rowell et al., 1964; deVries and Klafs, 1965; Glassford et al., 1965; Teraslinna et al, 1966; Davies, 1968; Coleman, 1976; Jessup et al., 1977; Louhavaara et al., 1980; Myles and Toft, 1980; Cink and Thomas, 1981; Patton et al., 1982; Siconolfi et al., 1982).

Using Fisher's Z statistic, a significant difference was found between the two correlation coefficients ($p<0.05$), (i.e. Astrand's $r=0.8043$ and current test $r=0.9791$) revealing a significant improvement in predictive ability using the new nomogram with separately defined predictive lines for trained and untrained individuals within a group. The standard error of estimate was also determined to be lower using the new predictive method than that determined using the A-R nomogram.

5.3 Basic Features of a New Predictive Nomogram

5.3.1 Age predicted Maximum

A major limitation in the predictive ability of any nomogram using any form of extrapolation from submaximal work at a fixed heart rate to maximum values of these parameters with regard to age during cycling, walking, and running or stepping, is the assumption of a fixed common maximal heart rate within any age group. In this study, only one age group was assessed. The maximum heart rate did not differ significantly between trained and untrained individuals. The results of this study suggest that if maximum performance is always ensured, maximum heart rate will not be found to vary significantly within an age group and may continue to be used in an extrapolation procedure. A reduced or even elevated attainable maximum heart rate in trained individuals, although an intrinsically appealing attribute of fitness, was not evident in this study.

The expression of heart rate values as delta heart rates provided the key to the improvement in predictive ability of the newly devised Banister-Legge nomogram. The extrapolation or curve fitting procedure was dependent solely on two sets of points. They were the heart rate measured during the fifth minute of unloaded pedalling and the maximum heart rate. Taken together, these values provided the minimum and maximum delta heart rates and therefore defined the span of delta heart rate values. Expression of cardiac frequency measures as delta heart rates provided for a coincident starting point for all individuals, regardless of fitness level, since performance of unloaded pedalling was defined as requiring a delta heart rate equal to zero. A difference with regard to fitness level was shown to be reflected readily in the delta heart rate for a given submaximum work rate. Maximum delta heart rate, which varied significantly between trained and untrained groups, defined the upper end of the delta heart rate scale.

5.3.2 Training and Age

Both age and training state have a major influence on the oxygen uptake/delta heart rate relationship. Trained individuals have been shown to have a more rapid oxygen uptake adaptation at the onset of exercise for the same absolute work rate and, therefore, oxygen uptake requirement, than untrained individuals (Whipp and Wasserman, 1972; Hagberg et al., 1978). The rate at which oxygen uptake increases to a steady state in response to the challenge of work below the onset of blood lactate accumulation is descriptive of the capacity of the circulation for delivery of oxygen and of the cells of active tissues to utilize oxygen (deVries et al., 1982). This fact may have contributed somewhat to the significantly different oxygen uptake/delta heart rate slope between trained and untrained group mean data.

The bradycardia associated with training will always confer a significantly higher delta heart rate maximum upon trained compared to untrained individuals. This has been verified for males within the age range 20 to 29 years in this study. The major factor differentiating ramps of trained and untrained individuals, therefore, was due to a significantly lower delta heart rate for trained individuals with respect to untrained for a given submaximum work rate since untrained individuals worked at a higher percentage of both their maximum oxygen uptake and maximum heart rate levels when each performed equivalent work rates. This was reflected in a reduced slope of the oxygen uptake/ delta heart rate curve for the untrained group since each work rate required the same absolute oxygen uptake but different delta heart rate values.

The mean maximum heart rates for trained and untrained groups assessed in the present study were not significantly different. This finding is in agreement with that of Ekblom and Hermansen (1968). Trained athletes are characterized by a large stroke volume (Ekblom and Hermansen, 1968; Astrand and Rodahl, 1977). This enables an athlete to complete a work rate with a lower heart rate since the cardiac output is not different when trained and untrained individuals are compared at equal levels of work (Rost and Hollman, 1983). Oxygen uptake or oxygen utilization for the same work rate is also the same for trained and untrained individuals, as determined in the present study. The increase in stroke volume is a dimensional adaptation and is reached after more than a year of training (Ekblom and Hermansen, 1968).

DeVries et al. (1982) determined the effect of age upon the kinetics of oxygen uptake in old and young men of equal fitness and found no significant difference between the two groups with respect to the rate of response to submaximum work rates. The investigators, therefore, cautioned the interpretation of agewise decrements observed in those physiological variables which may also be sensitive to physical fitness status.

Variations in maximum heart rate within an age group, by decade, because of a decrement in maximum attainable heart rate with age, were typically modified by Astrand with an age correction factor. The interrelationship between age and training status and their effect on the prediction of maximum oxygen uptake may be accounted for by the use of delta heart rate measures. In this way, an older, trained individual may have the same delta heart rate maximum as a younger unfit individual and use of this factor obviates the need for an arbitrary age correction factor.

The linear regression equations describing the relationship between percent maximum oxygen uptake and delta heart rate for trained and untrained group mean data had similar slopes. This was the case since, though both groups were working at different percentages of their maximum oxygen uptake for a given submaximum work rate, they were also working at different percentages of their maximum heart rate. The delta heart rate, however, was the same. The relationship between oxygen uptake and delta heart rate was therefore, maintained. Intercepts of the regression equations, however, were significantly different. This reflected the ability of trained individuals to work at a lower percentage of their maximum $\dot{V}O_2max$ for a given delta heart rate.

5.4 Performance of Test Protocol

When the original A-R nomogram was constructed in 1954, it had been demonstrated that identical $\dot{V}O_2max$ values were elicited during cycle ergometry and treadmill running. These two forms of exercise were consequently used interchangeably in the application of the A-R nomogram to predict $\dot{V}O_2max$. Many studies have been conducted since 1954 which refute this generalization and show that treadmill running elicits significantly higher $\dot{V}O_2max$ values on the order of 4 to 18% greater than those on the bicycle ergometer (Glassford et al., 1965; Chase, 1966; Hermansen and Saltin, 1969; Hermansen et al., 1970; McArdle and Magel, 1970; Kamon and Pandolf, 1972; Miyamura and Honda, 1972; McArdle et al., 1973; McKay and Banister, 1976; Bergh et al., 1976; Matsui, 1978; Hagberg et al., 1978; Miles et al., 1980; Keren et al., 1980; Pannier et al., 1980; Verstappen et al., 1982). Despite this finding, since the development of the nomogram in 1954, inumerable investigations have been undertaken to determine the validity of the nomogram by correlation of predicted $\dot{V}O_2max$ values from the A-R nomogram with directly measured values. An important element of all such predictions and validations, of course, lies in the exact replication of the test protocol each time a test is performed.

Despite this logical requirement, investigators of numerous studies of the validity of prediction have continued to utilize testing modes or methods inconsistent with the basic premise (deVries and Klafs, 1965; Teraslinna *et al*., 1966; Coleman, 1976; Jessup *et al*., 1977; Louhevaara *et al*., 1980; Myles and Toft, 1980; Patton *et al*., 1980; Siconolfi *et al*., 1982). Inappropriate comparisons have resulted and include using maximal treadmill running with submaximal cycle ergometer test (Jessup *et al*., 1975; Glassford *et al*., 1965). Maximal and submaximal treadmill tests would be a valid check of the nomgram (Rowell *et al*., 1964) but due to the different heart rate and oxygen uptake responses in treadmill running compared to bicycle ergometry, use of the treadmill reduced the accuracy of any treadmill predicted $\dot{V}O_2max$. Even those studies using a bicycle for submaximal and maximal tests used a specified time of six minutes and not the A-R quoted criterion of heart rate greater than 130 $b{\cdot}min^{-1}$ differing by no more than 5 $b{\cdot}min^{-1}$ during the fifth and sixth minute. However, when the A-R protocol was followed exactly (Glassford *et al*., 1965; Cink and Thomas, 1982) investigators still report quite low correlation coefficients ranging from 0.63 to 0.80. Pedal rate must not vary within the same test as outlined in the World Health Organization (WHO) test (Louharvaara *et al* ., 1980), but must remain constant due to the variation in oxygen uptake with variations in pedal rate at a constant power output (Banister and Jackson, 1967).

With all these constraints in mind, it is apparent that for the current predictive nomogram to be of any value, the protocol upon which the nomogram was constructed must be performed exactly as outlined for the predictions to approximate most closely with directly measured maximum oxygen uptake. It is entirely reasonable that the test be performed as it was designed and validated so that the resluts lie within the related nomogram's standard error of estimate.

The current protocol was specifically devised to include features which would help to elicit a response that would provide greater insight into the actual capacity of the individual being tested. Precise details of the protocol were outlined after a thorough review of the limiting features of the A-R predictive test which included the slow pedal rate (50 rpm) and the single work rate required. Specifically, new features of the test include a five minute warm-up period of unloaded pedalling followed immediately by progressively increasing work rates each performed for three minutes duration. For individuals within the age group assessed in this study (20 to 29 years), the endpoint of the submaximal test was reached when the delta heart rate had attained a value of between 50 to 70 $b \cdot min^{-1}$. It is essential that a pedal frequency of 90 rpm be maintained throughout the entire test, since oxygen uptake has been shown to change with various combinations of pedal rate and resistance despite a constant power output (Banister and Jackson, 1967). The current protocol also includes a three minute recovery period to be completed after the final three minute work rate. Thus this investigation has attempted to go a step further than previous investigations whose intent of producing a more accurate means of predicting $\dot{V}O_2max$ was similar. The new nomogram has resulted from a radical alteration in test protocol and nature of the analysis of the results.

Despite numerous studies which have been successful in improving the accuracy of prediction of maximum oxygen uptake (Myles and Toft, 1980; Patton et al., 1980; Louhevaara et al., 1982; Siconolfi et al., 1982), the A-R predictive test remains firmly entrenched in the armoury of exercise testing regardless of its relatively low predicitive power. Thus, it seems, in order for a new predictive test to replace the A-R test, it must be compellingly simple and yet provide an improved power of predicting maximum oxygen uptake.

The test protocol developed here has been shown to do just this and additionally shows an ability to distinguish between trained and untrained individuals within an age group. Tables of predicted $\dot{V}O_2max$ have been provided for ease of use and may be used successfully when all related protocol criteria have been completed. These data suggest that $\dot{V}O_2max$ predicted from the results of a relatively simple cycle ergometer test correlates well with directly determined $\dot{V}O_2max$ thus providing a suitable estimate of aerobic fitness.

5.5 Limitations of the Present Study

Predictions based upon extrapolation to an assumed maximum value are subject to considerable error. A method of predicting maximal oxygen uptake which measures a single submaximal work rate and corresponding heart rate only, will always provide only a rough approximation of true aerobic capacity. Completion of three or more submaxiaml work rates combined with the corresponding heart rate responses have improved the accuracy of prediction but any procedure assuming a maximum variable measure is still subject to error. If one wishes to obtain more precise information, it is necessary to measure the aerobic work capacity directly.

Subjects is this study were males, aged 20 to 29 years, and represented either highly trained cyclists or relatively untrained males. The results of the test, therefore, are limited and restricted to similar populations. The investigation has, however, been valuable in providing evidence that the use of delta heart rate and the chosen exercise testing protocol resulted in a more accurate estimation of $\dot{V}O_2max$ than had previously been determined using the traditional submaximal A-R predictive test. This study, then, has outlined a predictive method which may conceivably be extended to include predictive nomograms for both females and males of all ages and fitness levels. As yet, the validity of the protocol is unknown for such groups.

5.6 Constraints of Testing Apparatus

Due to the constraints of the electromagnetically braked bicycle used in this study, work rate could not be increased to levels above 2400 kpm•min^{-1}. This work rate did not provide a maximum stimulus for some individuals within the trained group. Work rate, which served as the forcing function, reached a maximum level at 2400 kpm•min^{-1} after which time the first order linear response between oxygen uptake and work rate became asymptotic. This was due to the discontinuence of the ramp slope forcing function which then became a step at 2400 kpm•min^{-1}. Since work rate had reached a maximum level, further increases in heart rate with time were the result of cardiovascular drift due to increased body core temperature.

If an adequate forcing function could have been maintained, it may be postulated that a continued linear response in oxygen uptake/ work rate at high work rates would have resulted as shown in the maximum portion of the untrained group oxygen uptake and work rate relationship. The derived relationship between oxygen uptake and heart rate may then have revealed a non-linear trend as exhibited by the untrained group data in the maximum portion of the relationship. One minute steps of 100 kpm•min^{-1}, in contrast to half-minute 100 kpm•min^{-1} steps, may serve as a suitable work rate forcing function (Whipp *et al.*, 1981).

5.7 Future Considerations

New groups of both males and females varying in age and fitness level must be tested in a similar fashion to that outlined in this study and the oxygen uptake/delta heart rate relationship examined. Related tables for the prediction of maximum oxygen uptake from delta heart rate responses to submaximum work must be constructed and validated on similar groups of individuals and the full set of age decade, sex and training state nomograms completed. The effectiveness of the use of delta heart rate measures, as related to a decrease in maximum heart rate with increasing age, combined with a high level of cardiovascular fitness, may also be assessed.

5.8 Conclusion

In conclusion, this study has investigated the basic oxygen uptake/ heart rate relationship during submaximal and maximal work performed on a bicycle ergometer according to a well-defined protocol at a pedal rate of 90 rpm in two groups of male subjects age 20 to 29 years varying in fitness level. It had originally been hypothesized that a non-linear, exponential relationship existed between these variables, however, while this was apparent in individual cases, interindividual variations obscured the non-linearity when group data were analyzed. The relationship between $\dot{V}O2$/delta heart rate for both trained and untrained group mean data was found to be expressed best statistically by linear equations. Slopes of the two linear equations were found to differ significantly. The exponential hypothesis was abandoned and the remaining analysis dealt strictly with the attained linear relationship.

A nomogram for predicting $\dot{V}O_2max$ values from submaximum heart rate and work rate was constructed following a procedure similar to that used to construct the Astrand-Ryhming nomogram (1954). The linear regression equations expressing the % $\dot{V}O_2$ max/delta HR data for untrained (n=15) and trained (n=20) group mean data were as follows:

Untrained $y = (0.70304)\ x + 31.906$ (Equation 15)

Trained $y = (0.71486)\ x + 20.919$ (Equation 16)

The new nomogram has been validated with similar but distinctly separate groups of subjects from the test groups from which the nomogram was constructed. The predictive power was assessed from the correlation coefficients and standard errors of estimate, derived from a plot of observed versus predicted $\dot{V}O_2max$. These showed a statistically significant improvement in predictive power over the A-R nomogram predictions.

The nomogram described is unique in that it provides for a distinction to be made regarding the state of training or fitness level of the individual. The nomogram, therefore, may replace the A-R nomogram when the prediction of $\dot{V}O_2max$ is sought for trained and untrained males 20 to 29 years of age.

Use of the nomogram demands that the work protocol be strictly adhered to, with the inclusion of a five minute warm-up period of unloaded pedalling, and performance of work on a bicycle ergometer at 90 rpm. Delta heart rates between 40 and 70 $b \cdot min^{-1}$, or heart rates between 140 and 160 $b \cdot min^{-1}$ for 20 to 29 year old males will result in the best estimate of $\dot{V}O_2max$.

This is the first nomogram of its kind to provide a simple method using delta heart rate values that allow a distinction to be made for variations in fitness level. The developed nomogram should prove very useful in predicting maximum aerobic power from submaximum tests.

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APPENDIX A

Efficiency of Work

1) Gross Efficiency $= \frac{\text{work accomplished}}{\text{energy expended}}$

$$= \frac{W}{E} \times 100$$

2) Net Efficiency $= \frac{\text{work accomplished}}{\text{energy expended above that at rest}}$

$$= \frac{W}{E-e} \times 100$$

3) Work Efficiency $= \frac{\text{work accomplished}}{\text{energy expended above that in cycling without a load}}$

$$= \frac{W}{El-Eu} \times 100$$

4) Delta Efficiency = $\frac{\text{delta work accomplished}}{\text{delta energy expended}}$

$$= \frac{\Delta W}{\Delta E} \times 100$$

where W = caloric equivalent of external work performed

E = gross caloric output including resting metabolism

e = resting caloric output

El = caloric output, loaded cycling

Eu = caloric output, unloaded cycling

ΔW = caloric equivalent of increment in work performed above previous rate

ΔE = increment in caloric output above that at previous rate

APPENDIX B

Borg Scale for Rating of Perceived Exertion, 1981

0	Nothing at all	
0.5	Extremely weak	(just noticeable)
1	Very weak	
2	Weak	(light)
3	Moderate	
4	Somewhat strong	
5	Strong	(heavy)
6		
7	Very Strong	
8		
9		
10	Extremely Strong	(almost max)
•	Maximal	

APPENDIX C

Oxygen Cost of Performing Steady State Work

Let X represent work rate in kgm·minute^{-1}

X kgm·minute^{-1}

Convert to gm cm·min^{-1}	$X \cdot 1000 \cdot 100$ gm cm·min^{-1}
Convert to dyne cm·min^{-1}	$X \cdot 1000 \cdot 100 \cdot 981$ dyne cm·min^{-1}
1 dyne cm = 1 erg	$X \cdot 1000 \cdot 100 \cdot 981$ ergs·min^{-1}
10^{7} ergs = 1 joule	$\frac{X \cdot 1000 \cdot 100 \cdot 981}{10^{7}}$ joules·min^{-1}
1 calorie = 4.18 joules	$\frac{X \cdot 1000 \cdot 100 \cdot 981}{10^{7} \cdot 4.18}$ calories·min^{-1}
1000 calories = 1 kilocal	$\frac{X \cdot 1000 \cdot 100 \cdot 981}{10^{7} \cdot 4.18 \cdot 1000}$ kcal·min^{-1}

Assuming 25% efficiency (total efficiency in transforming food energy into muscular work):

Metabolic Work $\frac{X \cdot 1000 \cdot 100 \cdot 981 \cdot 4}{10^{7} \cdot 4.18 \cdot 1000}$ kcal·min^{-1}

Using 4.82 kcal as calorific value of each litre of oxygen consumed at the R value of 0.80:

$$\frac{X \cdot 1000 \cdot 100 \cdot 981 \cdot 4}{10^{7} \cdot 4.18 \cdot 1000 \cdot 4.82} \text{ litre } O_2 \cdot \text{min}^{-1}$$

Therefore, Work $\dot{V}O2 = X \cdot 0.00195$ l $O2 \cdot min^{-1}$

$= X \cdot 0.00195 \cdot 1000$ ml $O2 \cdot min^{-1}$

Total $\dot{V}O2$ = Work $\dot{V}O2$ + rest $\dot{V}O2$

$= (X \cdot 0.00195 \cdot 1000) + 300$ ml $O2 \cdot min^{-1}$

$= (X \cdot 1.95) + 300$ ml $O2 \cdot min^{-1}$

At a work rate of 300 kgm $\cdot$ min^{-1}, oxygen cost is

$= (300 \cdot 1.95) + 300$

$= 0.885$ l $O2 \cdot min^{-1}$

$= 0.9$ l $O2 \cdot min^{-1}$

At a work rate of 600 kgm $\cdot$ min^{-1}, oxygen cost is 1.5 l $O_2 \cdot min^{-1}$

WORK RATE ($kgm \cdot min^{-1}$)	OXYGEN CONSUMPTION ($litre \cdot min^{-1}$)
300	0.9
600	1.5
900	2.1
1200	2.8
1500	3.5