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The objective of this research was to investigate the physiological effects of body posture on cycling. The familiar positions of bicycle riding have been the touring posture (hands stretched on top handlebar) and the racing posture (hands bent at the elbow, with the back horizontal). However, a relatively new stance has been gaining in popularity since the mid-1970s. This is the semi-recumbent posture, in which the rider is seated on an office-like chair, adopting body angles similar to that of an automobile driver, with the pedals located in front of the cyclist.

This study tested the above-mentioned positions, with the addition of a fully supine recumbent posture, at a moderate commuting workload (90 watts), pedaled at 60 revolutions per minute frequency. Among male volunteers, 8 healthy subjects performed a sequence of

4 posture trials on a mechanical ergometer, each lasting for 8 minutes with intermittent rest period averaging 27 minutes. Several physiological responses were measured during rest and steady-state conditions, the most prominent of which were the oxygen (caloric) consumption and heart rate.

The results of the analysis of variance, using Latin Square design, showed that the heart rate during steady-state in the racing posture was significantly (α = .05) higher than that in the semi-recumbent posture. The oxygen uptake for the racing posture also expressed a higher average, but the difference was not statistically significant. The behavior of oxygen expenditure and heart rate in the other two postures resembled that of the semi-recumbent posture. Air ventilation exhibited the least volume per minute in the semi-recumbent posture and shared with the touring position in statistically different results (α = .05) from the racing posture.

The Physiological Effect of
Posture on Cycling

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DEDICATION

To the soul of my father, whom
I wish could have witnessed the results
of his initial inspiration.

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THE PHYSIOLOGICAL EFFECT OF POSTURE ON CYCLING

I. Introduction

Preface

Limited or scarce energy resources have encouraged the search for new resources which are different in type and nature. Ordinarily, industrial society prefers economical and practical methods to move the wheels of industry and throughout history a variety of sources of energy have been used to fulfill the requirements of life, sources which may appear primitive to succeeding ages but which at one time were essential.

The list of existing sources of energy ranges from human, coal, oil, and solar to nuclear energy. The theories underlying the reasons for the emergence of these sources are not universal and are unappealing to the industrial engineer. Although it is difficult to pinpoint the role of the industrial engineer within the industrial energy environment, widespread opinion points to the need for resource allocation.

This dissertation focuses upon the very first form of energy ever known to man, namely human power. Human muscles have been the basic source of energy since man has existed on earth, are still being used, and will not be dispensed with at any predictable future time.

Although present-day trends are to alleviate dependence on labor, the indispensability of human power throughout the centuries has attracted researchers from different backgrounds. In particular, industrial engineers have been attracted to this area because they are capable of incorporating the physical performance of humans into the man-machine interaction field.

The proposed study attempts to discover the optimum riding posture with which to propel the cranks of human powered cycle vehicles. The first question to be addressed is why this research is necessary or desirable? One answer was previously implied, namely the limitation or scarcity of energy resources. Oil and coal reserves decline with each passing day. Solar energy has not been extensively used and to a large extent is seasonal. Nuclear energy has safety problems that may well counterbalance the positive aspects of this energy source.

Human energy, on the other hand, is economical, profuse, and persistent. A conservative estimate of the number of miles per gallon of milk, containing 2,000 Kcal as fuel for human muscles, is 62, but Witt and Wilson (1983) stated an optimistic fuel rate of 95 miles per gallon of milk (p. 163). In terms of energy consumption, as a function of body weight moved over a

3certain distance, a person on a bicycle ranks first in efficiency among travelling animals or machines (Fa-ria, 1978). The profuseness of human energy is manifest everywhere humans have dwelled and the persistence of this energy source is obvious throughout thousands of years of human cultural development.

The human activity considered in this study, cycling, is considered a sound and healthy exercise. If at the same time cycling is used as a source of transportation, fitness-seeking individuals are able to minimize necessary exercise time. Examined from the point of view of the transportation engineer, the capacity (vehicles per time units) of roads would dramatically increase, especially in urban areas, if the use of smaller sized human-powered vehicles were more widespread. There would be a reduction in traffic congestion and a consequent decrease in motorist trip-time (Forester, 1983, p. 109). Other transportation benefits would include a reduction in parking space requirements, a drop in air pollution levels, and longer road life.

The list of incentives to pursue the research is lengthy, but the last one to be considered might be the most important. Not everyone can afford to buy a motor vehicle, but the majority of the human population is financially capable of purchasing human-

There are obvious limits to the uses of human energy. For instance, human energy is not intended to power an aircraft carrier for reason of its limitations in both magnitude and duration. However, such shortcomings should not preclude riding bicycles or, even better, a vehicle specifically designed to reach the office or supermarket which could take advantage of the above-mentioned characteristics.

Statement of the Problem

The purpose of this investigation was to determine the effect of changing the riding posture in cycling on the physiological responses of the cyclist. It is beyond reasonable doubt that other factors, such as the workload produced by the rider, the speed of pedaling, or the number of limbs employed to generate power, are among the factors influencing the efficiency of bicycling. However, body position has been the factor which has received the least attention in the available studies. The last decade has witnessed a trend to ride recumbent bicycles and tricycles. This study explores the effect and efficiency of cycling postures on selected physiological variables.

Scope of the Problem

Eight healthy male subjects were used to conduct the experiment. Some of the variables considered were oxygen uptake, the heart rate, stroke volume, cardiac output, minute ventilation, and efficiency. The pulmonary and cardiovascular variables were measured at rest and throughout the 8 minute exercise sessions. The recovery period following each session averaged 27 minutes.

Four riding postures were tested, two of which were the regular touring and racing postures. The others were a semi-recumbent posture where the subjects body rested on an office-like chair, and a full-recumbent posture with the face up. Both former postures are familiar from street cycling, while the third posture is each day gaining popularity . The last posture, however, is not practical for commuting purposes, but was included in the study in order to produce a comprehensive picture about the effect of posture in rotary cycling.

The workload was fixed at 90 watts and the pedaling frequency was set at 60 revolutions per minute. These controls are the equivalent of riding at ca. 15 mph in the street, which is suitable for commuter use of bicycles.

Limitations of the Study

There were two principal limitations to this study, the first of which concerns the quality of the subjects. The state of conditioning of the subjects varied, resulting in the enlargement of the differences among the physiological responses. However, several months would have been required to train the subjects in order to obtain a homogeneous sample and time limitations prevented such conditioning. Despite this obstacle many significant results were obtained, indicating that the effect of cycling posture is real.

The other limitation relates to the scope of the research. As far as the number of factors is concerned, a study investigating different workloads and speeds with the alternate use of hands and legs would have provided a base to search for the most efficient riding posture. In addition, other areas of science could have been blended with work physiology in order to seek more comprehensive, in-depth findings. With respect to cycling, biomechanics is the study of the forces applied to the pedal in three directions and kinesiology relates to the involvement of skeletal muscles. It is obvious, however, that the inclusion of these fields was beyond the limitations of a single research study. Knowledge from these fields of research was utilized throughout the study only insofar as it was appropriate and within the limits chosen for the study.

II. Literature Review

Bicycle studies have dealt mostly with the physiology of the body, as shall be discussed later in this chapter. However, a fair amount of studies have been directed at the biomechanics of cycling activities (Soden & Adeyefa, 1979; Hull & Davis, 1981) and there have been a lesser number of similarly directed kinesiology studies (Houtz & Fischer, 1959; Bigland-Ritchie & Woods, 1974). Studies compounded of more than one area are rare, although the work done by Lafortune and Cavanaugh (1983) does focus somewhat unevenly on both the biomechanical and physiological aspects. Ultimately, all three of these areas implicitly or explicitly seek the same end, a more efficient ride.

Physiological experiments have normally concentrated on the effects of load rates and pedaling speeds on heart rate and oxygen uptake. Biomechanical experiments have usually been oriented toward measuring the pattern of forces applied to the pedal and kinesiological experiments have typically correlated the behavior of participating muscles with joint range angles. The primary concern of this study, as indicated in the previous chapter, is the physiological responses of the rider and the other two areas will be engaged only in the design of the experiment and in the analysis of the results. A fourth area, directly related to any man-machine system that contributes to design problems, is human factors engineering, which will be referred to as appropriate in subsequent chapters. This chapter is concerned only with aspects of human physiology cited in the literature of the field.

Power

It is easier to comprehend the physical capacities of humans in terms of the power generated by the body. Power is a rate of work sometimes measured by horsepower (hp) (Sharp, 1982). The definition of horsepower stemmed from experiments showing that "a big horse could maintain for long periods a rate of lifting power equal to that of raising 33,000 lb., one foot, in one minute" (Witt & Wilson, 1983). Other units of power equivalent to 1 hp are 745.7 watts, 10.5 Kcal/min, 33,000 ft-lb per minute, 4562.4 kg-m per minute, and approximately 2.1 liters of oxygen per minute. Basically, power is the product of force by speed. With regard to a moving cycle, the major forces the vehicle must face are air resistance and rolling resistance (Whitt, 1971). Output power is also obtainable from the pro-duct of torque and angular velocity (Firth, 1981). Letting E = work, P = power, t = time, s = distance, f = force, and v = speed, then $P = E/t = f \cdot s/t = f \cdot v$. Sharp (1982) commented on the above sequence of equivalents, stating that a given power could be transmitted by a small force provided that the speed is high. For example, two ergometer riders having every-thing in common, but pedaling at different frequencies with a certain ratio, would have to exert a reciprocal torque ratio on the pedals in order to generate the same output power. However, in actual road riding the more speed attained, the more force is required on the part of the cyclist and in consequence, more power is demanded since power is directly related to the cube of speed. Air velocity must be accounted for, so the proper term for speed is relative velocity with respect to air. So far as work is concerned, in mechanics it is defined as the product of force and displacement or as the amount of change in potential or kinetic energy (Kroemer, 1970).

The level of human power that may be maintained over a period of time deserves mention. One fundamental contributing factor to increase power capacity is the level of body training. In a laboratory test a national cycle champion produced 2.02 hp for six seconds. The world record for ergometer exercise is held by a famous cyclist who produced 0.61 hp for one hour in 1975. The role of work duration is obvious. Optimistic power values may be achieved for very short periods, but are destined to decline over longer periods of time. Another example of this effect is the fall in the average power produced by 5 subjects after 20 minutes to almost one-fourth of the power produced after 6 seconds (Kyle & Caiozzo, 1981). An athlete rated in first class condition was able to generate 1.0 hp for 30 seconds, dropping to 0.5 hp over a 30 minute period and to 0.4 hp when measured for an entire day (Malewicki, 1983).

The above power figures were averaged over the length of the work time. Instantaneous power varies substantially throughout each crank cycle in accordance with the applied force (Kyle & Mastropaolo, 1976). Kyle and Caiozzo (1981) ran a one-tenth second test for a single thrust of one leg and a pull with the other and the output power was a staggering 4.15 hp. However, except for biomechanical studies, instantaneous power is not that crucial since a particular ride takes more than an instant. Rather, average power is more meaningful when considering human-powered vehicles.

When towards the end of the 19th century Sharp prepared his study, Bicycles & Tricycles (1982), there was a scarcity, if not a total lack, of human power studies. Sharp concluded that the average human power potential was about two-thirds of 1 horsepower. Witt and Wilson (1983) suggest that human power may reach 1 hp, but that the average circulates around 0.2 hp. These figures appear to be logical and have been substantiated by a value of 0.19 hp recorded as tolerable for as long as 270 minutes (Witt, 1971). It might not be a coincidence that Rasch and Burke (1978) mentioned the relatively close value of 0.187 hp as representative of human power, compared to 1 hp for horses.

Recumbent Man Powered Vehicles

As stated previously the power and speed of forward movement go hand in hand. For a moving bike, air drag constitutes the greatest proportion of the total resistance encountered on a level pavement. Air drag depends on several independent variables, one of which is the frontal area of the moving composite body, i.e. bike and rider. Consequently, a selected level of power would propel various vehicles, all else being equal except the frontal area, at different speeds. A value of 0.2 hp would move a touring cyclist 16 mph and a racing cyclist 18 mph, while a recumbent cyclist in the supine riding position may reach a speed of 20 mph (Malewicki, 1983). Although no specific documentation is available in the literature about the specifications of the recumbent posture performance, the cited data testifies to the fact that the general configuration of rider and cycle has a direct impact on the average speed, especially if a streamlined enclosure was provided. Additionally, the rider using such a mechanism is not disturbed by the rain or temperature in the freezing weather. All the rider must worry about is safety and because of the usually low height of recumbent, man-powered vehicles, an ideal solution is to install a distinguished colored flag at the eye level of automobile drivers.

The regular shape of the diamond frame bicycle has been maintained for almost the last century. There have been some studies of modifications to some parts of the bicycle, such as the crank arm length and head angles based on oxygen consumption (Astrand, 1953). Part of the reason for the sluggish progress in bicycle design was due to the ban imposed by the International Cyclist Union on the participation in speed events of any cycle which deviated from the standards set forth by the organization. Another factor may be the commuter's shift to the use of automobiles in the more industrialized countries (Gross, Kyle, & Malewicki, 1983).

The restrictions on bicycle design were relieved by the International Human Powered Vehicles Association (IHPVA) in the early 1970s through encouraging interested individuals to develop a cycle design that would break speed records. This paved the way for a dramatic changeover in the cycle industry, bringing the distinctive human-powered vehicle to the streets. Most of the new cycles introduced have adopted the recumbent position, either prone or supine, and some of them involve the hands to supplement power. Normally, the hands are used to steer a vehicle since using the head for that task can be a bit unnerving (Valkenburgh & Hargrave, 1979). A large number of these vehicles add a third or a fourth wheel to in-crease stability. The list of modifications has reached the drive system as well, where a low proportion of cycles use linear motion rather than circular (Aronson, 1980).

With regard to vehicles employing all four limbs, there are unpublished studies which imply that as much as 18 percent more power may be produced than when using leg power alone (Stevenson, 1982). However, the additional percentage generated by arm muscles was tested for only relatively short periods of time, not exceeding 1 minute. It is evident that such a duration is not practiced in ordinary street use. Whether the same power increase may be sustained for longer periods is not known. The advantage of adopting the arms as well as the legs may disappear over a period as brief as 5 minutes (Ball, 1981). It is believed that upper limbs have been employed only for the sake of beating speed records over the 200 meter distance set by the IHPVA. However, the production of more power in this manner may or may not decrease body efficiency. In fact, the practicality of arm power comes into play during hill climbing, when accelerating vehicles from a complete stop, and more prominently as a major power supplement for disabled persons. The last category are fortunate to be able to use their arms to ride, but the energy expenditure increases by a factor of 1.5 for cranking by hand than when cycling only with the legs at 100 watts (Robert, 1960). Lower arm efficiency does not necessarily stem from the nature of the arms, but may be explained by a fractional effort spent in stabilizing the body (Stenberg, Astrand, Ekblom, Royce, & Saltin, 1967).

Workload, Speed of Pedaling, Posture, and Efficiency

Generally, the efficiency of any machine is regarded as the ratio of output work to input work. In fact, this definition is a reflection of gross efficiency. Gaesser and Brooks (1975) offered these definitions:

1) gross efficiency = work accomplished/energy expended;
2) net (mechanical) efficiency = work accomplished/energy expended above that at rest;
3) work efficiency = work accomplished/energy expended above that in cycling without a load; and
4) delta (absolute) efficiency = delta work accomplished/delta energy expended.

In these definitions the work accomplished represented the work rate set at the ergometer and the energy expended was usually measured by oxygen consumption converted to the same units of the numerator. However, the authors did not arrive at an overall agreement about the best measure of efficiency.

Two factors cited repeatedly in the literature, load setting and pedaling speed, may affect cycling efficiency. The former is normally represented in power units (e.g., watts) and the latter is described by revolutions per minute (RPM). Gaesser and Brooks (1975) tested 12 well-conditioned young males and noted a decrease in efficiency when speeds were increased from 40 to 100 in 20 RPM increments, with comparable values at 40 and 60 RPM. However, gross efficiency and net efficiency were proportional to the work rate, between 32 watts and 132 watts in 32 watt increments. The optimum speed was 60 RPM at the largest workload, reflecting 20.4 and 24.1 optimum gross and net efficiencies, respectively.

Garry and Wishart (1931) performed an experiment on themselves and found an optimum speed of 45 RPM, based on gross efficiency (15.75%), when speeds of 25, 45, 70, 86, and 98 RPM were used while applying light and moderate loads. Efficiency for the moderate loads was always higher.

Early in this century, another publication by Dickinson (1929) on one subject resulted in an optimum pedal speed equivalent to 33 RPM, among a wide range of speeds (8 to 111 RPM), corresponding to 21.5 percent net efficiency at 3.0 kg applied on the rim of the wheel. Dickinson then used the optimum speed on a separate series of tests to examine the effect of varying the workloads on efficiency. No appreciable change in net efficiency was found in loads ranging from 1.15 kg to 7.2 kg.

Bobbert (1960) conducted an experiment on 6 healthy males using 85, 115, 165, and 190 watts at a pedal speed of 60 RPM. The results showed a linear relationship between energy expenditure and workload. The gross efficiency seemed to curvilinearly interact with the work rate curve, reaching 17 percent at 90 watts. It should be pointed out that if a linear relationship exists between the energy expenditure and the output work rate, then by definition gross efficiency demonstrates a curvilinear relationship with the latter variable. However, a linear type of relation occurs between net efficiency and the output work rate. Astrand's (1960, Part II) study on 5 young females pedaling at 50 RPM at workloads between 8 and 98 watts indicated an in-creasing net efficiency on a curve within zero to 49 watts, tapering off to 23.5 percent through 98 watts of load. This result ascertains that the relationship between oxygen consumption and work load was not linear. The test was extended to different age female groups where younger subjects (20 to 29 years) had significantly higher net efficiencies than the oldest group (50 to 65 years).

Michielli and Stricevic (1977) concluded from a study on 15 subjects that there are significant heart rate differences when cycling at 40, 50, and 60 RPM, as compared to 70 and 80 RPM at an equivalent 100 watt power output. The reported average heart beats were 129, 127, 132, 140, and 146, respectively. On the other hand, Pandolf and Noble (1973) found from examining 15 highly fit male subjects insignificant differences in oxygen uptake when working within the same pedaling speeds (40, 60, and 80 RPM) at three different work loads (90, 126, and 176 watts). Gross efficiencies did not deviate much from each other, but were consistently better at the 60 RPM speed, being 17.0, 18.1, and 18.1 with respect to the workloads.

The results obtained by Faria, Sjojaard, and Bonde-Petersen (1982), from testing 4 young male competitive cyclists (the hands on the drop bar and body at 40-50 degrees forward angle), revealed a constant average gross efficiency (22 percent) at 294 watts with various frequencies ranging at 60, 100, and 130 RPM. However, at a lower load of 130 watts the gross efficiency dropped to 18, 17, and 14 percent, respectively.

The largest network of speeds (50, 60, 70, 80, 100, and 120 RPM) and loads (59, 118, 176, 206, 265, and 343 watts) found in the literature belongs to Banister and Jackson (1967) and were performed on an Olympic athlete. From the regression equations given, it seems that at a workload of 90 watts the gross efficiency approaches 16.5 percent at speeds up to 80 RPM, then deteriorates at higher pedal speeds.

It is clear from these studies that the behavior of gross efficiency with respect to workload and pedal speed is still undetermined. However, Hill (1934) claimed a formula for gross efficiency as a function of muscle contraction time (half the time of a pedal cycle), irrespective of the workload. Dickinson (1928) ran an experiment to find three constants in the formula, which appears appropriate for only the touring posture. Hill's claim was substantiated by Dickinson (1929), who found no appreciable effect on efficiency by changing the load on the rim of the ergometer wheel when the speed of pedaling remained constant. However, Garry and Wishart (1934) could not correlate their results, obtained from two trained cyclists and one trained cyclist, with Hill's efficiency formula.

So far as posture is concerned, Bevegard, Freyschuss, & Strandell (1966) performed an experiment while subjects pedaled in the supine and regular sitting postures. Six healthy male subjects were employed and trained to perform the various types of exercise twice a week for a period of 2 to 3 weeks. The crank axle in the former posture was 16 cm above the table on which the subjects lay. At a leg load of 82 watts the mean mechanical efficiency in the supine position was 22.7 and the counterpart efficiency was 21.3. The stroke volume was larger in the recumbent position, but the heart rate behavior was reversed.

Blood apparently pooled in the extremities and thus less blood returned to the heart. As a result the stroke volume decreased (Fox & Mathews, 1981, p. 232). However, during leg exercise the leg muscles functioned as a pump, distributing blood back to the heart against gravity (Bevegard et al., 1966). The influence of gravity on blood return was still in effect, as shown by the higher stroke volume and cardiac output in the supine position.

The study by Stenberg et al. (1967) illustrated that oxygen uptake in the supine position was generally lower at submaximal loads than in sitting positions. The precise description of the supine position was not indicated in the following studies, but it is surmised to be lying with the back parallel to the ground. At 49 watts workload no appreciable difference in heart rates was observed between both positions. However, the difference was marked when the workload was tripled. The most notable difference was a consistently larger stroke volume in the supine position.

McGregor, Adam, and Sekelj (1961) used 3 healthy males and 1 female for their research. It contends a difference in heart rate between the touring and supine postures in favor of the latter at two levels of work loads (49 and 82 watts) when the cycling rate range was maintained between 70 and 75 RPM. However, the change in oxygen uptake was not as marked. At relatively heavier loads (131 and 262 watts), Bevegard, Holmgren, and Jonsson (1963) found little change in oxygen consumption at the 262 watt work load and a significant margin at the lower load when 8 well-trained cyclists were examined. However, in a separate study performed by the same authors (1960), using healthy subjects, no trace of difference in oxygen expenditure was found at unspecified and apparently variable loads governed by the heart rate. The effect of posture was clear on stroke volume in both studies.

Holmgren, Jonsson, and Sjostrand (1960) performed an experiment in the full supine position on 18 male and female subjects. The results of 14 subjects at 98 watts revealed a heart rate averaging 129 beats/min, a stroke volume averaging 121 ml/beat, 24.7 net efficiency, and 19.2 gross efficiency. The stroke volume change from rest to steady-state level was not significant. This finding is in agreement with the work done by Wang, Marshall, and Shepherd (1960), who found in addition that stroke volume depends on body position only during rest.

Hamley and Thomas (1967) studied the effect of changing saddle height on the time to complete a preset workload. They found that the optimum saddle height, in that regard, was 109 percent of the distance between the floor and the symphysis pubis bone of skilled cyclists. Then, they used this optimum height in the upright stance (touring posture) and grip and pull stance (racing posture) over a seemingly wide range of workloads pedaled at 90 RPM. Higher heart rates resulted from the touring posture at workloads less than about 250 watts. The trend in heart rate was reversed at higher workloads. Astrand and Saltin (1961) and Faria, Dix, and Frazer (1978) investigated the effect of posture on maximal level. Their findings will be referred to later as appropriate.

Stevenson (1982) has noted that

> a rider in a more or less horizontal position, with support behind the back, can easily generate 50 to 60 percent more power in pedaling than seated atop a conventional bicycle. This means riding faster or riding farther on the same expenditure of energy. (p. 177)

Whether or not this observation was based on scientific measurement methods is not stated.

It is noteworthy that human efficiency remains in the low twenties. Most of the energy that does not appear as useful work at the pedals is dissipated as heat (Witt & Wilson, 1983). The human body shares this phenomenon with numerous machines. For instance, internal-combustion engines are 20 to 30 percent efficient in converting fuel energy to mechanical work (Sharp, 1982). The lost work is due to the frictional resistance of parts and higher efficiencies may be expected from a system composed of fewer components. In contrast, the human body may not be simplified in order to improve its efficiency. Improvement is possible only through the adjustment of combinations of other relevant factors, such as pedaling speed, workload, and most important for this study, the posture of the body. This study is concentrated only on body posture since an adequate number of studies have been devoted to the other two factors.

III. Experimental Design

In retrospect, the research undertaken in this study reflects an experimental approach on human subjects pedaling an ergometer while seated at four positions: 1) the racing riding position (R, see Figure 1); 2) the touring riding position (T, see Figure 2); 3) the semi-recumbent posture (S, see Figure 3); and 4) the full-recumbent supine position (F, see Figure 4). The subjects were asked to pedal at 60 RPM at 90 watts work load. The physiological responses measured were oxygen consumption (Vo_2), heart rate (HR), stroke volume (SV), minutes ventilation (V_E), respiratory rate (RR), and tidal volume (TV) during rest and work performance. These measurements were sampled at 20 second intervals via the computer shown in Figure 5, except for SV values. The subjects inhaled Co_2 from a bag for 15 seconds during rest and steady-state just prior to the end of each exercise trial. The computer then estimated the stroke volume through a special software program.

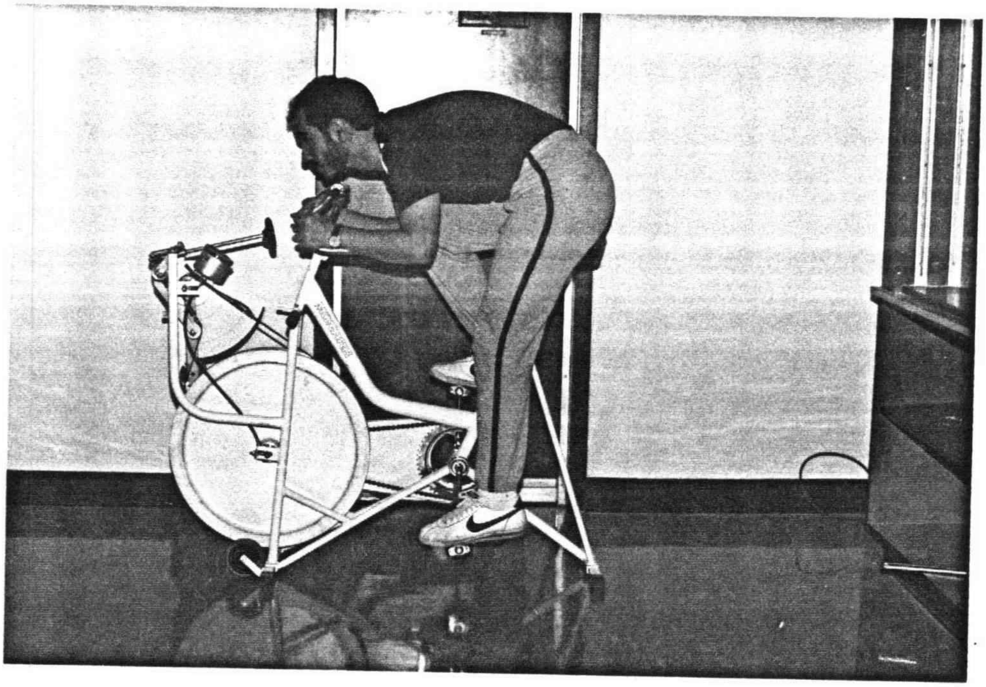

Figure 1. The Racing Posture (R)

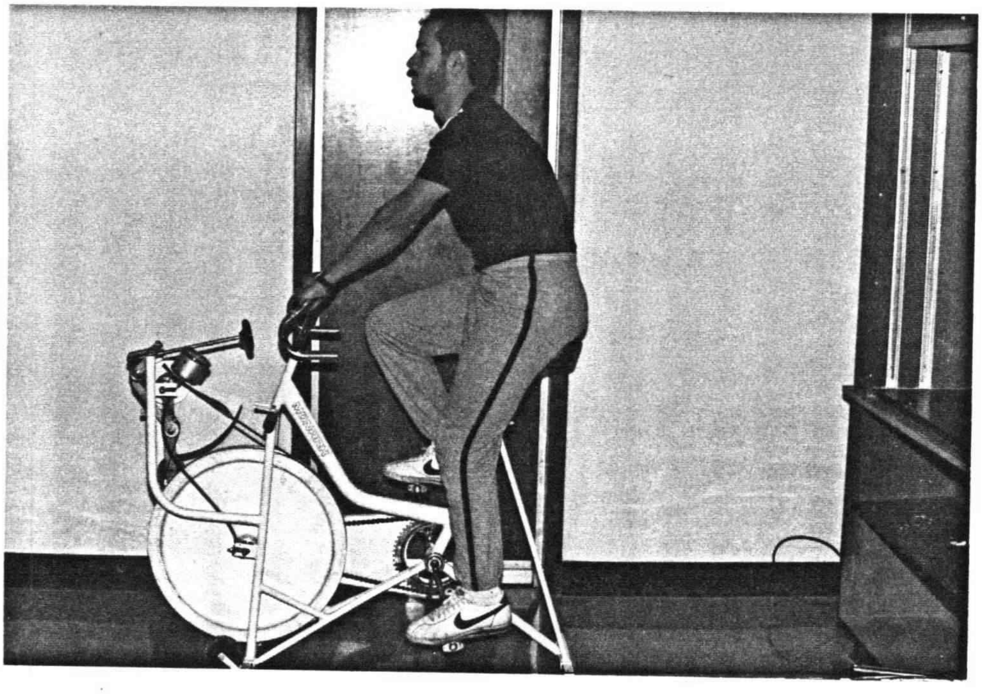

Figure 2. The Touring Posture (T)

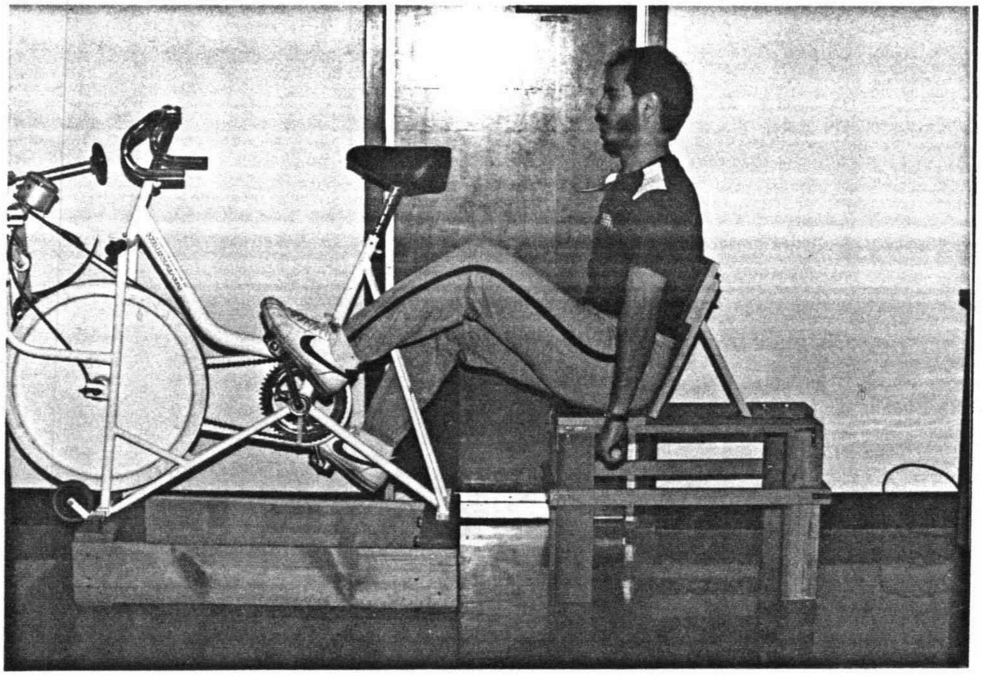

Figure 3. The Semi-Recumbent Posture (S)

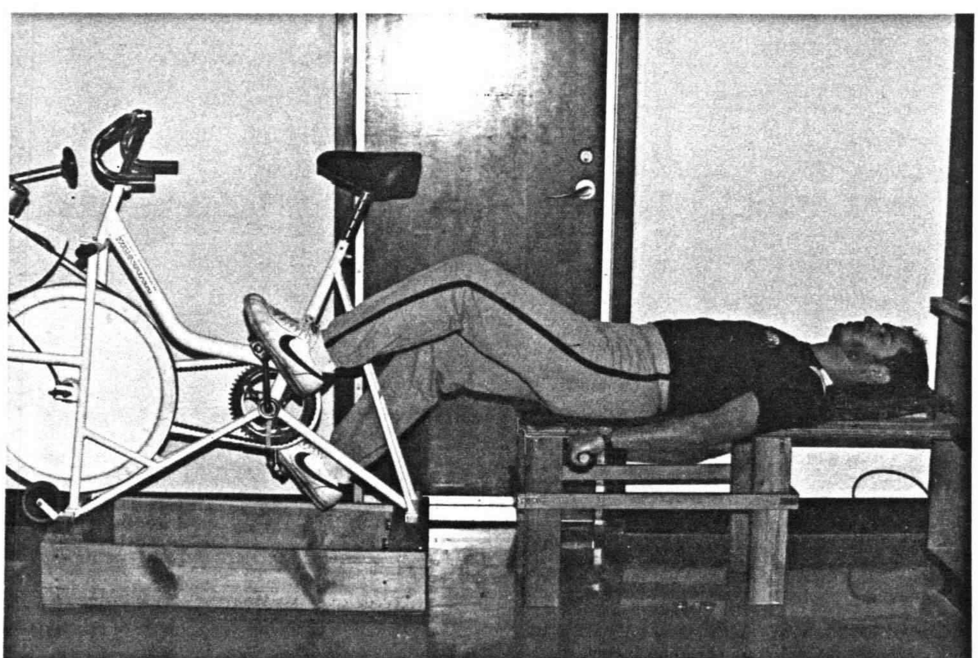

Figure 4. The Full-Recumbent Posture (F)

Age

Eight healthy young (22 to 30 years) males were the subjects of this study. Younger subjects were selected because they have a larger aerobic capacity (max Vo_2) than older people (Astrand, 1960). The study of Davies and Musgrove (1971) contended that older men (40 to 50 years) used the anaerobic system for energy supply more than did younger men (20 to 25 years) when overcoming the same load during a 6 minute ergometer test. Consequently, the use of the aerobic system (oxygen uptake) was less, resulting in the apparently higher efficiency of older men. The findings indicated that after converting the anaerobic work to aerobic, there was no significant difference in efficiency between the two groups.

Sex

Women also showed lower aerobic capacities at ages equivalent to those of men age (Astrand, 1960). This disadvantage causes fatigue among women and older men sooner than among younger men subjected to equal work conditions since a greater proportion of their work capacity is used. Despite the results of the study done by Adams (1967), which ruled out significant differences in energy expenditure, due to either sex or age (ranging from 20 to 52 years), during road bicycling at normal pace, only male subjects were used in order to eliminate a possible source of variation.

Clothing

Minimal clothing helps the body to rid itself of heat generated by means of heat conduction, radiation, and evaporation through the skin (Fox & Mathews, p. 457). The subjects wore long, light, and wide pants as a precaution against hip and knee joint impediments by heavy or tight pants. The upper part of the body was exposed, except for a narrow wrap around the electrocardiogram (EKG) electrodes. To warrant an equal chance of body cooling, the laboratory temperature was at all times regulated at a normal room temperature of 73°F.

The subjects' ordinarily wore sport shoes which provided sufficient friction with the pedal. Toe clips were not used because they allow the subject to easily pull the pedal and some degree of skill is desirable in coordinating pull-push movements. This issue is related to ankling technique and is beyond the scope of this study. However, the subjects were advised to push the pedal with the ball of the foot at all times. It has been claimed that leg muscles would be used effectively that way (Sloane, 1980).

Food

Subjects were allowed a light meal about three hours prior to reporting to the lab. Fox and Mathews (1981) prohibited "foods that, when consumed several hours prior to physical activity, will lead to super performances" (p. 497). Therefore, no restrictions were imposed on the quality of the diet so long as the quantity did not cause lethargic feelings. No food or drinks were supplied during work periods until the termination of the four test sessions.

Incentives

The subjects were volunteers. Research has shown that volunteer subjects are more efficient than paid ones (Rothstein, 1985, p. 45). No encouraging comments were directed at the subjects because it may or may not have improved their performance, depending on their psychological status.

Training

Research indicates that cycling results in specific training effect, whereas running is more general in its training responses. This means that individuals trained via cycling do not perform as well on running tests and vice versa. An elite group of bicyclists reached higher max Vo_2 in ergometer testing compared to treadmill running (Stromme, Ingjer, & Meen, 1977). In addition to improving the capacity of oxygen consumption, specific training effect in cycling appears to be increased leg strength, facilitating both oxygen transport and utilization at the involved muscles (Faria, 1978). Therefore, it was preferable to choose non-cyclist subjects because professional bicyclists may perform better in the regular sitting position than in the recumbent, or they may collectively show improved efficiency compared to non-cyclists. However, the subjects were introduced to the nature of the experiment and were asked to run the experiment, to determine heart rate measurements, a few days prior to the actual tests.

Information Sheet

The form of the information sheet is at Appendix A-3. Some essential data about the subjects were recorded, such as age, weight, sex, height, buttock to knee length, and chest circumference. Additional information which may or may not have affected performance were collected, such as the hours of sleep during the previous night, smoking habits, training program, and the time of the experiment. Moreover, the weight of the thigh, shank, and foot were estimated using a Clauser equation (Clauser, McConville, & Young, 1969; the Clauser equation may be found on the first page of Appendix A-4, under the notation "LW"). Leg weight was estimated using body weight

(W), maximum calf muscle circumference (MCC), and upper thigh circumference (UTC) as variables.

The weights of lower segments may help pedaling in the touring and racing positions since the pushing phase coincides with gravity direction. However, these weights must be lifted against the force of gravity in the other half of the cycle, a phenomenon which may influence energy expenditure. Therefore, a correlation test was done for each posture between the total weights of the thigh, shank, and foot and the average oxygen consumption.

Some of the above body measurements were shown to significantly correlate with movements of appropriate body parts. Clarke's (1957) study has shown significant correlation between knee extension strength and the thigh and leg girths (0.45 and 0.33, respectively) and with leg length (0.31) as well. Leg length was considered as the difference between standing and sitting heights, which is not a precise measurement. However, the correlation between hip extension strength and the above-mentioned anthropometric variables was insignificant at the .05 significance level, being .20, .27, and .04, respectively.

Height (H) was measured while the subjects stood erect in bare feet and weight (W) was measured by an electronic scale while the subjects were dressed in exercise clothing. It was assumed that the given weight could be around one pound more than the actual body weight. Leg length (LL) was measured from the buttock to the heel while the subjects sat on the floor. The inseam length (IL) was taken with the help of the subjects from the crest of the pubis bone, while the subject was standing, to the floor. This dimension was multiplied by 1.09 to determine saddle height at the racing and touring postures.

Chest measurements at all four postures were taken at rest at the xiphoid bone level. These anthropometric data are listed in Table B-1 (Appendix B). The work capacity (max Vo_2) was estimated from a monograph in Astrand's (1960) extended study on this area. Since the monograph was prepared from data obtained while subjects sat in the regular sitting stance, the individual Vo_2 and HR averages in the touring posture were used to estimate max Vo_2. These work capacities should not be projected to the other postures since some researchers have found an influence of type of exercise on max Vo_2.

Astrand and Saltin (1961) found max Vo_2 in full supine posture 0.62 l/min lower than that in the touring posture. This result was based on five well-trained male subjects. Similarly, the effect of posture was significant on max Vo_2 when hands rested on top handlebars (touring) against hands resting on lower handlebars (racing, but not crouched back). Faria, Dix, and Frazer (1978) found an increase in max Vo_2 averaging 0.24 l/min as a result of changing the posture from touring to the described racing postures for 8 male cyclists and one female cyclist.

Finally, the maximum heart rates were predicted from age (max HR = 220 - Age) according to Konz (1979).

Apparatus

The best test of research with the stated objectives of this study may be a real road test in order that the effect of the frontal area on the air drag force, among other factors, may be incorporated. However, the potential problems of this type of test are obvious, ranging from a shift in wind velocity to the distractions of the test surroundings. Although road tests have been done (Adams, 1967), the trend is to select other alternatives, such as wind tunnel tests ("Power Output of Racing Cyclists," 1957). The experimental costs of this type of test are prohibitive and some investigators have preferred a load simulator fitted to a bicycle in order to simulate the air and rolling resistance (Firth, 1981). The majority of physiological studies, however, were done by using ergometers which imitate the normal sitting positions on bicycles and allow variations of loads and speeds.

Ergometers are produced with different styles and functions, but the basic feature distinguishing one from another is whether the driving mechanism is mechanical or electronic. The latter is naturally more accurate and reliable, but none were available for this study. Instead, a Monark mechanical ergometer was used. Normally, these devices do not adjust the workload as a result of pedal speed variation and the experimenter must constantly observe the speed display in order to alert the subject when such variations occur. The ergometer used in this study accommodates both the racing and the touring postures. The recumbent posture was tested with a specially designed seat (see Figure 3), located behind the ergometer.

Pulmonary variables were measured by a gas analyzer (Gould, 9000 IV) and the heart rate was measured by an EKG monitor (Tektronix 400 Recorder). The pedaling speed was determined by a Cateye solar computer. A photograph of the equipment used is shown in Figure 5.

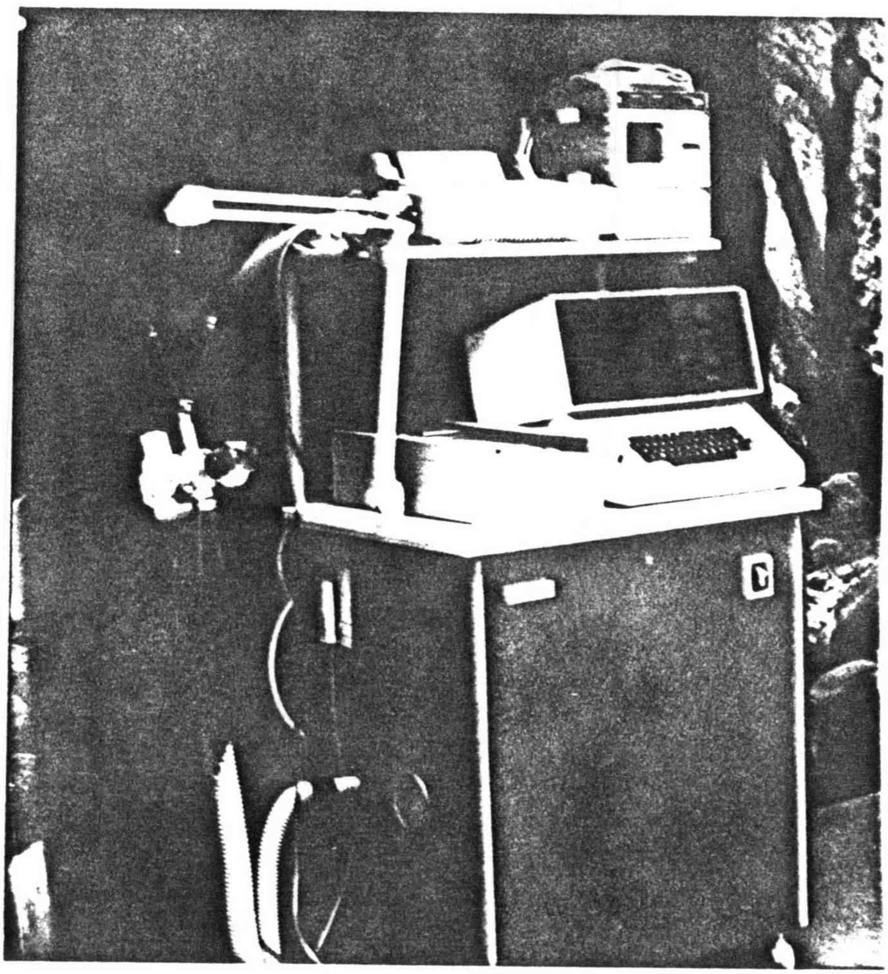

Figure 5. The Gas Analyzer, Heart Rate Monitor, and the Interfacing Computer.

Crank Axle Height

The experiments focused on efficiency fluctuations for four different pedaling postures. It cannot yet be demonstrated which posture yields the optimum efficiency based on a given work rate and pedaling speed. With regard to the semi-recumbent posture, the axle placed above the seat level is a well-known design, ranging from 12 to 14 inches (Aronson, 1980). However, this design is not practical for road riding since the pedals interfere with the view of the road. Therefore, an axle height equivalent to seat level was chosen for this study.

The fully supine posture is not common, but it may prove to be the most efficient since the blood does not force its way against gravity when pumped back to the heart by the muscles. The nature of this particular posture reduces the frontal area of the vehicle to a minimum, at the same time allowing a streamlined enclosure resembling the common cross section of an airplane wing. For consistency with the semi-recumbent posture, the pedal axle was located at the level of the horizontal surface.

The touring posture, where the upper body leans on handlebars and the arms are stretched, and the racing posture, where the back is almost horizontal, are the most familiar postures. The height of the saddle is determined by the generally accepted 109 percent rule. Experiments have shown that the most efficient saddle height is 109 percent of the inside leg measurement from the crotch bone to the floor while standing erect without shoes (Hamley & Thomas, 1967). In tests of females, oxygen consumption was least at 107.1 percent of crotch height (Nordeen-Snyder, 1977). The saddle height is then adjusted with the crank arm parallel to the seat tube, an arrangement which respects the recommendation by Hull and Butler (1981) that the seat should be as high and as far back as possible.

Seat to Pedal Axle Distance in the Semi-Recumbent Posture

The human display in Figure 6 illustrates some of the linear distances and angles which affect the semi-recumbent posture (S). The important human factor design principle, which allows for a specified range of individuals by providing adjustments (Kantowitz & Sorkin, 1983, p. 476), fits the context. In the semi-recumbent position the seat is adjusted back and forth to accommodate variations in buttock to foot lengths. Seat adjustments, fore and aft, may lie within a range of almost 8 inches, based on the differences in buttock to foot lengths between the 5th and 95th percentiles given by McCormic and Sanders (1982). The anthropometric data for the relevant dimensions differs in fractions of an inch from those given by Hutchingson (1981). Neither of these sources reflected the measurements of the potential user population since they were taken from military personnel.

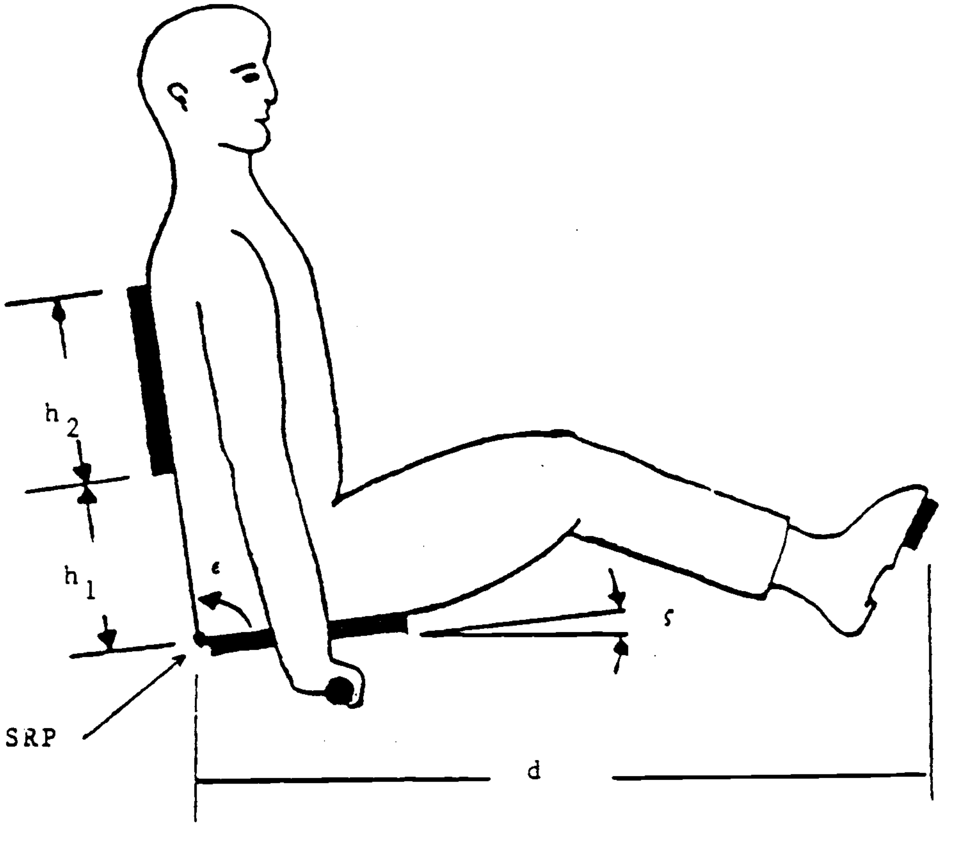

Figure 6. Angles and Dimensions Involved in the Semi-Recumbent Posture. Based upon a figure provided in Kroemer, 1975, and modified.

In this study the seat was adjusted so that the foot, with shoes, just reached the farthest position of the pedal while the crank arm was in line with the stretched leg. Roebuck, Kroemer, and Thomson (1975) illustrated a related issue under static conditions. Maximum leg force against a stationary peddle located about 1 to 2 inches below SRP was found at 0.95 leg length, corresponding to a knee angle of 160 and a thigh angle range of 15 to 19. These joint angles were reproduced in the current study. However, Rees and Graham (1952) found that a backrest with lumbar concavity offers the greatest push in isometric exercises when the pedal was about 5 inches above SRP. This height occurred in the present experiment when the crank axle was set at seat level. Since the average crank arm is about 7 inches in length, the best 5 inch pedal height is encountered during the pedal revolution just past the vertical crank arm position.

On the other hand, Kroemer (1972) concluded that maximal leg strength may be applied to a pedal located at near SRP with the leg almost fully extended. This conclusion was also asserted in Vancott and Kincake (1972, p. 571). The discrepancy concerning the pedal location which offers the maximum force is obvious. The reason could be the failure to standardize specific variables, such as the backrest angle, the seat pan angle, the backrest height and the length. This reasoning makes sense when recalling the theory which effectively states that the maximum leg push can be attained when the backrest, knee, and pedal lie in a straight line (Muler's theory, cited in Rees & Graham, 1952).

However, when the line of knee thrust passes below the backrest, there is a tendency for the upper part of the body to be pushed forward. Conversely, if the line of action passes above the backrest, the tendency is to lift the body backward (Weddell and Darcus, 1947). By placing the pedal axle at seat level, the backrest-knee-pedal axle line would be fulfilled throughout the push stroke.

The maximum leg force is apparently not reproduced in dynamic tests such as leg pedaling (see Kroemer, 1970), but the biomechanical principles apply in both cases as pertain to this study. Kroemer (1975) stated that "the generality of biomechanical principles must hold as long as the relations between such things as body dimensions, mechanical advantage, and pull angles are the same." On the other hand, force distribution on the pedal in the touring posture increases gradually from top dead center position to reach a maximum at 100° crank angle, then the applied torque declines to zero at nearly 200° angle (Davis & Hull, 1981). Unfortunately, similar biomechanical studies for the semi-recumbent posture do not yet exist. Generally speaking, in leg extension the extensor muscles (quadriceps group) shorten when the leg is nearly stretched and muscle tension decreases accordingly (Haxton, 1945a). However, the lever arm (the perpendicular distance from the line of tension to the center of rotation) increases and compensates for the tension loss (Hugh-Jones, 1947). In another paper, Haxton (1945b) discovered that the patella holds the patellar tendon away from the axis of rotation, thereby increasing the extending moment of the quadriceps pull.

It should be noted that the distance from the seat reference point (SRP) to the pedal axle (d) is a variable distance depending on the cycle angle. However, in this study each subject was seated as close to the far edge of the seat as possible and the leg was extended to touch the pedal axle. Standardization of this procedure allowed the subjects to flex the foot at equivalent angles when they exerted force during cycling. Consequently, the knee angles for all subjects varied minutely and full leg extension was avoided since foot plantarflexion compensated for the buttock-pedal distance required. At full leg extension, with the knee angle close to 180°, the available exertion force drops sharply (Kroemer, 1972), not to mention the instantaneous pain usually felt at the back of the knee.

Seat Design in the Semi-Recumbent Posture

Seat design is crucial to an efficient posture in the office, plant, and particularly for cyclists. Its importance stems from the objectives of relieving the back muscles in order to delay fatigue and to provide a reaction force. As illustrated in Figure 2, the seat is described by the seat pan angle (ς), the backrest angle (ϵ), the backrest height (h_1) and the backrest length (h_2). Each of these variables was assigned a numerical value according to the specification required. The natural shape of the spine should be maintained to produce both an optimum pressure distribution over the vertical discs and an optimum level of static load on the intervertebral muscles (Osborne, 1982). A trunk-thigh angle of about 115 degrees has been suggested to attain the natural spinal shape. Although this angle was not a constant in the present study, the suggested angle implies a backrest angle (ϵ) exceeding 90 degrees. When the backrest is at 90 degrees, disc pressure is at maximum (Frankel & Nordin, 1980). Backward inclination to about 110 degrees results in less disc pressure, whereas the addition of a lumbar support further decreases the pressure. This criteria has been adopted for seating in motor vehicles as well. A range of 10 to 30 degrees below the vertical has been recommended as a back comfort zone (Diffrient, Tilley, & Harman, 1981b), but an angle in excess of 30 degrees requires a head support. To avoid muscle strain in the neck and to maintain low disc pressure, a backrest angle of 110 degrees was chosen.

The backrest is also essential during force application through the pedals. Rees and Graham (1952) showed that comparatively smaller forces were exerted on a fixed pedal when no backrest was provided. The location of the backrest with respect to the back also plays a significant role.

The main point taken into account, however, was to sufficiently raise the back support to clear the sacral region to avoid losing the effect of the adjustment (Craney, 1981). The available literature does not agree on the height of the backrest from SRP (Murrell, 1971, specifies not less than 8 inches above SRP, while Craney, 1981, specified 6 to 8 inches above SRP). The optimum height of the backrest corresponds to the level of the maximum concavity of the lumbar curvature (Weddell & Darcus, 1947). Therefore, the height h_1 was decided subjectively, since human backs vary in length. The choice of depth of the backrest (h_2) also reflected the same conflict (4 to 8 inches in Murrell and 4 to 6 inches in Craney) and a compromise value of 6 inches was assigned to h_2.

The backrest should be curved at a radius of about 16 inches and should not be more than 13 inches wide to avoid hitting it with the elbows. At the same time it should be wide enough to accommodate the back width (Murrell, 1971) as well as allowed to freely swivel about a horizontal axis in order to properly fit the curved lumbar area (Tichauer, 1978, p. 75). However, in this study a plain, fixed back-rest seemed to provide a reasonable level of comfort for all subjects.

The main weight of the body should be carried by the bones of the buttocks, technically known as the ischial tuberosities (Kantowitz & Sorkin, 1983, p. 478). The seat pan should not press on the tissue of the thighs, which are not created to withstand pressure as are the tissues of the buttocks. Therefore, the seat pan was designed to accommodate only the buttocks. This design was also a necessary feature to eliminate impeding the thigh movements during pedaling. Unfortunately, the anthropometric sources searched offered no statistics concerning buttock length. However, an 8 to 9 inch seat pan length has been observed in more than one recumbent human-powered vehicle. This length seemed to be reasonable and was adopted for this study.

The seating surface should be slightly padded and covered with a porous rough, fabric that facilitates heat loss (Tichauer, 1978, p. 74). In fact, this kind of fabric increases friction in the contact area between the body and the seat pan, which aids in the prevention of sliding and to minimize unnecessary movements.

The seat pan angle (ς) was fixed at zero, i.e. a horizontal pan, and the pan width was set at 12 inches, which seemed to accommodate both ischial tuberosity bones.

Work Rate and Pedal Frequency

The determination of the assigned 90 watts work-load was based on the total resistances facing a cyclist riding at 15 mph. The major force resisting this man-machine system is air drag expressed by the equation:

$$AD = 0.005093 \times C_D \times A \times V^3 \text{ (watts)}$$

where the product of C_D and A represents the effective area and V is the velocity of the bicycle (Witt & Wilson, 1983, p. 92). The other form of resistance, which is less important but relatively significant at low speeds, is the rolling resistance caused by the contact of the wheels with the ground, given by the equation:

$$RD = 1.99 \times W_T \times C_R \times V \text{ (watts)}$$

where W_T is the total weight of rider and vehicle and C_R is the rolling coefficient (Blair, 1983). The latter term depends on the particular man-powered vehicle, whereas the coefficient of air drag depends on the posture of the rider as well. The following table summarizes reasonable numerical values of the independent variables and the required output power in watts to ride at 15 mph.

Table 1. Estimation of Output Power During Actual Cycling at Different Postures.

Posture	$C_D \times A$ (ft^2)	C_R	W_T (lbs)	AD	RD	Output Power (watts)
Racing	3.4	0.003	180	58.4	16.1	74.5
Touring	4.3	0.0045	185	73.9	24.9	98.8
Semi-rec.	2.9	0.005	187	49.8	27.9	77.7

The estimated output power at the racing posture seems to be the least. However, if a streamlined fairing were incorporated for the semi-recumbent posture, the air drag reduction would vary between 13 and 68 percent (Witt & Wilson, 1983, p. 98), depending on the aerodynamical laws followed in the production of the enclosure.

At any rate, the average output power (from the table) was 83.7 watts. A few watts were added to this average to account for the power lost in transmission friction in actual road riding, making the assigned workload 90 watts. This workload elicited an overall average energy consumption of 8.009 kcal/min across all 4 postures (Table B-49 of Appendix B). This calorie burning rate approaches the rate of energy expended by untrained cyclists (7.75 kcal/min) when they are allowed to select their own speed (see Faria, 1978). Although in this study the subjects were assigned a pedal speed (60 RPM), rather than allowing them to choose their own speed, Faria confirms that the given load (90 watts) should be an acceptable load for most subjects. It should be pointed out that there were no measures taken to control the output power except for observing the pedal speed. The power output calculated from crank-force and velocity measurements by Hoes, Binkhorst, Smeekes-Keyl, and Vissors (1968) ranged between 89.2 to 117.2 percent, in 3 subjects, of the 100 watts shown in the ergometer sitting.

A velocity of 15 mph and a moderate gear of 85 inches require a cadence of 60 revolutions per minute (RPM) deduced from the following equation (Sloane, 1980):

$$V = \text{Gear} \times \pi \times \text{cadence}/1052$$

The gear value is obtained from the ratio of the number of teeth in the chainwheel (N_1) to the number of teeth in the freewheel (N_2) multiplied by the diameter of the driven wheel (D). Consequently, the frequency of pedaling was determined to be 60 RPM. It should be added that the chosen velocity, gear, and cadence have evolved from the personal experience of the experimenter in commuting by ten-speed bicycle and from the feedback of other commuters. Additionally, a pedaling speed of 60 RPM seems to be the common speed in physiological research (e.g., Robert, 1960) and it turned out to be the optimum pedal speed among combinations of speeds and workloads (Gaesser & Brooks, 1975). Finally, a crank speed of 60 RPM fits the desirable range determined by Faria, who concluded that "there is considerable agreement that physiological responses generally indicate a metabolic similarity for cycling over a wide range of speeds, 40 to 80 RPM" (1978).

Duration of Exercise and Rest

All four trials were conducted the same day, separated by rest durations and preceded by a one minute warm-up at 30 watts and 30 RPM. In fact, the use of a warming-up prior to the actual exercise is controversial. Fox and Mathews (1981, p. 271) preferred the use of a warm-up in order to increase muscle temperature and, most importantly, to prevent inadequate blood flow to the heart during abrupt intensive exercise. In this study each test was eight minutes in length, enough to reach a steady-state condition.

Physiologists generally agree that in submaximal efforts a steady-state condition may be reached within 5 minutes. This period seemed sufficient for steady- state achievement by all 8 subjects, at all 4 body positions, and with regard to both HR and Vo_2. In order to reach this conclusion, the last 10 data points for each trial (i.e. the last 3 minutes of data), occurring immediately after the initial 5 minutes of exercise, were linearly regressed to the form $Y = b_0 + b_1 X$, using the computer program SSTEST (Appendix A-5). The program calculates the regression line parameters b_0 and b_1, then checks for the statistical significance of the latter value. If the results are insignificant, i.e. the slope of the line is negligible, then a steady-state condition is assured. The output of the SSTEST program is summarized in Appendix B, Table B-67, where the "t" values are extremely minute. The slopes of the lines were not only statistically insignificant, but in most cases they also carried a negative sign indicating a trend towards body stabilization. The interception with the y-axis (b_0) reflects the steady-state level itself, but consideration in the analysis of variance (ANOVA) tables (see Appendix B) was directed toward the actual average of the last ten data points rather than the estimated parameter. The procedure to find the test statistics is included in Appendix A-4.

The rest period averaged 27.5 minutes with a minimum of 20 minutes (see Table 65 of Appendix B). This recovery duration was sufficient to bring the subjects almost back to base-line state. This speculation was confirmed by the resting measurements of some subjects, where Vo_2 and HR readings became less at the beginning of later exercises. The decrease in Vo_2 and HR resting values then reflects the effect of the change in posture. Additional detail will be provided about rest period selection in the carry-over section of Chapter IV. Coincidentally, the same amount of time was needed to set-up the equipment for subsequent tests.

The subjects were expected to complete all four tests prior to reaching the exhaustion state, since the workload level was only 90 watts and the pedal speed was 60 RPM. A study done by Hermansen, Hultman, and Saltin (1967) revealed insignificant differences in oxygen consumption for trained and untrained subjects among four periods of intermittent tests. The subjects undertook a heavier load (77 percent of max Vo_2) compared to nearly 61.5 percent max Vo_2 in this study (see Table 1, Appendix B). Duration of work performance was also longer (20 minutes) than in this study, whereas rest periods were shorter (20 minutes). The pedal speeds were comparable (50 RPM versus 60 RPM). The glycogen level was almost depleted at the end of the exercises, but the severity of this experiment was obviously much less. The total amount of carbohydrates stored in the form of glycogen has been estimated to be as high as 800 grams (Faria, 1978). It is estimated that about 3 grams/min are consumed for the work intensity given to our subjects, based on the research done by Saltin and Karlsson (1971). For the prescribed load in this study the depletion time for glycogen would take as long as 260 minutes. However, the total exercise time for all 4 postures included in this study did not exceed 32 minutes. Therefore, it was not expected that an exhaustion state would occur. Another precaution taken into account was the degree of fatigue experienced by the subjects. During cycling excess lactic acid is said to begin accumulating at 55 percent of max Vo_2. Muscle fatigue during intense cycling is probably due to lactic acid (Faria, 1978). Fortunately, the workload intensity in this study averaged 61.5 percent of max Vo_2, which was not anticipated to escalate the amount of lactic acid. Moreover, the statistical experimental design selected (Latin Square), in part was chosen to detect any trace of fatigue.

Statistical Design

The Latin Square design was chosen to perform the ANOVA on the dependent variables. The advantage of this design over the Randomized Block design is that in addition to isolating the sum of squares due to subject variations, it also restricts another nuisance variable, i.e., the sequence of the test trials given to the subjects. Initially, the major concern about the experimental design was the development of fatigue due to performing successive bouts. Therefore, the adoption of the Latin Square Design is appropriate (Mendenhall, Schaeffer, & Wackerly, 1981, p. 499).

Since there are four treatment levels (postures) in this study, the schematic square should be 4 x 4, i.e. containing four rows corresponding to the subjects and four columns corresponding to the test trials. However, a sample size composed of eight subjects required two independent Latin Squares. The preparation of these squares was based on randomizing the treatment levels, columns, and rows (Edwards, 1968, Ch. 10). The results of the randomization process is shown in Table 2. In each square each posture appears once in a certain combination of rows and columns. The single Latin Square analysis was taken from Wine (1964).

Table 2. Sequence of Posture

Subject #	Trial #1	Trial #2	Trial #3	Trial #4
	Latin Square #1			
1	T	R	S	F
2	F	T	R	S
3	S	F	T	R
4	R	S	F	T
	Latin Square #2			
5	R	S	T	F
6	F	T	R	S
7	S	R	F	T
8	T	F	S	R

Since two Latin Squares were used, a combined ANOVA table is formed by algebraically adding the respective sum of squares and degrees of freedom (Edwards, 1968, Ch. 10) (The ANOVA tables in Appendix B are combined Latin Squares). Therefore, an additional source of variation should be considered, which is represented by the difference between both squares with respect to the dependent variable. A summary of Latin Square Design is included in Appendix A-4.

IV. Experimental Results and Discussion

Subjects' Specifications

The anthropometric measurements and physical characteristics of the subjects are summarized in Table B-1. (The tables referred to in this chapter, designated by an "B" placed before the table number, are in Appendix B.) All 8 male subjects were non-cyclists, except for subject #7 who commutes twice a day for about 5 minutes. This duration is barely close to reaching steady state condition at the estimated 10 mph speed he is accustomed to riding. His performance fits in the range of the other subjects with regard to all the physiological variables considered. Therefore, specificity from his usual touring posture riding style is not obvious. It is fair to mention that he experienced the least Vo_2 at the touring posture, compared to readings of the other postures (Table B-2), but the same incidence was observed in subject #6 who had not cycled for many years. In fact, conditioning due to cycling requires a duration of at least 20 minutes per day at a heart rate level between 60 to 80 percent of maximum heart rate (Shaping up Through Diet and Exercise, 1985). The first condition had not been met by subject #7, who was subjectively attributed a moderate physical fitness, putting him among the majority of subjects (#2, #3, #5, #7, and #8) having an approximately equal level of conditioning.

In fact, the fears expressed by the non-homogeneous subjects were most apparent because of subject #1, who enjoyed an excellent physical fitness level. In addition to playing 2 hours of soccer weekly with the rest of the subjects, he practiced basketball, volleyball, and weightlifting for almost 30 minutes each per week. This training effect was obvious from the low HR elicited at steady-state (Table B-14).

The other element causing experimental non-homogeneity was subject #6 who was thought to reflect moderate conditioning, but who indicated inferior performance based on his HR level (Table B-14). The highest average HR for this subject should not be attributed to smoking since

> chronic smoking of cigarettes results in increased airway resistance. This in turn means that the respiratory muscles must work harder and thus consume more oxygen in ventilating a given amount of air (Fox & Mathews, 1981, p. 197).

This phenomenon was stated in relation to maximal exercise but for an estimated average of 83 percent of the maximum body capacity (Table B-1) the smoking effect on Vo_2 seems to be minimal since the average Vo_2 for all the postures of subject #6 were not extreme cases. Furthermore, the average Vo_2 consumption of subject #8, who smokes 2 more cigarettes daily than subject #6, exhibits the lowest figure among the rest of the subjects (Table B-5).

Maximum heart rate estimation (Konz, 1979) was based on age. This estimation basis was reasonable for all subjects except subject #1, who happened to be the oldest subject. Considering that he was also the best trained subject confirms the point. The average percent of maximum heart rate (74 percent) falls within the 60 to 80 percent range desired for any training effect sought by cycling commuters if they maintain a 15 mph speed, equivalent to about 90 watts at 60 revolutions per minute for 20 minutes or longer. In addition, the average Vo_2 uptake (61.5 percent of max Vo_2) classifies training of that nature as a submaximal aerobic exercise.

Oxygen Consumption (ml of O_2/min)

Rest

The oxygen consumption at rest is listed in Table B-2. Subject #1 consumed the largest amount, apparently because he was also the heaviest subject. In contrast, subject #7 on the average consumed the least and he weighed the least of all the subjects.

The most surprising result emanates from the different Vo_2 uptakes due to posture changes (Figure 7). The racing posture (R) resulted in the highest Vo_2 consumption (360 ml), compared to 243 ml in the full-recumbent posture (F) as the lowest, i.e.

changing the posture from R to F reduces Vo_2 by almost 32.5 percent at rest. The ANOVA executed shows that the treatment effect on Vo_2 at rest was significant at $\alpha = .05$ (Table B-3). To see how each posture differed from the others, a single degree of freedom test (see Appendix A-4) was performed (Table B-4). The test revealed that all three postures are sigificantly better than R with regard to Vo_2 at rest. The test also shows insignificant differences among T, S, and F.

Steady-State:

Table B-5 reflects the steady-state Vo_2 uptake. The maximum average Vo_2 was shown by subject #4 (1752 ml/min) and the minimum value belonged to subject #8 (1409 ml/min). The general behavior of the subjects imitated Vo_2 at rest where the average values in descending order were 1632, 1607, 1562, and 1559 ml/min for, respectively, R, T, S, and F (Figure 7). Unfortunately, the treatment effect was not significant (Table B-6).

Dividing Vo_2 by weight does not change the order with regard to posture (10.64, 10.47, 10.21, and 10.18 ml/min/lb for, respectively, R, T, S, and F; see Figure 8), but it reversed the subjects' order. The heaviest body weight (subject #1) indicated the most efficient reading (8.89 ml/min/lb), as opposed to the lightest body weight (subject #2) reflecting the largest ratio (12.26 ml/min/lb). When the net Vo_2 (Table B-9) is considered by subtracting the baseline Vo_2 from the steady-state values, the racing posture is demonstrably the most favorable (1272 ml/min, compared to 1326 for T, 1300 for S, and 1315 for F; see Figure 9).

The smaller Vo_2 for the racing posture may be attributed to the added leverage obtained from the recruitment of the gluteus maximum muscle (located at the back of the hip). This muscle is called into action in hip extension at hip joint angles in excess of 45° (Rasch & Burke, 1978). Such a range of angles is manifested in the R posture more than in the other postures.

It is logical to say that the involvement of additional muscles during a full pedal cycle would relieve the other muscles from assuming the whole load. Astrand and Saltin (1961) showed that combined arms and legs cycling exercise in three strenuous workloads prolonged the exhaustion time of subjects as opposed to performing the same levels of work only by the legs. The EMG study done by Tate and Shierman (1977) contends that the hamstring muscle group (at the back of the thigh) and the calf muscle (at the back of the lower leg) were active for a longer period during a pedal cycle when toe clips were used. The function of toe clips is to strap the foot to the pedal in order to pull the pedal during the back stroke by one leg. The calf and the hamstrings are thereby called upon to relieve the load from the quadriceps muscle group (at the front of the thigh) during the push stroke by the other leg. Lafortune and Cavanaugh (1983) showed that less oxygen was consumed when cleats and toe clips were used, when compared to pedaling without them, in overcoming 155 watts workload and a pedaling frequency of 60 RPM. These findings support the analysis made with regard to less net oxygen consumption at the racing posture (R). In fact, net Vo_2 values do not reflect the actual performance and are included because this has been the classical approach of most researchers. As far as statistical significance is concerned, the lack of significance in Vo_2/weight and net Vo_2 persisted (Tables B-8 and B-10, respectively).

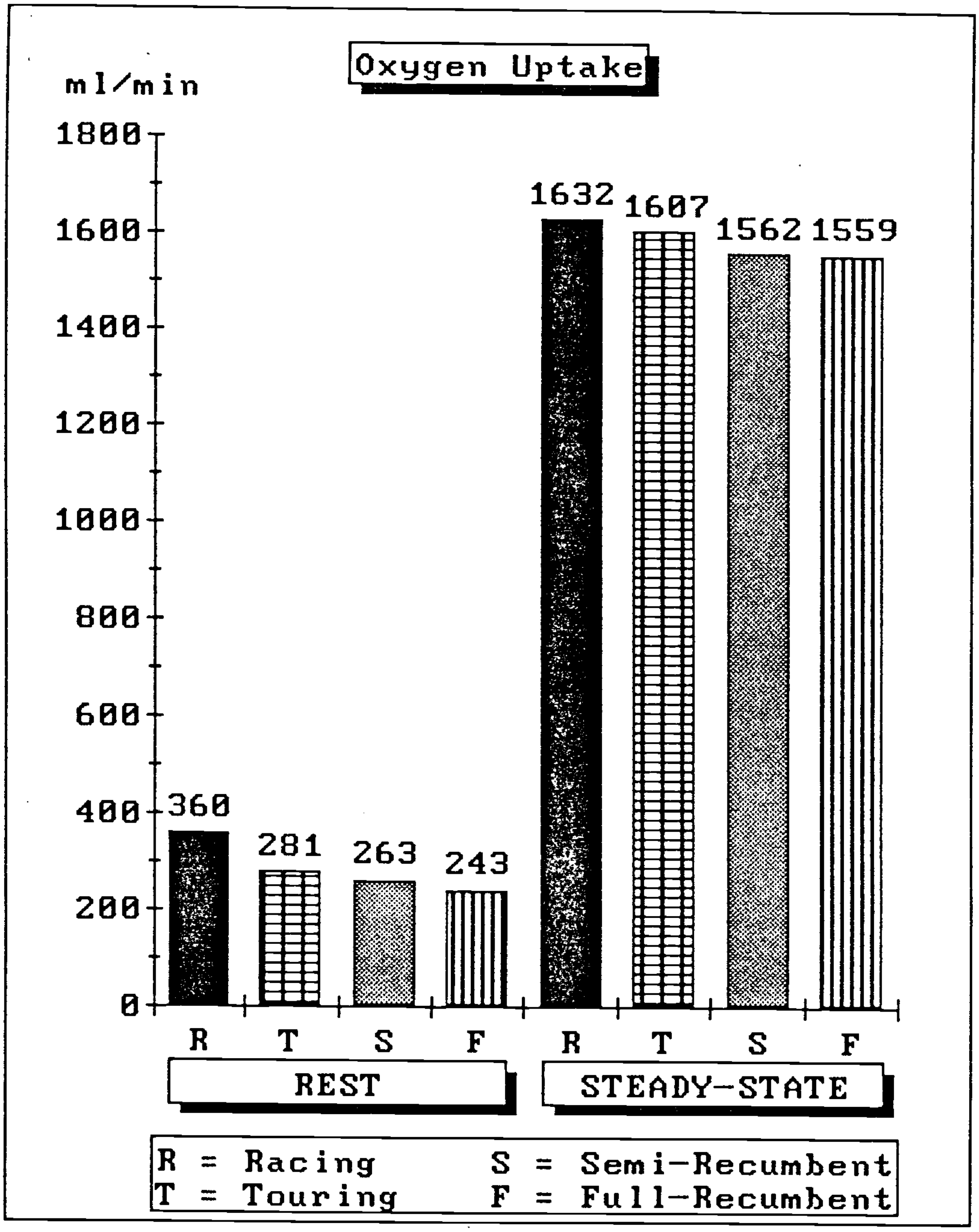

Figure 7. Average values of oxygen uptake at rest and steady-state.

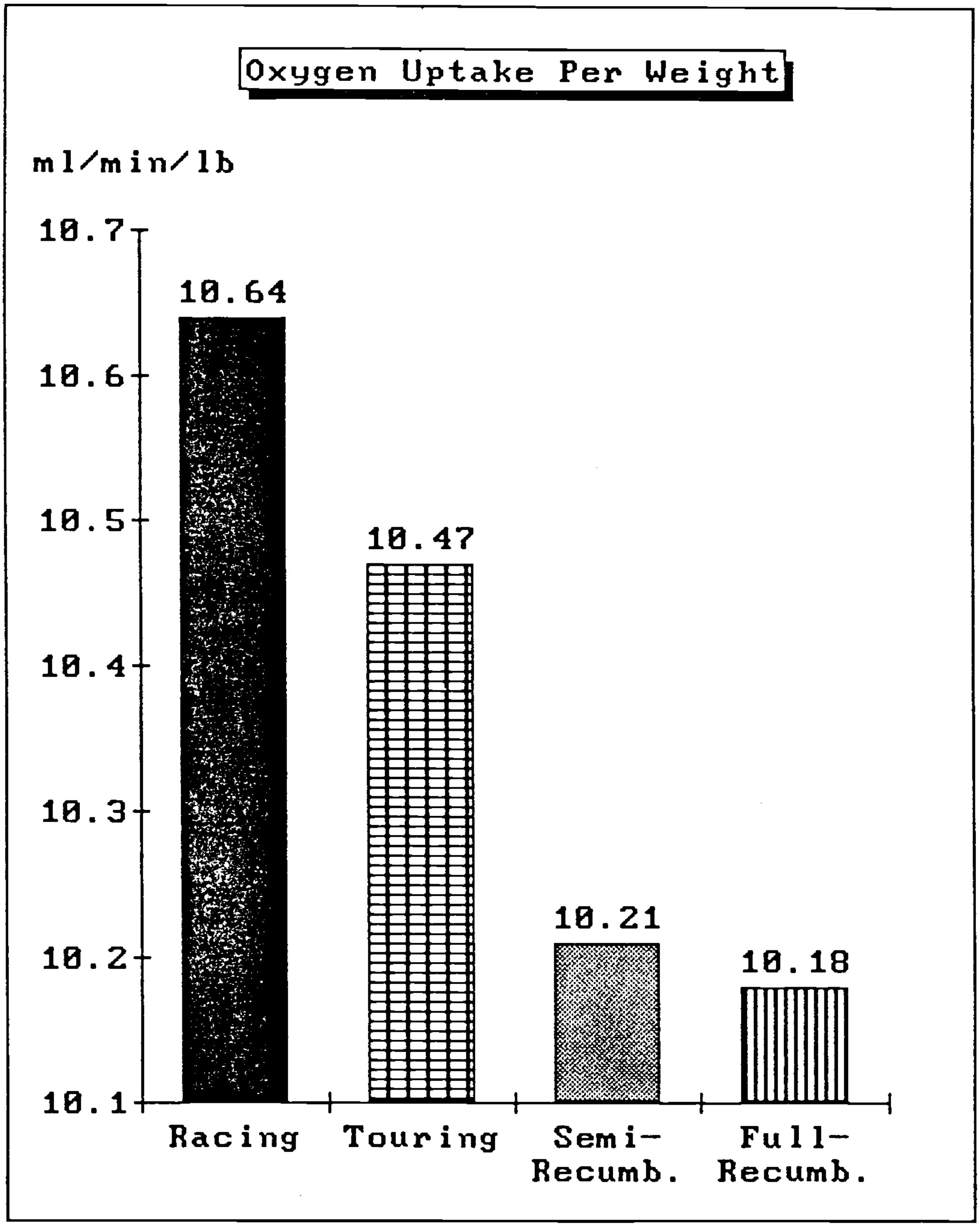

Figure 8. Average values of oxygen uptake per weight at steady-state.

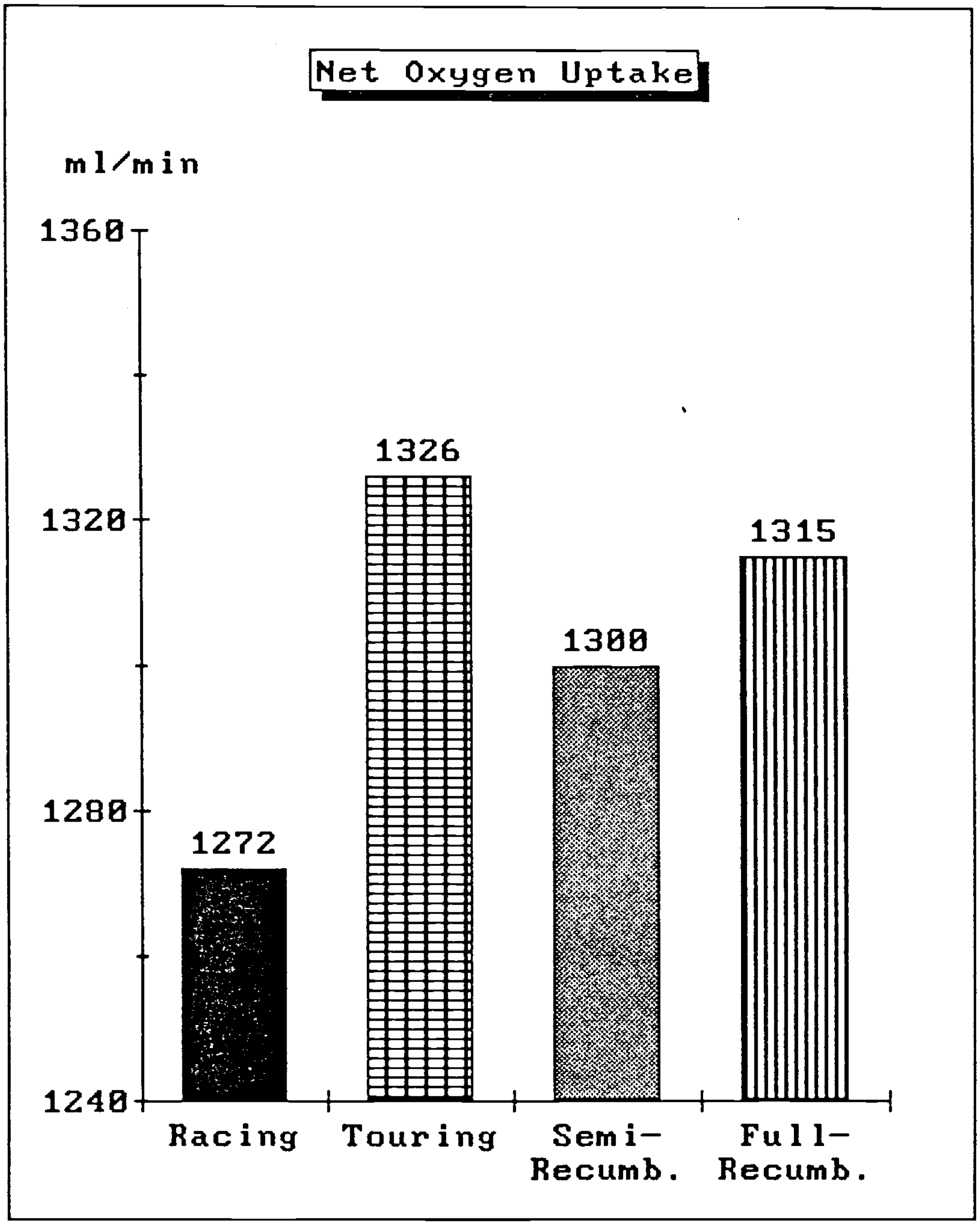

Figure 9. Average values of net oxygen uptake

Heart Rate (beats/min)

Rest

The heart rates during rest, prior to each exercise session, are shown in Table B-11. Subject #1 was supposed to have the lowest resting heart rate due to practicing physical activities more than the others. Apparently he was not comfortable with the mouthpiece which measures the pulmonary variables. His breathing pattern was irregular, often punctuated by deep sighs. The limitation for ventilation seems to have affected him psychologically, which in turn was reflected in his heart rate. The rest of the subjects did not complain as much about the mouthpiece, and their heart rates largely represented their expected heart rates. The average heart rate of subject #6 was the highest (92 beats/min), reflecting his poor body conditioning, whereas that of subject #8 rested at the lowest rate (62.2 beats/min), although both of them are moderate smokers.

So far as the posture effect is concerned, the magnitude of HR in descending order were 87.6 for R, 82.1 for T, 78.3 for S, and 68.0 for F (Figure 10). It is evident that changing the posture from F to R, while at rest, raised the HR by almost 29 percent. The treatment effect turns out to be significant at the 0.05 level of significance, as shown in Table B-12. In order to see the statistical differences among the four postures, Table B-13 is included, showing F to be of greater significance than S, T, and R with respect to HR at rest. Also, S is preferable to R in this regard.

Steady-state

Table B-14 reflects the heart rates of the subjects at steady-state. Subject #1 reflected the best performance, reaching an average of only 116.0 beats/min. In contrast to his HR at rest, it would seem that concentration on the exercise alleviated the psychological irritation caused by the mouthpiece. Therefore, steady-state condition may reveal the physical fitness of the subjects in a more representative manner than heart rate at rest. Accordingly, subject #6 was judged to have a low state of conditioning when his average HR reached 173.1 beats/min.

The effect of riding posture on heart rates was significant (Table B-15) at $\alpha = .05$. The average difference between the highest HR (150.3 for R) and the lowest (140.8 for S) amounts to 10 beats/min (Figure 10). On the scale of maximum heart rates (Table B-1), the S heart rate is only 72 percent of max HR, while R reaches 77 percent of max HR.

The single degree of freedom test in Table B-16 testifies to the fact that R is inferior to the rest of the postures with respect to HR. It should be noted that lower heart rates during any activity are extremely desirable for both trained and untrained individuals. However, for a certain workload exercise, "a relatively slow heart rate, coupled with a relatively large stroke volume, indicates an efficient circulatory system. This is true because, for a given cardiac output, the heart does not beat as fast" (Fox & Mathews, 1981, p. 233).

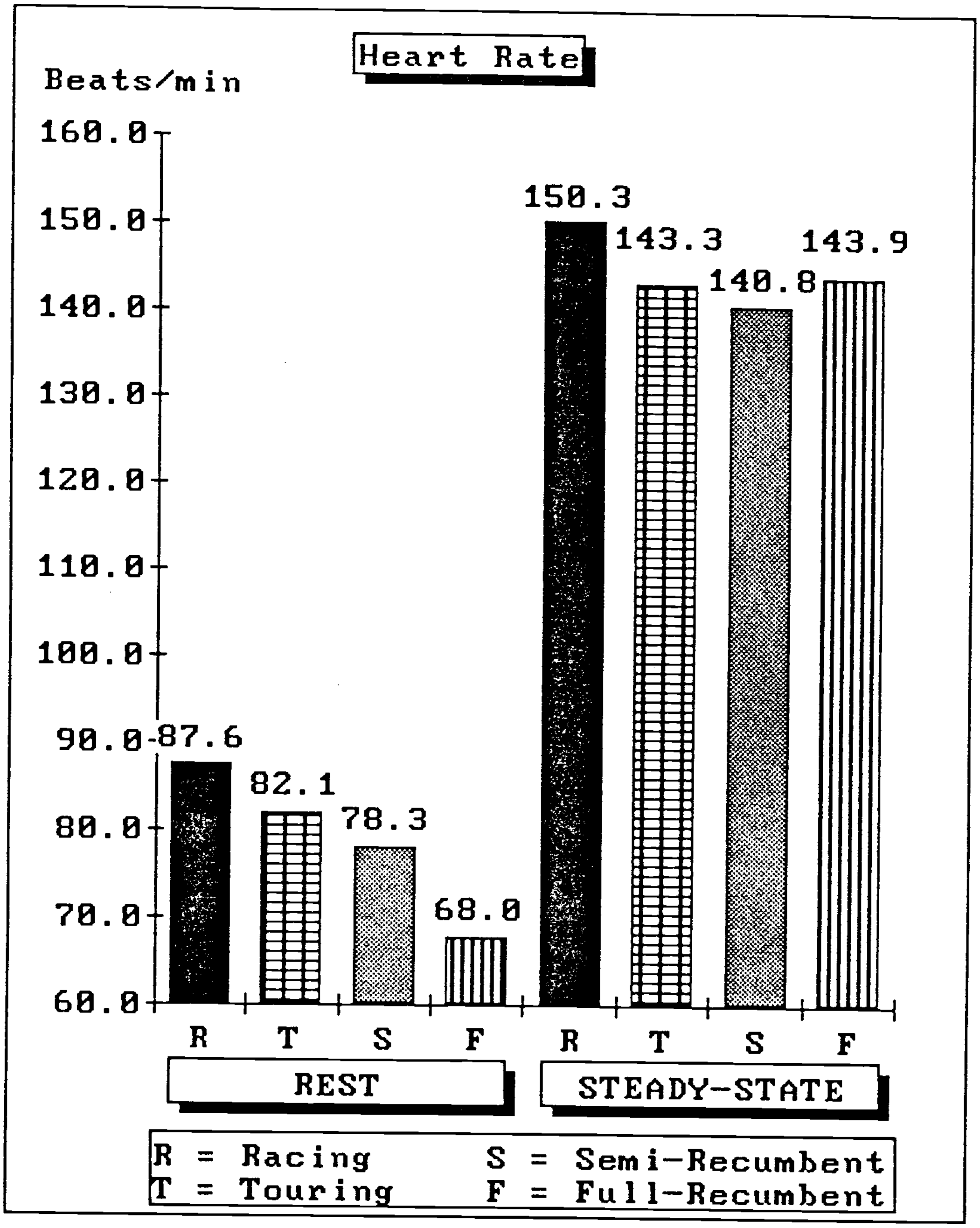

Figure 10. Average values of heart rate at rest and steady-state.

Stroke Volume (ml of blood/beat)

Rest

Stroke volume (SV) magnitudes are listed in Table B-17. The largest SV at rest (100 ml/beat) belongs to subject #5 who consistently reflected higher values for all of the postures. This feature is an indication of a healthy heart, because trained individuals have resting SV ranging between 100 and 120 ml/beat (Fox & Mathews, 1981, p.232).

As shown from the mean SV values in Figure 11, it is noted that the average value at F is the highest (70 ml/beat) because the body is in a horizontal posture. Consequently, the blood does not encounter gravity resistance throughout its return to the heart and blood pooling in the extremities is minimal, paving the way for a substantial blood return to the heart during the diastole stroke. This, in effect, allows more blood to be ejected to the body (i.e., more SV) during the systole stroke.

The touring posture could be described as a non-erect standing posture where blood accumulation in the limbs is inevitable. In fact, this phenomenon is clear in thin persons whose blood veins inflate when the limb is below the heart muscle level. A value of 58 ml/beat for T is not unreasonable. The semi-recumbent posture (S) borrows the torso position from T and the position of the legs from F and its SV value (62 ml/beat) fits nicely between the two other postures. However, the resting SV average for R matches that of F, reaching 69 ml/beat. The reason for the relative increase over SV averages at T and S could be that more working muscles are recruited in the back and arms to stabilize the body on the ergometer, in addition to using the neck muscles to hold up the head. The stress on the arm muscles may be visually noticed and this is confirmed wherein R consumes more oxygen (Table B-2) and elicits more heart beats (Table B-11) than the other postures. Therefore, the muscles used in posture R requires more blood transportation at rest, which is reflected in the SV and HR values and consequently more oxygen is metabolized. This point is confirmed in a study (cited in Stenberg et al., 1967), where static arm work (holding weights in elevated arms) was added to dynamic (bicycle ergometer) work and an increase in Vo_2 and HR was noticed. Regarding the current study, it would seem that the relative increase in Vo_2 and HR at steady-state are partially explained by these findings. The significant increase in ventilated air at R, when compared with the other postures (which will be discussed subsequently in this chapter), also contributes to the increase in Vo_2 because the respiratory muscles have to work harder, thereby consuming more oxygen.

Fox and Mathews (1981) stated that the respiratory muscles consume 1 to 2 percent of total oxygen consumption at rest. The consumption percentage increases to a range of 8 to 10 at heavy exercise (p. 197). The given work rate in this study could be classified as an optimal heavy exercise according to the classifications given by Fox and Mathews (p. 75).

The treatment effect turned out to be insignificant (Table B-18), probably due to subject differences, and this of course undermines the detection of the treatment effect.

Steady-state

SV values at steady-state are shown in Table B-19. The effect of gravity on R and T are evident where matchable values of 117 and 116 ml/beat, on the average, were attained, compared to 129 and 128 ml/beat for S and F, respectively (Figure 11). The similarity of leg positions in S and F and the backward tilt of the back in S helped to produce the nearly equivalent average SV values of these two postures. The difference in SV between the regular and recumbent postures exceeds 12 ml/beat. This would seem significant, but the ANOVA test (Table B-20) did not reveal any statistical significance. These SV values should be considered maximal because normally the stroke volume level reaches its maximum at a work rate requiring 40 percent of max Vo_2 or more for trained or untrained males or females (Fox & Mathews, 1981, p. 232). Therefore, the insignificant results of SV at steady-state were not unexpected.

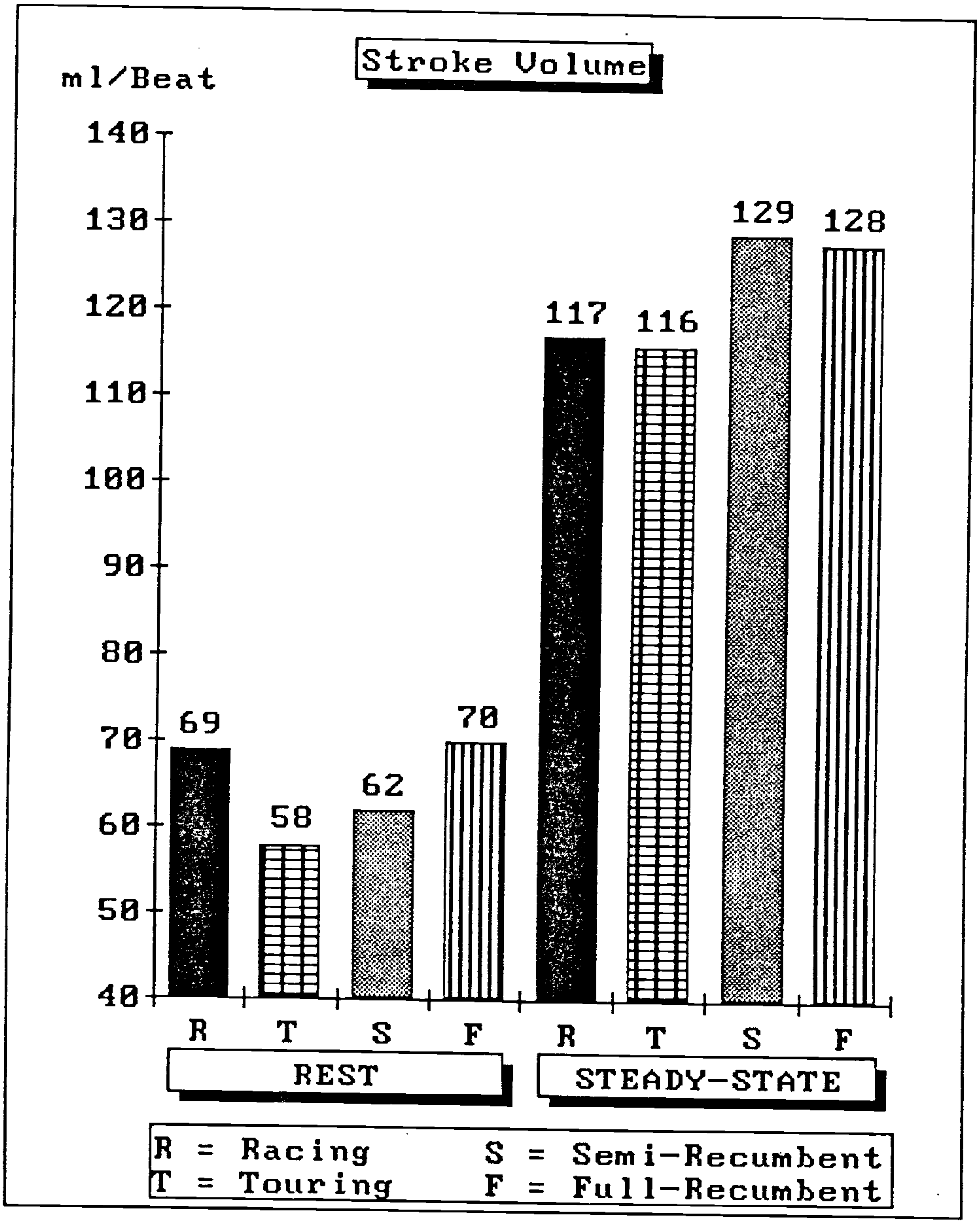

Figure 11. Average values of stroke volume at rest and steady-state.

Cardiac Output (ml blood/min)

Rest

Table B-21 shows cardiac output (Q) values for the subjects at rest. The average Q values for T, S, and F are exactly the same, 4.7 ml/min (Figure 12). It is not surprising to see the average Q value for R (5.9 ml/min) higher than the others, given the HR (see Table B-11) and a high SV average (see Table B-17) for the R posture (Note: Q = HR $\times$ SV) (Fox & Mathews, 1981, p. 232). However, with regard to the other postures both elements composing cardiac output varied in order to coincidentally bring about the exact value 4.7 ml/min. Table B-22 demonstrates a significant difference between R and the rest of the postures with respect to Q at rest, based on α = .05. The single degree of freedom test reveals that R is significantly different from the remaining positions with regard to Q at rest.

Steady-state

Data points for Q at steady-state are presented in Table B-24 and mean values are displayed in Figure 12. No appreciable statistical difference was displayed among the different postures (α = .05) having Q at steady-state as the variable. Although there is almost a 2 l/min difference between T and F, the ANOVA failed to signify it. As shown in Table B-25, subject differences are significant, but not to the point where treatment difference are concealed. So it may well be stated that all of the postures require a certain blood rate at the same workload and speed of pedaling.

With the assumption in view that each liter of blood transported to the working muscles per minute contains a certain percentage of oxygen, why don't the average Q values (Table B-24) correspond to the average Vo_2 values (Table B-5)? The answer to this question is revealed by the introduction of a variable, $(a\text{-}v)O_2$ difference, in ml O_2/l blood. This variable represents the difference in the blood content of oxygen between the arterial and venous systems. The values of $(a\text{-}v)O_2$ difference are calculated from $Vo_2 = Q \times (a\text{-}v)O_2$ difference (Fox & Mathews, 1981, p. 237), where the only unknown is the last term.

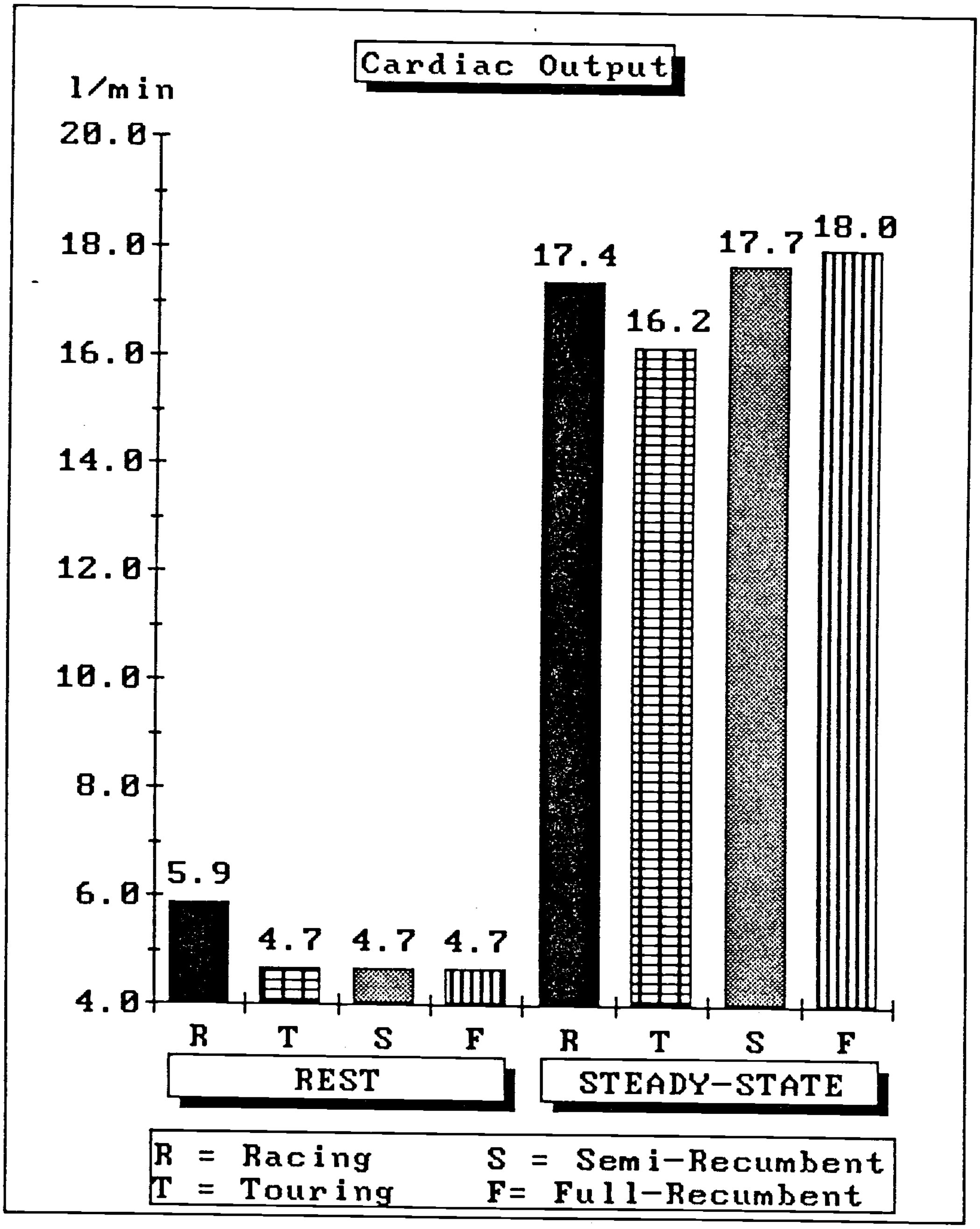

Figure 12. Average values of cardiac output at rest and steady-state.

$(a-v)O_2$ Difference (ml O_2/l blood)

Rest

The artivenous oxygen difference values were computed according to the equation mentioned above and listed in Table B-26 and Table B-28, respectively, at rest and steady-state. It is noted that the $(a-v)O_2$ difference value at F is the least (Figure 13) because at this posture Q is the largest (Table B-21) and Vo_2 is the least (Table B-2). This result does not seem to be a coincidence, since relaxation is naturally sought by lying down, a position manifested in the sleeping posture. Therefore, the muscle cells extract the least amount of oxygen from the blood, i.e., the least $(a-v)O_2$ difference value. Unfortunately, the difference was not significant at $\alpha = .05$ (table B-27).

Steady-state

The same point made for the rest condition could be projected for the steady-state condition, where the $(a-v)O_2$ difference value is 88.9 ml O_2/l blood at F (Figure 13). The other extreme is the higher $(a-v)O_2$ difference value of T, 105.4 ml O_2/l blood, where the body is almost upright. Most of the physical activities in our daily life are accomplished at standing or close to standing postures (e.g., the touring posture). The skeletal muscles must utilize the oxygen transported by blood as much as possible. Therefore, they seem to be designed to have more $(a-v)O_2$ difference values at upright as opposed to a recumbent posture. The values of the R and S postures are comparable at 97.7 and 96.1 ml O_2/l blood, respectively. Again, subject variations may have blocked statistically significant results at $\alpha = .05$ (Table B-29).

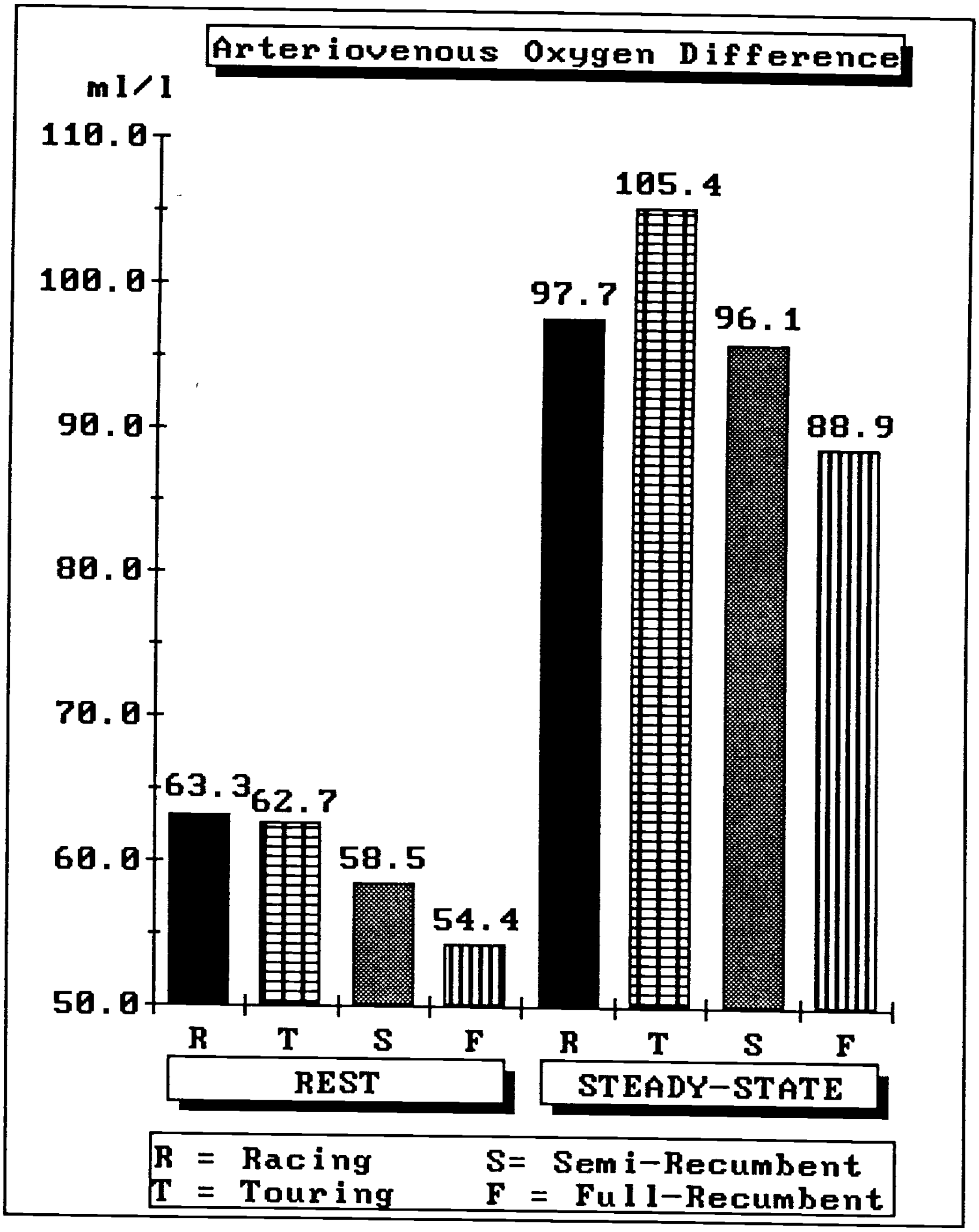

Figure 13. Average values of $(a\text{-}v)O_2$ diff at rest and steady-state.

Ventilation (l air/min)

Rest

The exhaled air volume per minute (V_E) at rest is shown in Table B-30. The largest volume of 13.9 l/min is reflected by the posture R, followed by 11.5 l/min for T, 10.5 l/min for both S and F postures (Figure 14). The average V_E values for each subject are proportional to their body weight, which is in conformance with Fox and Mathews point (1981, p. 184). Despite subject differences, ranging from 15.6 l/min for subject #1 to 9.5 l/min for subject #7, significant results emerged among the postures used (Table B-31). Table B-32 is a summary of the single degree analysis for V_E at rest, showing the racing posture elicits a significant increase of V_E at rest. This seems to be facilitated by larger thorax cavity as indicated by larger chest circumference than in the rest of the postures (Table B-1). The racing posture has the advantage of relieving the weight of the arms and shoulder girdle from the thorax. "This reduced weight plus the suspended chest appears to ease chest expansion thereby enhancing pulmonary ventilation potential" (Faria et al., 1978).

Steady-state

The ventilated air at steady-state is listed in Table B-33. The higher values attributed to R were repeated, reaching an average of 53.0 l/min, which stands in contrast to the lowest V_E values maintained at S, 45.9 l/min (Figure 14). The difference between the two postures amounts to 7 liters of air exhaled or inhaled each minute. The ANOVA measures a significant statistical difference among the postures at $\alpha = .05$ despite the highly significant differences between the subjects. The higher V_E at R may be attributed to more Vo_2 requirement (Table B-5) to overcome the given 90 watts load since it is well established that a linear relationship exists between Vo_2 and V_E at submaximal exercises (Fox & Mathews, 1981, p. 185). Consequently, the increase in V_E at R requires more Vo_2 for the respiratory muscles. The advantage of chest expansion disappears at steady-state since TV means at R and T are almost equivalent (Table B-43).

The mean V_E values vary from 67.9 l/min (#4) to 40.3 l/min (#8). Although V_E values should correspond to body size, the training level of subjects lowers ventilatory response to exercise. The physiological reasons for this are not entirely known, but genetic and familial influences have been suggested (Fox & Mathews, 1981, p. 185).

The single degree of freedom analysis shown in Table B-35 differentiates between T vs R, R vs S, and S vs F. To fully appreciate these differences the components of V_E should be explored, i.e., the respiratory rate in breaths/min (RR) and the tidal volume in l/breath (TV). The relationship between these three variables is obvious from unit conversions, i.e. $V_E = RR \times TV$ (Fox & Mathews, 1981, p. 184).

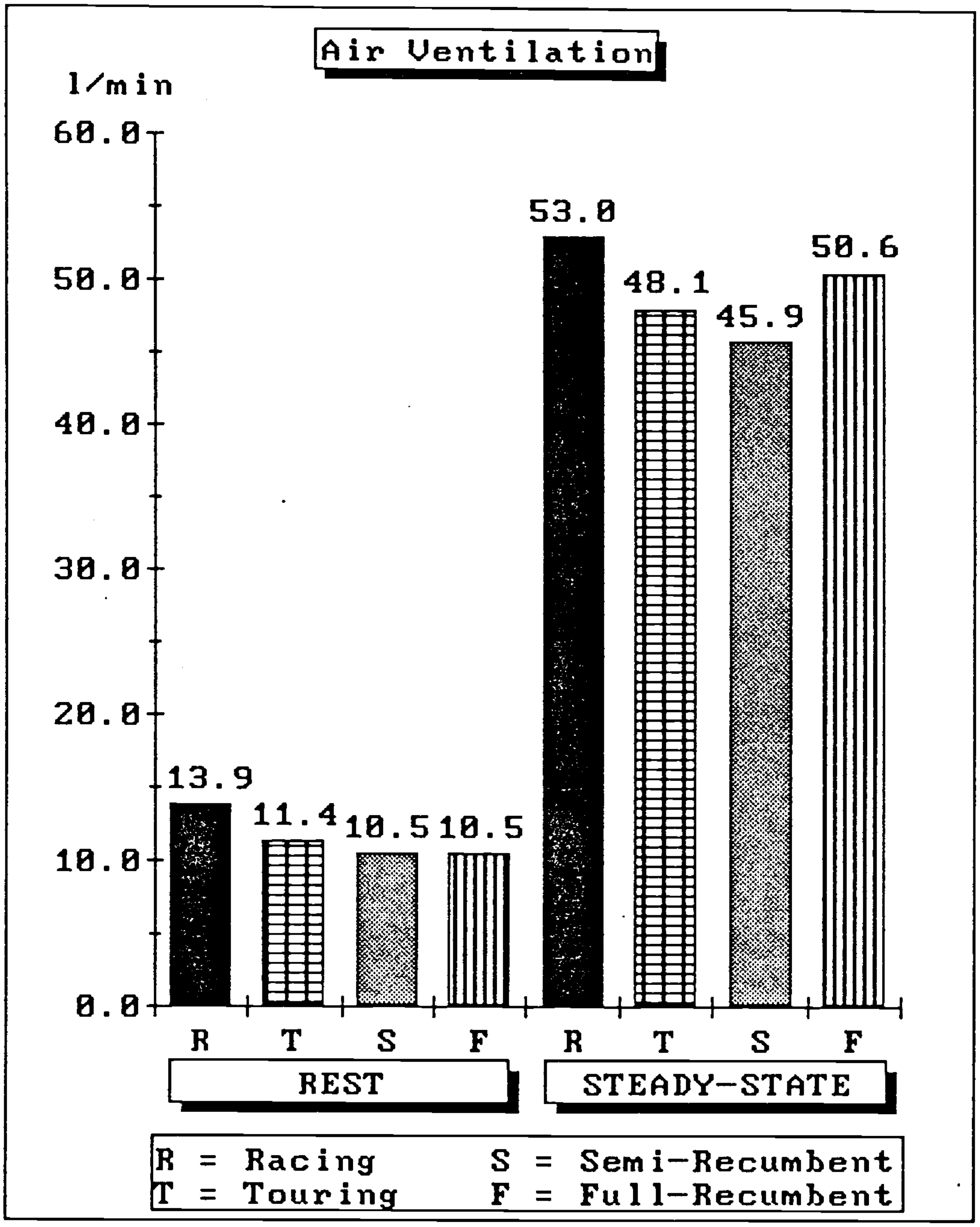

Figure 14. Average values of air ventilation at rest and steady-state.

Respiratory Rate (breaths/min)

Rest

The respiratory rate (RR) magnitudes are presented in Table B-36. The average breathing rate at the posture R (19.2 breaths/min) was a factor in boosting the V_E, compared to, respectively, 18.1, 17.6, and 16.8 for T, S, and F postures (Figure 15). Therefore, there are almost 2.5 breaths/min increase in RR by just changing the posture at rest from F to R. Subject variations were significant (Table B-37), ranging from 21.9 for subject #5 to 12.4 for subject #1, making it difficult to detect treatment effect differences.

Steady-state

The data shown in Table B-38 does not follow the same trend established for the rest condition. In contrast, RR values for R and F postures are roughly equivalent (36.8 and 36.2 breath/min, respectively) and they are higher than those for T and S (Figure 15).

As far as the subjects are concerned the wide range in RR was mainly caused by subject #4, who respired at a rate of 47.7 breaths/min, almost 20 breaths/min more than subjects #7 and #8. Incidentally, he inspired the largest average volume, 67.9 l/min, compared to 40.3 l/min for subject #8

(Table B-33). However, it would seem that subject #4 should not need all that much air for the particular exercises given, since his Vo_2/weight average fits correctly within the range of the other subjects' ratios. Therefore, the increase RR average experienced by subject #4 is a reflection of his low physical condition, indicated in Table B-1. This subject was definitely uncomfortable at the R posture, to the point that he repeatedly gestured to learn what time had expired. His V_E value at R was a staggering 83.5 breaths/min, substantially exceeding that of all the other entries in the table. Relatively high average V_E, HR and Vo_2, coupled with a lower SV average, links subject #4 to the low conditional category (Fox & Mathews, 1981, p. 231, p. 185). The wide range between subjects (19.0 l/min) may conceal the effect of posture on RR at steady-state (Table B-39).

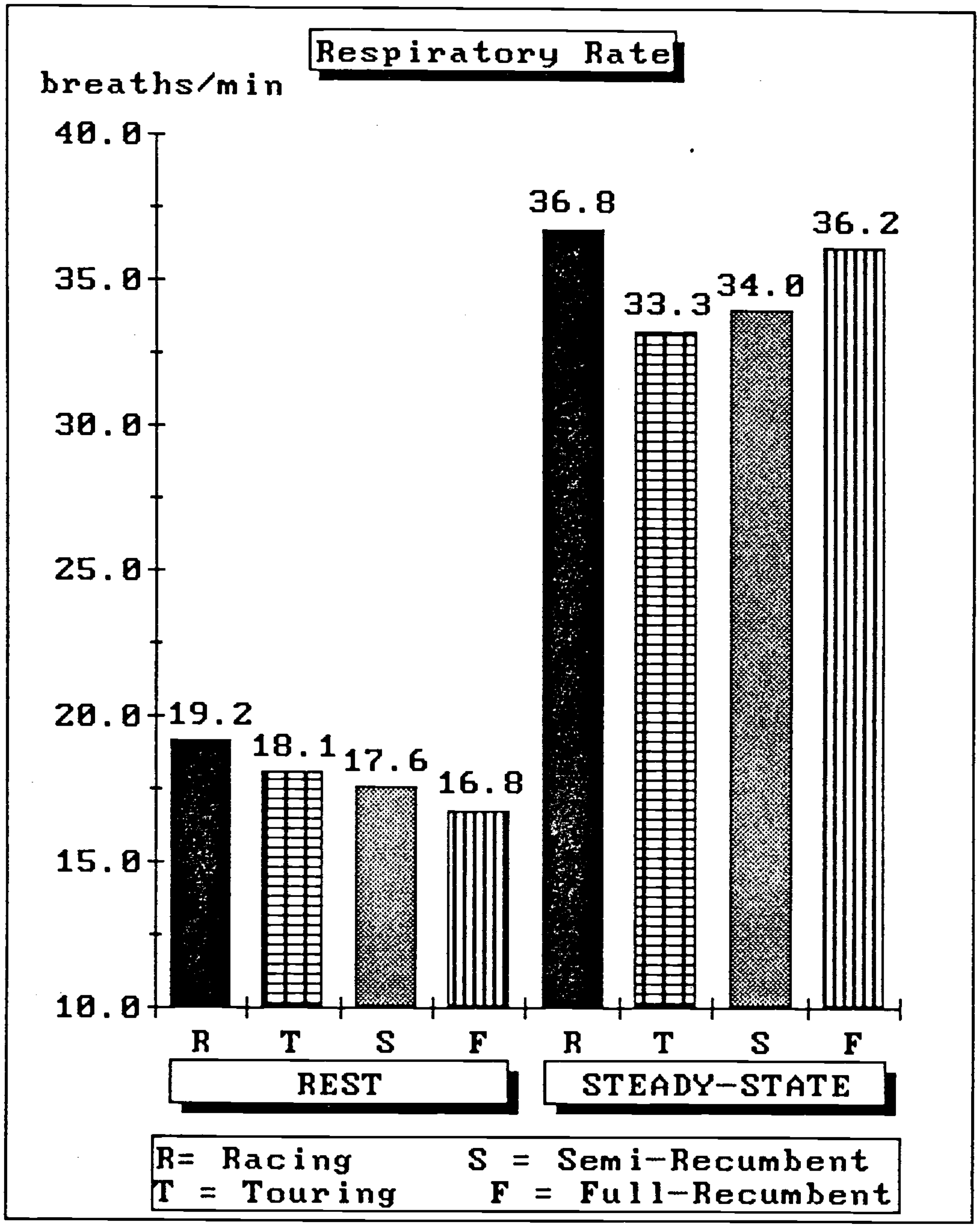

Figure 15. Average values of respiratory rate at rest and steady-state.

Tidal Volume (l air/breaths)

Rest

The average tidal volume (TV) at the R posture plays a major role in increasing V_E at rest. Table B-40 and Figure 16 indicate that almost 100 ml air/breaths more are respired in R than for the rest of the postures, which maintained an average value of 680 ml/breaths. This difference is significant at $\alpha = .05$ (Table B-41), despite the TV differences among subjects. The latter effect was mainly attributable to subject #1, who often sighed deeply at rest, even without the hose attachment, causing his average TV to be more than double that of the overall TV.

The single degree of freedom test projects R as more significant than every other posture with regard to TV at rest.

Steady-state

The average TV values at R and T are equivalent (1.47 and 1.48 l/min, respectively, see Table B-43 and Figure 16), indicating that the size of the chest was a limitation for even a higher TV average and the fulfillment of larger air demand came from an increase in RR (36.8 and 33.3 breaths/min). On the other hand the average TV value at S was the least, reaching only 1.38 l/min. This result, however, was not at the expense of RR, which reached a moderate value at 34.0 breaths/min. All subjects expressed satisfaction while exercising at this posture, which in many respects resembles the posture of driving or riding in an automobile.

As expected, subject #1 had the highest TV average value (1.67 l/breaths), corresponding to his large average chest size. However, the second highest TV value (1.58) belonged to subject #3, whose chest size was among the smallest. Although chest circumference is proportional to TV at rest, it cannot be projected to steady-state TV values. Therefore, a good reflection of TV values may be associated with chest circumference and the longitudinal dimension of the chest as well. However, it is very difficult to measure either dimension while the subjects are exercising.

The low extreme in TV values was registered by subject #6 who unintentionally depends on RR to provide him with the required V_E value. The ANOVA results show insignificant differences ($\alpha = .05$) among TV values at steady-state (Table B-44).

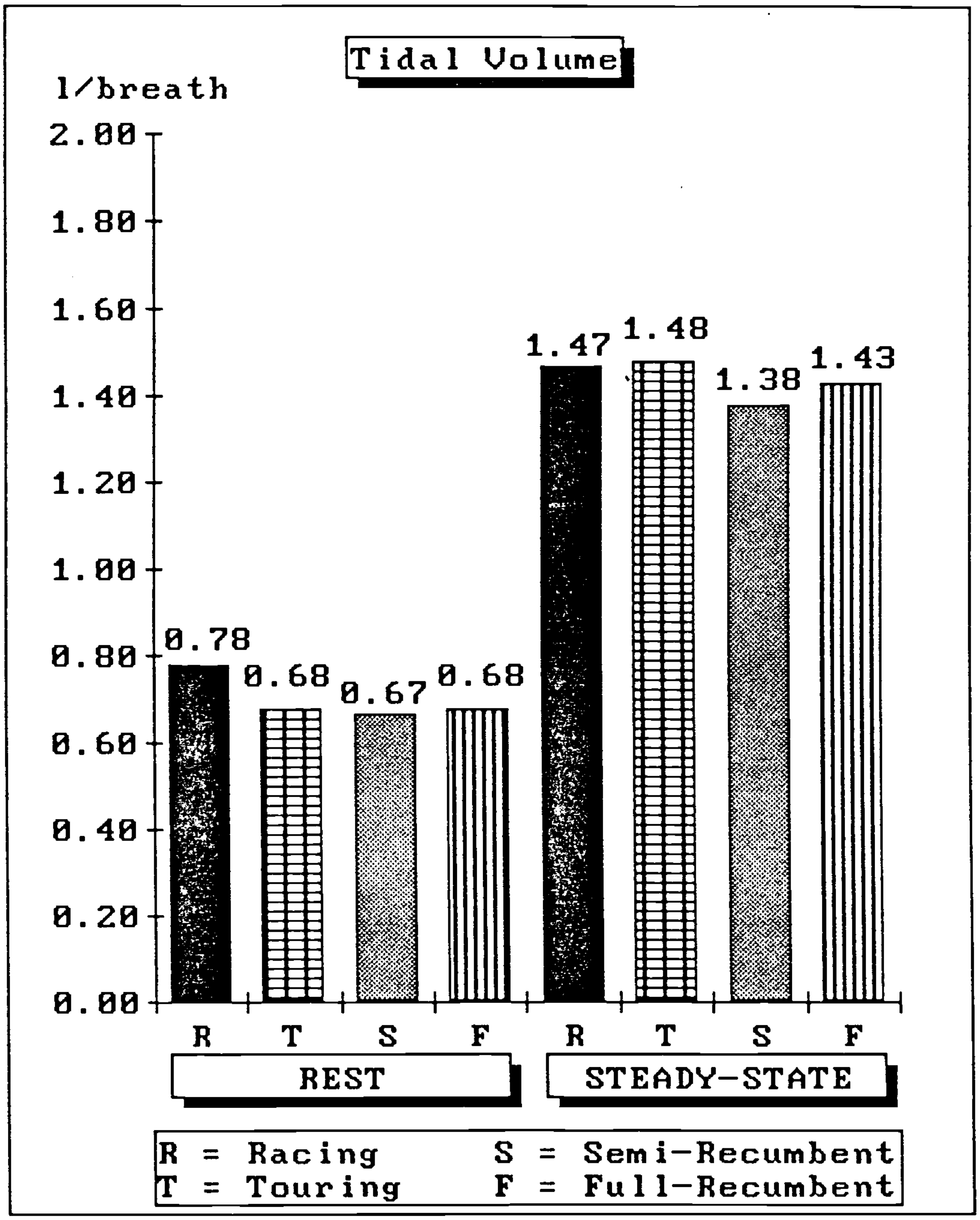

Figure 16. Average values of tidal volume at rest and steady-state.

Caloric Equivalence of Oxygen (kcal/min)

"The caloric value of 1 liter of oxygen consumed depends on which type of food is being metabolized" (Fox & Mathews, 1981, p. 60). The Respiratory Exchange Ratio (RER) is the ratio of the volume of carbon dioxide expired per minute (Vco_2) to the volume of oxygen consumed during the same time interval. A value close to 1 for RER, which in almost all instances persisted among the subjects, means that most of the foods metabolized were carbohydrates, whereas a value close to 0.70 would indicate that fat is being oxidized (p. 61). The caloric equivalence of the oxygen consumed (E_c) is presented in Table B-45. In many instances the RER value exceeded unity for the subjects, apparently because of psychological stress which resulted in excessive carbon dioxide loss. This problem was overcome by rounding off the RER value to one, which is a tactic customarily adopted by physiologists (p. 62).

The data points for E_c are summarized in Tables B-46 and B-49, respectively, at rest and steady-state. The outcomes of the ANOVA tests (Tables B-47 and B-50) duplicate the results obtained from Vo_2 statistical analysis. The treatment effect at rest is significant where it is indicated that the R posture consumes a significantly higher amount of calories than the rest of the postures (Table B-48), but no statistical significance is displayed at steady-state condition.

Although these results were anticipated, the computation of E_c, both at rest and steady-state, provides awareness about the calorie expenditures. For example, a person lying on his back consumes on the average 1.2 kcal/min, while when seated on a chair the amount increases to about 1.3 kcal/min if body weight is around 155 lbs (Figure 17). In other words a supine male person consumes 7.7 cal/min/lb and around 8.4 cal/min/lb seated at a desk. For commuting cyclists the energy expenditure at 15 mph would be 8.221 kcal/min at R, 8.078 kcal/min at T, and 7.868 kcal/mi at S (Figure 17). On the average, a value of 8 kcal/min should be expended, regardless of the cycling posture. However, the total resistance facing the cyclist and his vehicle vary from one posture to another, depending on the total frontal area, the coefficient of air drag (whether a streamlined enclosure is used), the number and size of the wheels, and the total weight of this particular man-machine system. At 90 watts, the given workload in this experiment, a rider who normally reaches 15 mph in the racing posture can attain speeds up to 25 mph when using a well-designed streamlined vehicle and riding in the semi-recumbent posture (Malewicki, 1983).

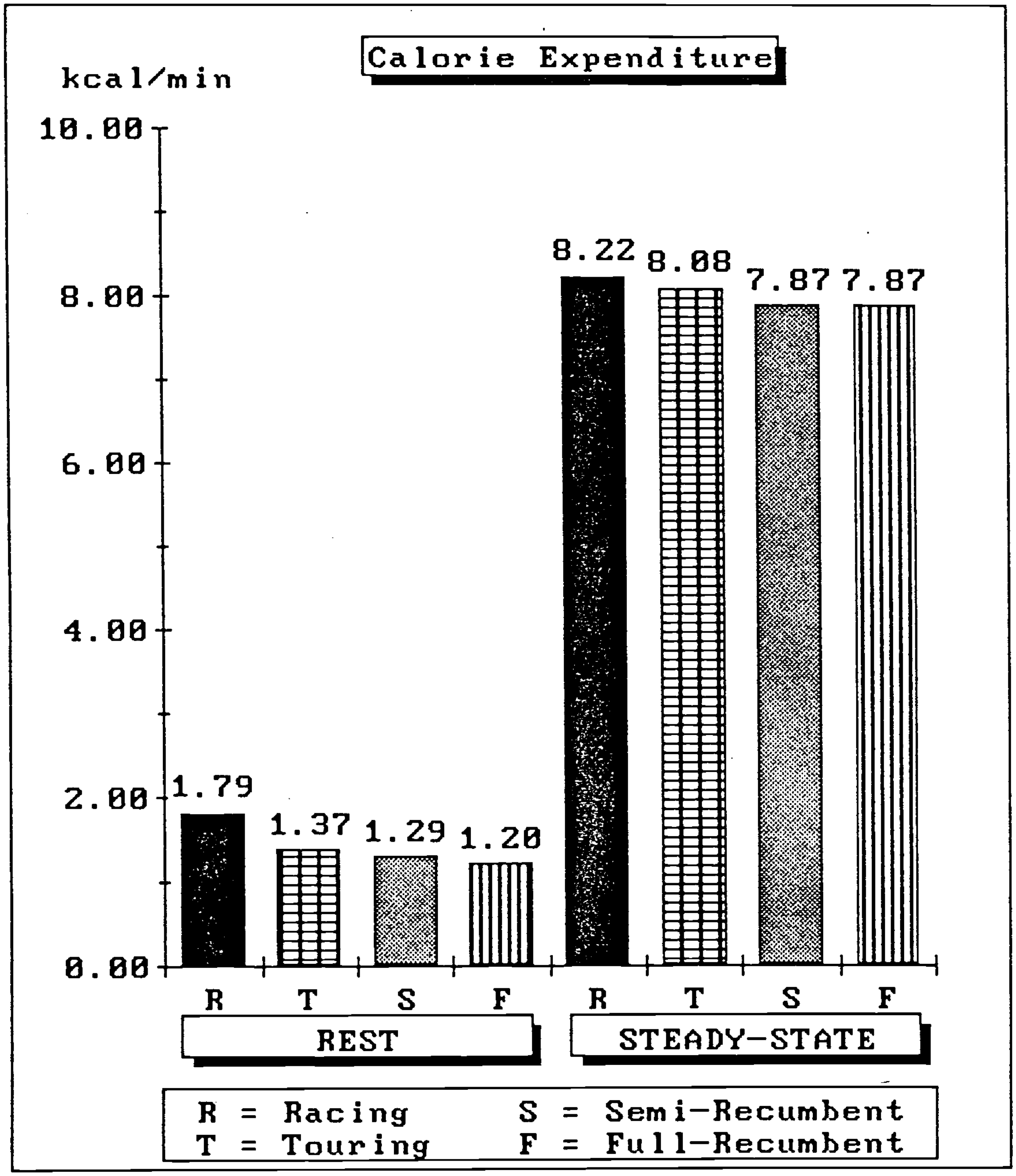

Figure 17. Average values of calorie expenditure at rest and steady-state.

Efficiency

Generally, efficiency is the ratio of output to input for a particular system, whether it's a machine, a factory, or a human body. Two efficiency definitions are considered, each of which has a common output of 90 watts. Net efficiency is based on the net power generated, i.e. calorie consumption at steady-state, minus that at rest in the denominator. Table B-51 places net efficiency between 19 and 20 percent for all postures. However, it is unsurprising that the net efficiency of R is marginally higher than the rest of the averages (Figure 18), since the average resting Vo_2 consumption at R outweighs the other postures.

So far as the subjects were concerned, there was a difference of 5 percent, caused by subject #8 at the top of the range (22.6 percent) and subject #4 at the other extreme (17.5 percent). The difference between individual data points in the table is consistent across all four postures for both subjects. Although subject #4 was in poor physical condition, which may have partially have caused his low efficiency reading, the unintentional movement of his back sideways in order to help him exert the necessary force on the pedal may be attributed the greatest responsibility in increasing his Vo_2 consumption, thereby lowering his net efficiency. Since his Vo_2 consumption at rest was regular (Table B-2), his low efficiency may be attributed to the rocking motion, i.e. if his Vo_2 at rest had been lower than it actually was, then his net efficiency would have been equally as low without the sideways motion. Subject #8 on the other hand performed the experiment with great confidence and calmness, although both subjects were equally lacking in techniques for efficient cycling.

The other definition of efficiency, gross efficiency (Table B-53), ignores the baseline oxygen uptake resulting in an overall average of around 16 percent. This figure is lower than those given in Table B-51, however, such modest average efficiency values should not lead to a negative general impression of cycling. The fact is that gross efficiency reflects the actual performance of the human system, whereas net efficiency is only a partial evaluation of the effort expended. Gross efficiency mean values are shown graphically in Figure 19.

Although net and gross efficiencies were based on the actual calories consumed, where internal food burning is taken into account, the results of the ANOVA are almost a copy of the results obtained for net Vo_2 and Vo_2 at steady-state (Table B-52 and B-54, respectively).

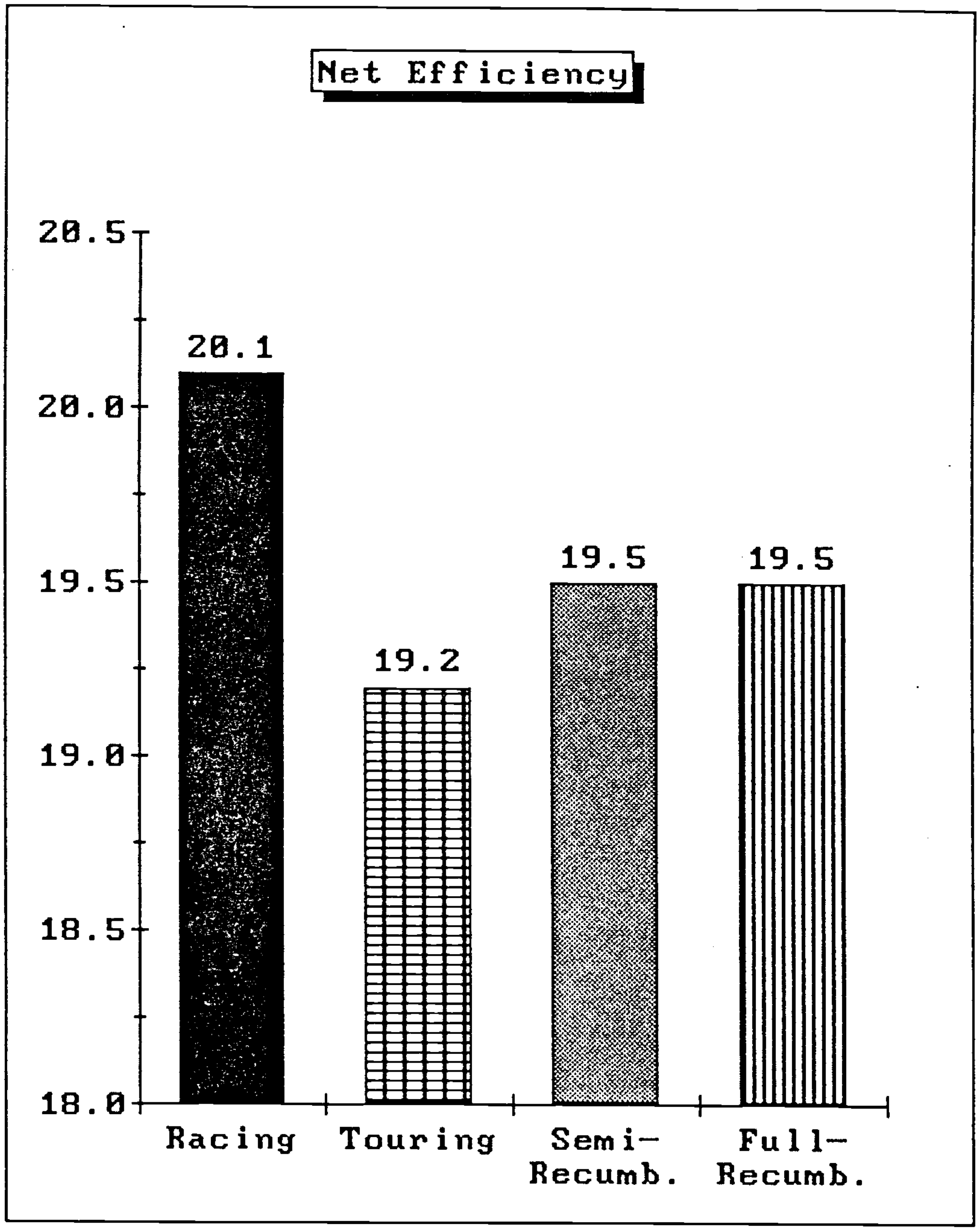

Figure 18. Average values of net efficiency.

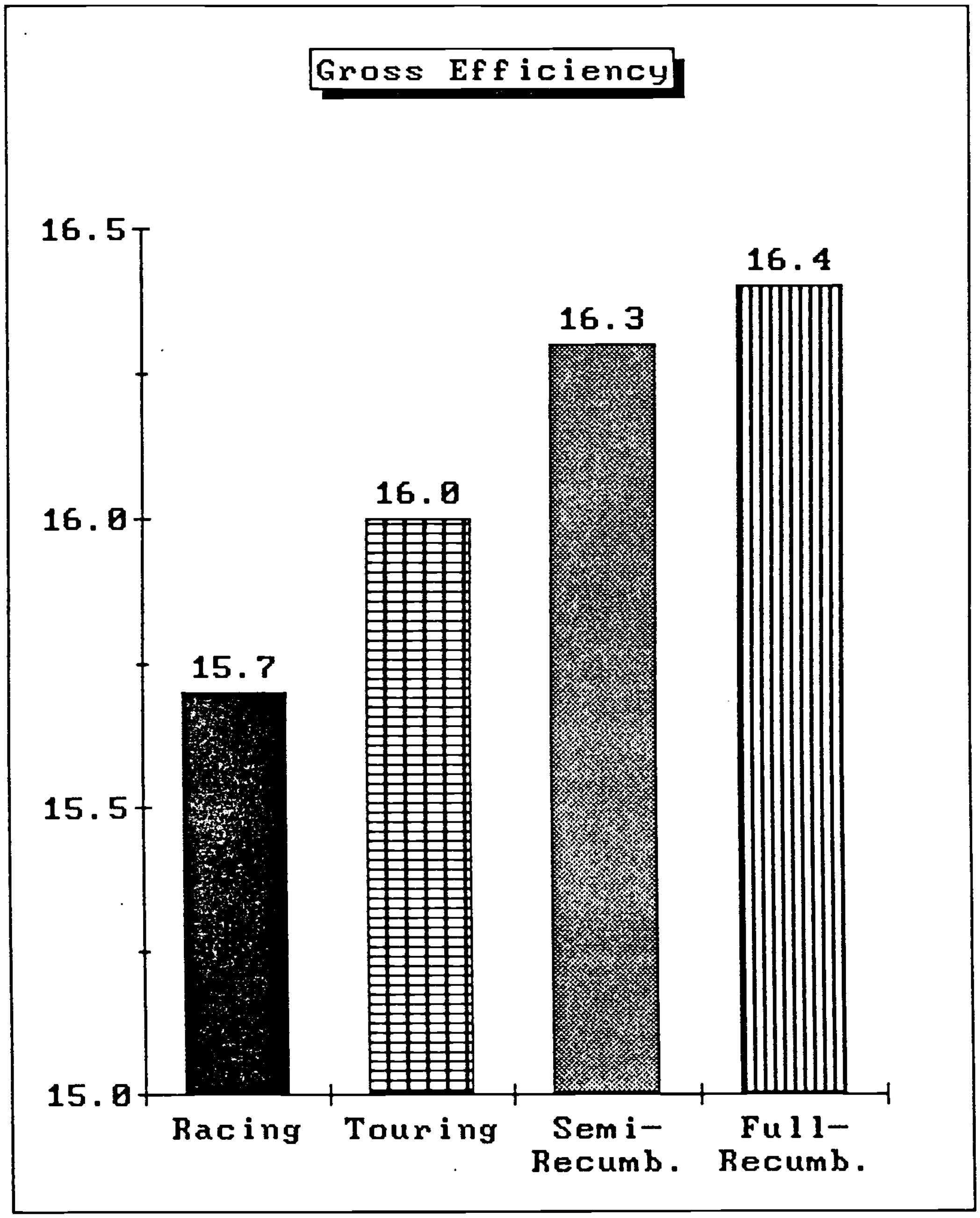

Figure 19. Average values of gross efficiency.

Oxygen Consumption vs Heart Rate

It was assumed that oxygen consumption and heart rate are somehow correlated. In general this is true, but some reservations must be expressed. Table B-55 lists a set of correlation coefficients (r), including this study and other related research. These coefficients were computed from individual performances, covering various subjects, loads, postures, and numbers of subjects, in order to provide a better understanding of the behavior of Vo_2 vs HR. All of the r values became nonsignificant, as deduced from the Z values, indicating a lack of dependence between Vo_2 and HR data points. However, this finding contradicts the common sense assumption that there is a correlation of heart rate and oxygen consumption.

In fact, linear correlation between Vo_2 and HR does exist when additional specifications are attached to such a general statement. Tables B-56 to B-63 contain a summary of individual heart rates and oxygen uptake, with the average of HR and Vo_2 computed across time for all eight subjects and given in the last column of each table. The correlation coefficient between Vo_2 and HR were found to be high with respect to the time of exercise (0.93 at R, 0.96 at T, 0.98 at S, and 0.96 at F). It is concluded that in the transition from rest to a steady-state condition, the beating of the heart and the acquisition of oxygen by the working muscles go hand in hand. Such a correlation is of course intuitive and would seem to be the source of the above-mentioned common sense assumption.

Figures 20, 21, 22, and 23 depict Vo_2 vs HR for each posture. The square symbols in the figures represent the coordinates of the average Vo_2 and HR at a particular time during the 8-minute exercise session. The regression lines fit the average Vo_2 values in accordance with the calculated high correlation coefficients. The parameters of the regressed equations are given in Table B-64.

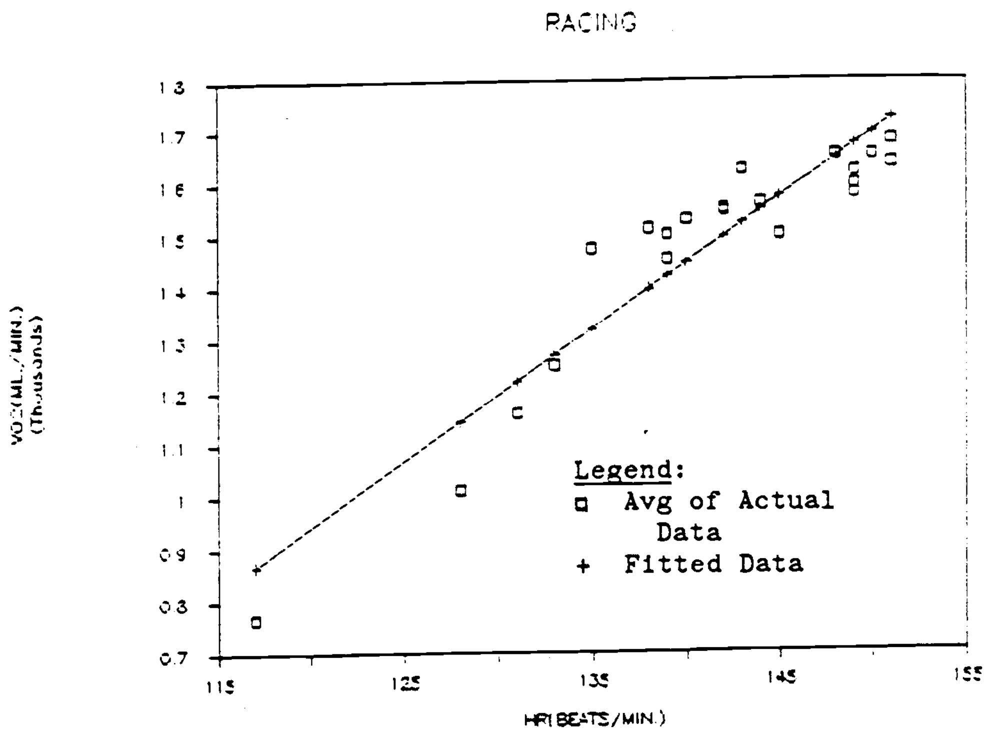

Figure 20. Regression Line of VO_2 vs HR at R Based on Average Data.

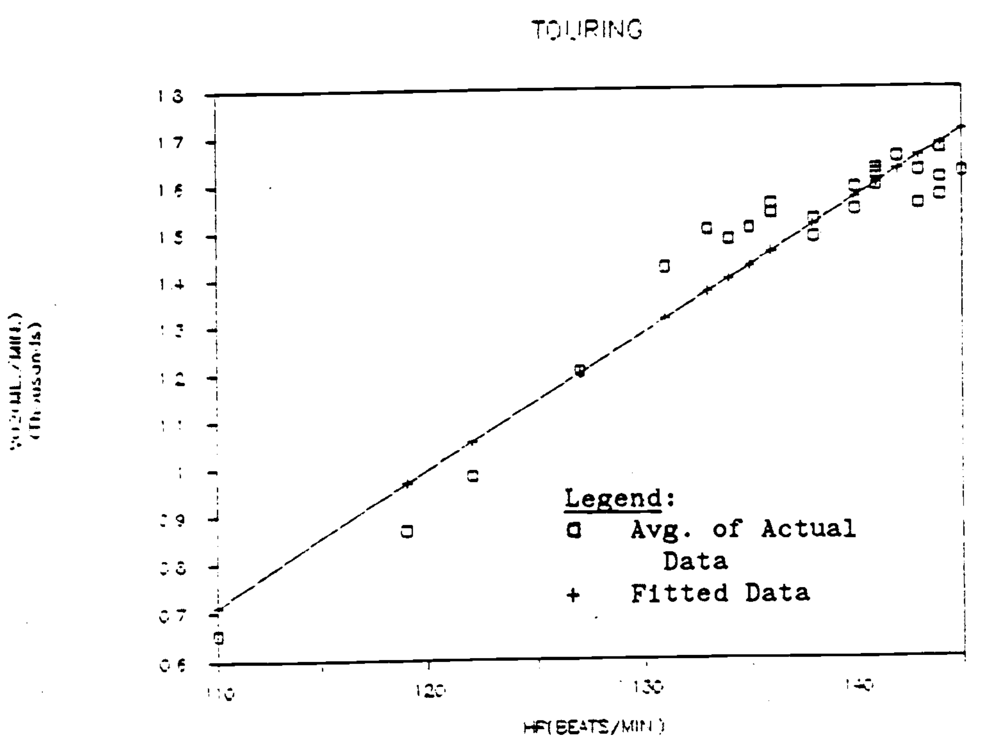

Figure 21. Regression Line of VO_2 vs HR at T Based on Average Data.

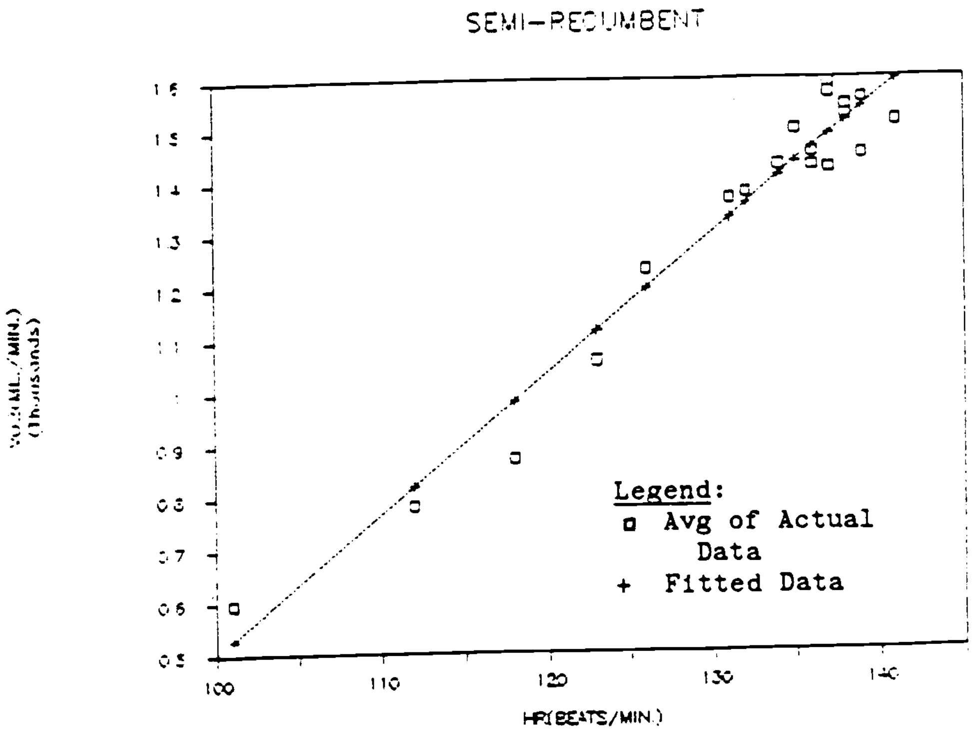

Figure 22. Regression Line of VO_2 vs HR at S Based on Average Data.

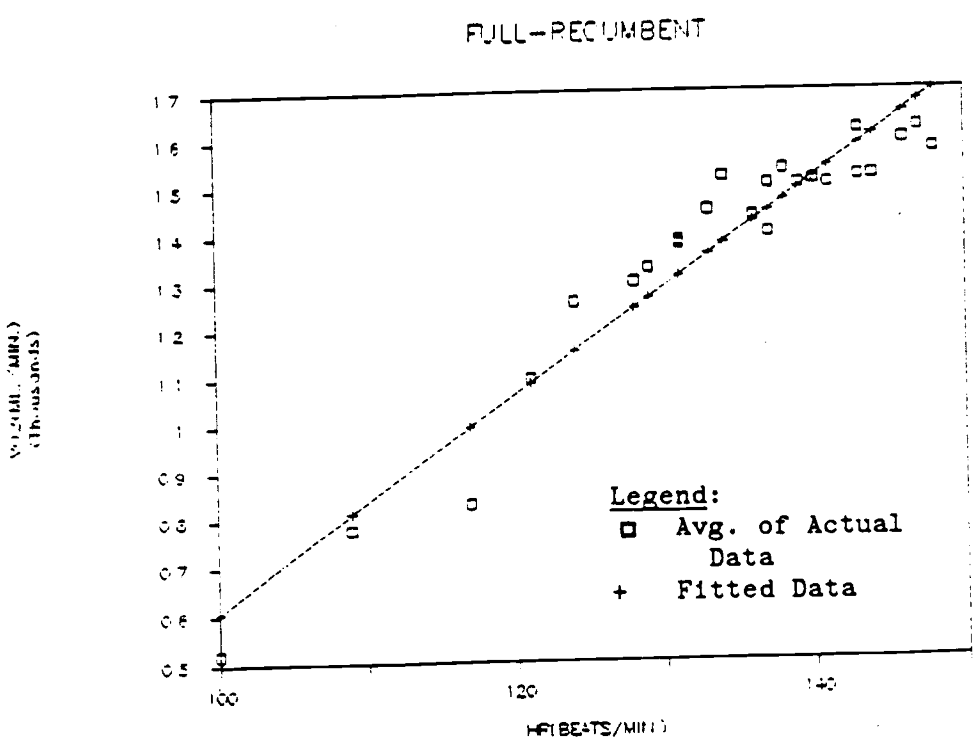

Figure 23. Regression Line of VO_2 vs HR at F Based on Average Data.

Regarding the issue of correlation it is fair to state that Vo_2 and HR are linearly correlated so far as workloads are concerned (Fox & Mathews, 1981, p. 231). In other words, at the different workloads assigned to the subjects, a positive linear relationship exists between Vo_2 and HR in the sense that for every change in Vo_2, there is a corresponding change in HR due to either increasing or decreasing the output work rate given the subjects.

Therefore, determining the correlation between Vo_2 and HR requires specifying the scale on which these variables were considered. As previously discussed, a lack of correlation was displayed on the subject scale, while a high positive correlation was indicated on the time scale as well as the workload scale.

With these findings in view it becomes clear why a significant treatment effect was present on the HR scale (Table B-15) and why an insignificant posture effect was found on the Vo_2 scale (Table B-6). The data points fed into the table cells of the ANOVA tests were individual averages of HR and Vo_2 for a particular workload (90 watts) and a particular time (steady-state). Therefore, the relationship of HR and Vo_2 belongs to the first category of correlations, where a weak relationship exists between HR and Vo_2 as concerns the subjects used (Table B-55). Examining this seemingly contradictory issue from a physiological point of view, the Vo_2 equation [Vo_2 = HR × SV × $(a\text{-}v)O_2$ diff] reveals that factors other than HR make up Vo_2. Training programs reduce the HR level and increase the SV and $(a\text{-}v)O_2$ diff (Fox & Mathews, 1981, p. 231) at the same level of Vo_2 uptake. When these considerations are taken into account, a positive correlation between HR and Vo_2 should not be assumed. Even when the correlation coefficient happens to be significant, based on the scale of the subjects (as done in this study), there would still be room for discrepancy so long as r is less than 1. The reason is that if large positive or negative values of r are observed, it is incorrect to conclude that a change in x will cause a change in y. The only valid conclusion is that a linear trend may exist between x and y. As indicated in Table B-55, based on the individual averages of the well trained athletes, there is not even a consistent trend between HR and Vo_2, not to mention an inconsistency of values (positive and negative) on the part of normal subjects.

It is hoped that these findings have clarified the mystery underlying the differences in significant treatment effect between HR and Vo_2.

Body Weight and Leg Weight

The weight of each leg (LW) was estimated by taking the anthropometric measurements as shown in

Table B-1. The weight of the leg partially helps apply force to the pedal during the down cycle, but the other leg must simultaneously be raised in touring and racing postures. Phrasing this differently, the positive work done by the weight of one leg is canceled by the negative work generated by the other during each complete revolution. This is true irrespective of the force exerted on the pedal by the leg muscles on both sides since the leg weight clearly does not change throughout the cycle.

However, non-cyclists may not coordinate lifting the passive leg during the down stroke with the active leg, which results in an unnecessary burden on the latter leg. "The force necessary to lift does not contribute to the power output. Thus the overall efficiency of the body will be lower" (Hoes et al., 1968). This conjuncture can be verified only by measuring the forces on the pedals and the oxygen consumption.

On the other hand, the weight of the leg is carried back and forth in both the S and F postures in addition to the canceling effect for only about one-quarter of the cycle. In free cycling (no load cycling) it is expected that the physiological costs in the recumbent postures are greater than in the regular postures due to the energy requirement of both the front and back strokes of S and F, whereas the energy required to move the legs in R and S is supplied by the weight of the legs.

A correlation between the weight of both legs for each subject and the oxygen consumption per minute (Vo_2) at steady-state was computed. The coefficients of correlation (r) are not statistically significant, being 0.48 at R, 0.48 at T, 0.41 at S, and 0.27 at F. (The correlation test was taken from Mendenhall et al., 1981.) It would seem that the weak trend found between LW and Vo_2 was not true as regards the the partial weight of the body, but the same kind of trend was repeated for total body weight (W) and Vo_2, where r equals 0.58 at R, 0.55 at T, 0.51 at S, and 0.34 at F. A lack of dependence between W and Vo_2, although r values are close to r critical = +0.62, was not expected.

Malhotra, Ramaswamy, and Ray (1962) found a linear relationship between body weight and energy expenditure during cycling, most apparently in the touring position. Astrand, Astrand, and Stankard (1960) have shown that obese men had higher oxygen intakes than subjects of normal weights. They attributed the cause to the great amount of adipose tissue that is moved when exercising on the ergometer. The subjects of this study are not at all obese. Seemingly what occurs is that some of the subjects repeatedly produced undesirable movements by swinging the torso sideways in all postures, making their oxygen expenditure disproportionate to their weights. This point is clearly exemplified by subject #2 whose Vo_2/weight ratio was the highest at 12.26 ml/min/lb (Table B-7). It is probable that these additional body movements caused marginally significant r values, rather than solid linear relationships. It should be pointed out though that the torso movement was noted in all postures for subjects #2, #4, and #6, who were warned against this habit, and therefore it had the same effect in all positions for each particular subject.

Carry-over Effect

The question to be addressed is whether it is possible to ensure that the status of each subject is not different prior to the commencement of each trial? This legitimate concern assumes higher baseline values in successive trial attempts, i.e. when asked to start a new trial the subject may still be recovering from the previous trial. The concern is that the resting-values of the variables are at stake if insufficient resting periods are intermittently given (the resting durations for the subjects are listed in Table B-65). In fact this concern would arise even if the different postures were presented in the same sequence for all subjects.

As previously mentioned, the carry-over effect from one exercise to the following one was insignificant for all of the physiological variables considered. This result was unsurprising since a more severe exercise reaching up to 77 percent of max Vo_2, repeated 4 times in 20 minute periods separated by 20 minutes of rest, did not show significant differences in Vo_2 (Hermansen et al., 1967). Despite these findings, a Latin Square Design was chosen to detect the effect of fatigue trend because each treatment level was applied in each position of the stimuli-time administering sequence (Mendenhall et al., 1981, p. 499). This design reduced the experimental sum of squares of the error since the sequence is considered as a source of variation, thereby offering the results a better opportunity of being significant.

In summary, the carry-over effect due to posture sequence was almost negligible, as shown in the ANOVA tests for the physiological variables at steady-state. In consequence, it may be concluded that in the present study the given rest periods (average, 27.5 min) were adequate to return the body to its normal state.

Analyzing each subject's average values at steady-state across the four trials according to the particular sequence given, does not indicate any trend of either higher or lower values. This finding confirms the results of the ANOVA table and it may be maintained that the listed physiological values reflect the effect of the adopted posture where recovery from the proceeding exercise is ensured statistically. In fact, the sequence effect was found to be negligible for all physiological variables considered, both at rest and steady-state, indicating that a trend due to fatigue or any other undesirable factor was absent. In other words, the experiment could have been designed according to Randomized Block Design and the results would not have dramatically changed. However, Latin Square Design was selected as a precautionary measure against biased results. The sequence effect at rest has no real meaning and is provided in the ANOVA tables for consistency.

Curve Fittings

In order to inspect steady-state achievement visually, two mathematical models were used to fit the oxygen uptake and heart rate of every subject covering all four postures. The models are denoted by:

$YP1 = B_0 + B_1 \times \lambda^t$ and $YP2 = A_0\ (1 - e^{-kt})$,

where

B_0 = steady-state level;

λ = rate of transition from rest to steady-state;

B_1 = resting level minus steady-state level;

A_0 = steady-state level minus resting level;

K = rate of transition from rest to steady-state;

t = time.

These model parameters were found by feeding the data points of the measured Vo_2 and HR to the FITTING program shown in Appendix A-6. The program uses a set of equations (3 in YP1 and 2 in YP2) to solve for the desired parameters using Powell's Search (Beightler, Phillips, & Wilde, 1979, p. 192). The development of the simultaneous equations are presented, step by step, in Appendix A-4. The tolerance for stopping the iteration process was consistently chosen to be 0.005. Only the post warm-up data of Vo_2 were considered in order to allow the lungs to wash out the carbon dioxide (CO_2), which was inhaled through a bag to estimate the stroke volume at resting state. The warming-up period lasted for one minute, which was sufficient to expel CO_2 from the pulmonary system. It was found that in many respects the YP1 model fits the data better than YP2 model. The first priority was given to the sum of squares of the error (SSE), where with minor exceptions it was predominantly less in YP1 than YP2. As a result, the mean SSE at YP2 overweighs that at YP1 in both the Vo_2 and HR physiological variables (Table B-66). Accordingly, the mean coefficients of correlations (R^2) are overwhelmingly higher in the YP1 model.

The second item in the list of priorities was deviation from the steady-state levels. As shown in

Table B-66, both models seem to be even where B_0 values are better than (A_0 + resting) values in $\dot{V}o_2$ data fittings, but they reverse these attitudes in HR data fittings.

A third consideration was the number of iterations (I) required to complete the optimization process of the models' parameters. Although both models employed the same Powell's Search method for that purpose and although the same stopping criterion were applied, the saving in computer time for the YP1 model was appreciable.

The last priority concerned the number of optimized parameters. Both mathematical models share the estimation of the rate of state transfer from rest to steady-state (λ and k) and computations of the net change of magnitudes between both states ($-B_1$ and A_0). However, the YP1 model predicted a third parameter (B_0), representing the asymptotic level independent of the resting level. It is fair to say that the YP2 model predicts the steady-state values better than the YP1 model with respect to the HR variable. However, the tighter prediction of $\dot{V}o_2$ steady-state values, using the YP1 model, counter-balanced the situation.

All of the above considerations classified the YP1 model as superior to the YP2 model for the purposes of this study. The individual parameters for both models are listed in Tables B-68 to B-83.

The application of both model parameters to a symbolic graph is shown in Figures 24 and 25. The meanings of A_0 and B_1 become comprehendable and one may readily deduce that both parameters refer to the increase in the amount of the physiological variable from rest to steady-state. With respect to Vo_2, they represent net oxygen consumption and with regard to HR they project the increase in heart rate elicited by the given exercise.

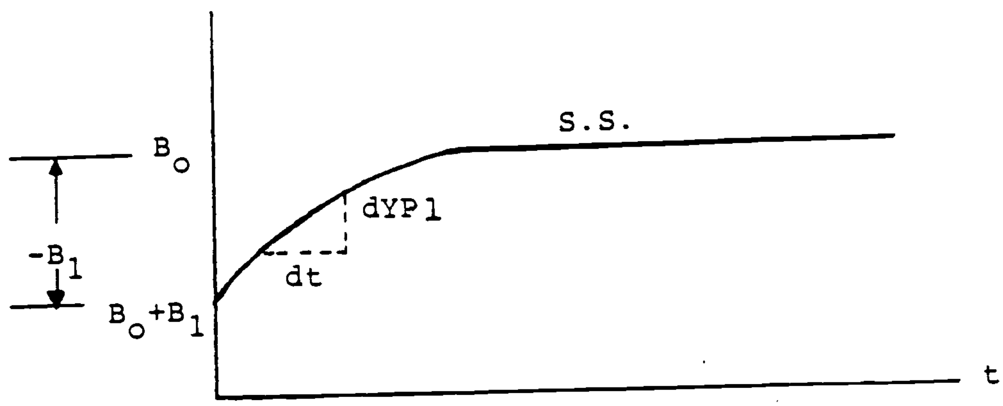

Figure 24. Parameters of YP1 Model
$(YP1 = B_0 + B_1 \lambda^t)$

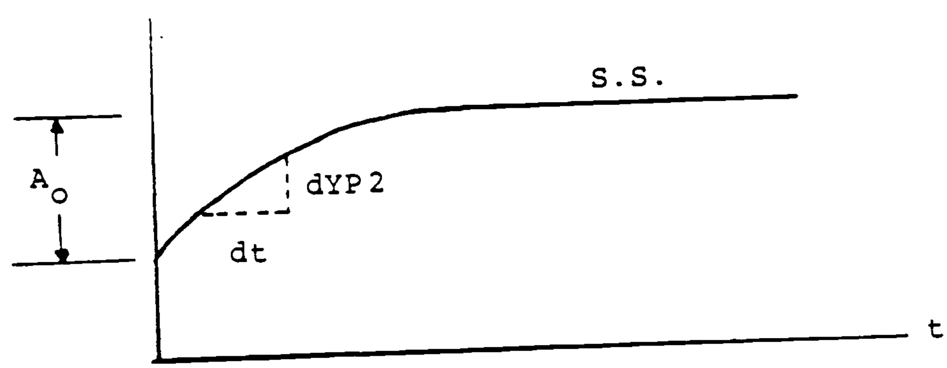

Figure 25. Parameters of YP2 Model
$(YP2 = A_0 (1 + e^{-kt}))$

The asymptotic levels were obtained by taking the limits of the functions as time approaches infinity:

$$\lim_{t \to \infty} YP1 = B_1 \quad \text{and} \quad \lim_{t \to \infty} YP2 = A_0$$

However, both parameters differ by the baseline level as given in the definition above. As time passes by in a particular exercise, the terms λ^t and e^{-kt} diminish, reducing the mathematical models YP1 and YP2 to merely B_0 and A_0, respectively.

As concerns the rate of transfer from the rest condition to the steady-state condition, it should be pointed out that λ and k do not solely describe the rate of conversion. Careful analysis of both mathematical models shows that the λ parameter causes a faster steady-state attainment at lower values, whereas larger k fractions lead to a faster conversion, with the assumption that every other variable remains constant. In other words, less time is consumed to reach the asymptotic level as λ falls and K rises, so long as the other parameters are maintained unchanged. However, an in-depth analysis of the models revealed the real rate of transfer by taking the derivative of both functions with respect to time:

$$\frac{dYP1}{dt} = \lambda^t \times \ln\lambda \times B_1 \quad \text{and} \quad \frac{dYP2}{dt} = k \times A_0 \times e^{-kt}$$

These derivatives represent the infinitesimal change in the physiological variables (Vo_2 and HR) at a certain time (t), i.e. the instantaneous slope of the fitting curve as shown in Figures 24 and 25. These positive slopes gradually decrease in magnitude until they vanish at the steady-state level. However, it is obvious that not only λ or k will bring the curve to a horizontal line. In both cases, three terms interact to form the needed slope as shown below:

Table 3. Details of the Terms Influencing the Rate of Curvature.

YP1

λ	λ^t	$\ln\lambda$	$\ln\lambda B_1$	$dYP1/dt$	S.S. achiev.
down	down	more negative	up	less	faster

YP2

K	A_0	$k\ A_0$	e^{-kt}	$dYP2/dt$	S.S. achiev.
up	cons-stant	up	down	less	faster

The terms λ^t and e^{-kt} are more influential numerically and therefore the slopes follow the directions of either term at constant B_1 and A_0 values. The fitted curves using YP1 model are pooled in Figure 26 (Vo_2) and Figure 27 (HR). It should be noted that these curves were constructed using the average data points listed in Tables B-56 to B-63, rather than using the average of the individually fitted parameters at the bottoms of Tables B-68 to B-75. The basic reason for exercising this choice is the dramatic and consistent difference in the corresponding

SSE value. Additionally, the curves of R and T in figure 26 reach the steady-state slightly faster than the other two postures and the corresponding λ values are minutely smaller (0.719 at R, 0.726 at T, 0.768 at S, and 0.778 at F), which confirms the influence of λ on the rate of curvature.

The same phenomenon is reflected in Figure 27, where the heart rate reaches a plateau at R and T faster due to smaller λ magnitudes (0.802 at R, 0.797 at T, 0.853 at S, and 0.867 at F). With respect to physiology, the average steady-state data of Vo_2 and HR (Table B-66) suggests that the aerobic oxygen system was working slightly harder in the racing and touring postures. This implies that to a large degree the aerobic system was also involved during the transition from rest to steady-state, where the rate of oxygen absorption by the muscles was greater. This is made obvious in the rate of curvatures, i.e., dy/dt. Astrand and Saltin (1961) graphically displayed Vo_2 and HR against time for different submaximal workloads. Their curves demonstrate clearly that escalation of Vo_2 and HR was faster in the heavier workloads. These findings confirm the point made earlier. However, the difference among the λ values in each figure was insignificant, as is shown by the ANOVA results in Tables B-84 and B-85, where the λ values were obtained from Tables B-68 to B-75.

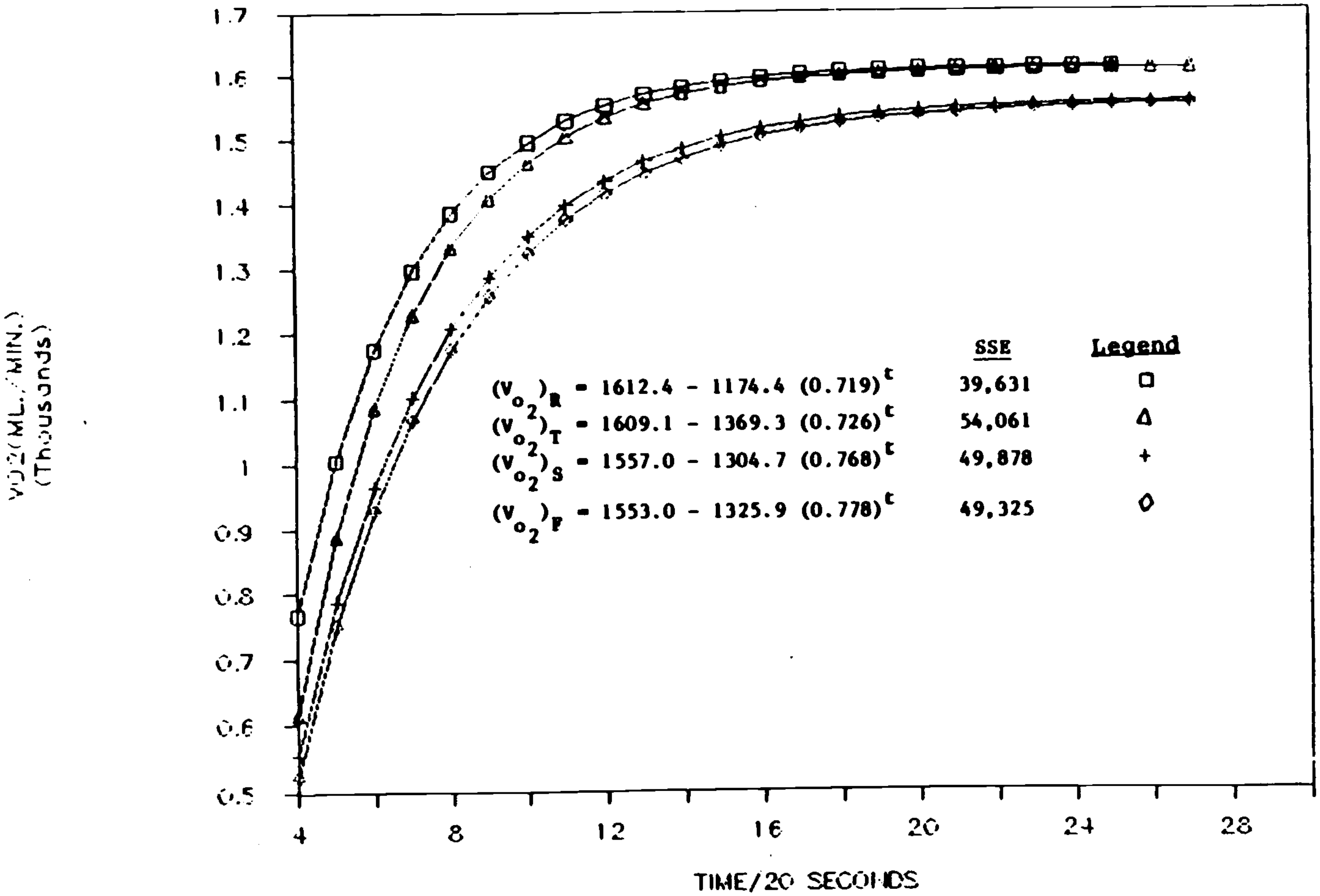

Figure 26. Fitting Curves of all Four Postures Based on Average Data of Vo_2, Using YP1 Model.

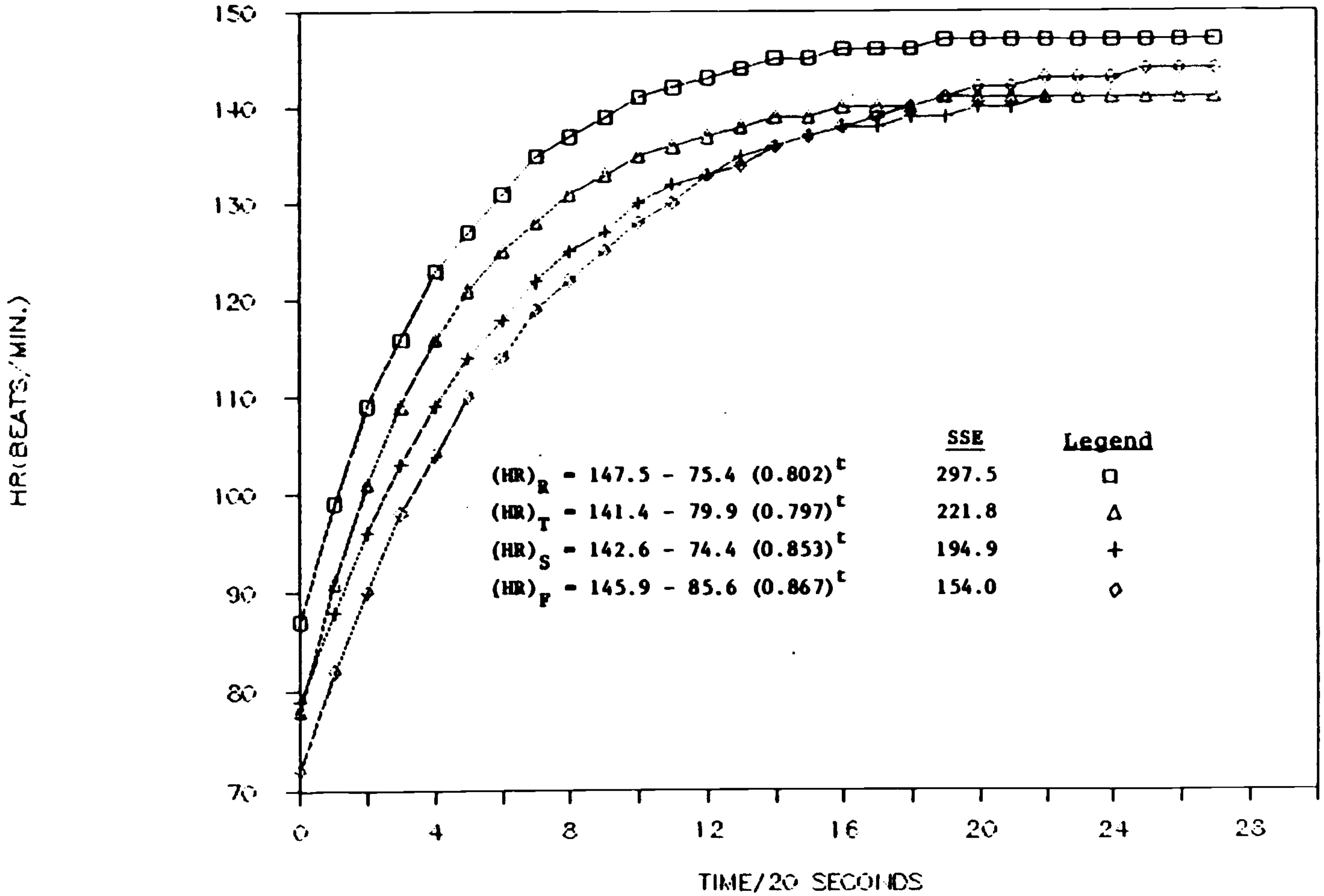

Figure 27. Fitting Curves of all Four Postures Based on Average Data of HR, Using YP1 Model.

Discussion of Results; Current and Related Studies

Although some studies exist which touch upon the issue of posture effect on the body responses, they fall short of studying more than two postures. Faria, Dix, and Frazer (1978) tested the racing and touring postures of a maximal exercise. The racing posture used did not imitate the crouched racing posture used in this study and the back angle differed only by 10° from that used in the touring position. The authors found a significant increase in maximum oxygen consumption (max Vo_2) at the racing body position, but an equivalent heart rate (max HR) at the 0.05 significance level. With respect to the results of this study, the significance of the results was reversed. However, no explanation was offered for the lack of matchable results. According to Faria et al. (1978), a higher max Vo_2 in the racing posture could be due to more muscle mass employment. This same reason was referred to earlier in this study as a plausible theory. Unfortunately, Faria et al. did not perform an electromygraphic (EMG) study for the racing posture to confirm the theory.

There have been a few studies concerning the subject of muscle involvement in cycling (EMG). The first (Houtz & Fischer, 1959), adopted the touring posture to two different saddle heights (21 and 25 inches) and used surface electrodes to pick-up the action potential. Although the three subjects used in the experiment varied in height and (most probably) varied in inseam height, it was concluded that the magnitude of muscle action potential was less at the higher seat level when pedaling at the same resistance. Standardization of saddle height, as done in this study by setting it at a variable formula (1.09 × individual inseam length), would have more accurately reflected the actual muscle involvement. However, the Houtz study did develop an awareness about the importance of saddle height, or posture in general, for efficient cycling.

Later in 1969, Thompson repeated the EMG analysis on the same muscles studied by Houtz and Fischer, using surface and intramuscular electrodes. Large muscles, such as the quadriceps and the hamstrings, resulted in a period of activity in agreement with that found by Houtz and Fischer. The resulting periods of activity for narrow muscles, such as the tensor fascia late, gracilis, and sartirious, differ from both kinds of electrodes.

Another EMG (Bigland-Ritchie & Woods, 1974) study dealt with the semi-recumbent posture, although it was not specified as such. Only three subjects were tested, two males and one female. The outcome of the experiment correlated Vo_2, force applied to the pedal, and integrated EMG in a linear relationship. Therefore, it was assumed that "the total electrical activity of a whole muscle is related in a simple way to the energy it expends and to the force it exerts."

The remaining investigations concerning the effect of posture on body performance during exercise were limited to the full-recumbent posture and the touring posture, referred to as the sitting position. From these studies it would seem that disagreement on the degree of significance between HR and Vo_2 results is not uncommon. In the Bevegard, Holmgren, and Jonsson (1963) study it was found that Vo_2 at T is significantly greater than Vo_2 at F, but that the heart rate was not significantly different for each posture at two different loads (131 watts and 261 watts). Again, explanation for the apparently contradictory results was not provided.

In this study it has been suggested that careful statements about the relationship of Vo_2 and HR should be drawn. A linear relationship exists between Vo_2 and HR in submaximal cycling exercise during the transition from rest to steady-state and at various load levels. However, such a relationship should not be taken for granted at the steady-state level working at a particular load where the only scale is constituted by the subjects themselves. Naturally, the physical differences among them are reflected in their physiological performances, leading to apparently inconsistent results.

In an experiment involving four subjects (McGregor et al, 1961), with RPM between 70 and 75, and the workload at 82 watts, an insignificant difference of 15 ml/min in Vo_2 was found between postures F and T, with a significant difference in HR amounting to 8.1 beats/min. This finding in some respects resembles the overall result of the current study, but with a larger average difference in Vo_2 (48 ml/min) and a narrower average gap in HR (0.6 beats/min). Pursuing this line, Bevegard et al. (1960) failed to find a significant difference in Vo_2 between F and T postures at two different unspecified loads.

So far as stroke volume is concerned, significant differences were found between T and F in several studies. Stenberg et al. (1967) expected such behavior at load work intensity below 65 percent of max Vo_2. Above that level the heart pumps blood at maximum liters per beat and stays almost constant, although Vo_2 progressively increases to max Vo_2. At an estimated max Vo_2 average approaching 62 percent in this study, a significant difference in SV between the sitting postures and the recumbent postures is improbable. The SV average values of the 6 subjects tested under 82 watts by Bevegard et al. (1966) reached 132 ml/beat in posture F and 119 ml/beat in posture T, close to the corresponding SV averages found in this study (128 and 116 ml/beat, respectively). However, the method of measurements used in each study differed. The present study employed an indirect SV measurement through CO_2 ventilation, whereas the Bevegard study used a direct cardiac catheterization. Fortunately, Wang, Marshall, and Shepherd (1960) have discussed SV measurement procedures and have concluded that both methods are competent. In fact, the introduction of catheters, although providing a better SV reading, may alter blood circulation and consequently increase both HR and Vo_2, especially at rest (Bevegard et al., 1963).

It is worthwhile to consider the mechanism whereby SV is increased during exercise. Evidently blood is not induced into the body in the same way as is oxygen. Fox and Mathews (1981, p. 232) noted that for a long time Starling's law of the heart seemed to provide the answer. "This law states that stroke volume increases in response to an increase in the volume of the blood filling the heart ventricle during diastole" (p. 232), i.e. heart relaxation. The increase in blood volume in that compartment causes greater stretch of the heart fibers, which in turn promotes a more forceful blood ejection during systole, i.e. heart contraction. However, according to Fox and Mathews, a more recent study has shown that diastolic volume does not increase during exercise. The blood volume in the ventricle during the diastole phase remains relatively constant, whereas only about

40 to 50 percent of the total diastolic volume is pumped at rest during each systole. However, a stronger heart contraction during an exercise promotes the emptying of more blood, and therefore a larger stroke volume. It should be added, however, that this finding may be true for a particular posture at a given time, but it does not contradict the principle of blood pooling in the extremities due to gravitational force. Moreover, when different body positions are considered during an exercise the gravity effect, as discussed above, persists.

The same consistency in quantitative hierarchy with conflicting degrees of significance may be applied to the [$(a-v)O_2$ diff] variable. It was generally found that [$(a-v)O_2$ diff] at posture T exceeds that at posture F during a submaximal exercise ranging from 82 watts (Bevegard et al., 1966) to some unknown load estimated to be double the former workload (Bevegard et al., 1960). The average values of [$(a-v)O_2$ diff] in the present study are in agreement with this generality, on the average reaching 105.4 ml/l at T and 88.9 ml/l at F. The average values found by Bevegard et al. (1966) are very close, amounting to 102 ml/l and 91 ml/l, respectively.

Unfortunately, though the literature was extensively searched, no comparative studies were found which adopted the semi-recumbent or the racing postures. Therefore, the present study is first of its kind in the sense of comparing four different body positions rather than only two, at a workload (90 watts) and pedaling speed (60 RPM) practical for commuting purposes.

V. Summaries, Conclusions, and Recommendations

Summary of Procedure

The purpose of this study was to investigate the effect of different body positions on rotary cycling motion from a physiological point of view. Tests were conducted on 8 healthy young male subjects on a mechanical ergometer at 4 postures: racing, touring, semi-recumbent and supine full-recumbent. The postures were randomly presented to the subjects in successive trials, each lasting for 8 minutes in order to attain a steady-state level. Each test was preceded by baseline measurement and a warm-up period of 1 minute and succeeded by a recovery period averaging 27 minutes. The workload rate and pedaling speed were designed at 90 watts and 60 RPM, respectively, amounting to an average road speed of 15 mph.

Summary of Results

The mean data points and experimental results of the experiment are summarized in Tables 5 and 6:

Table 4. Summary of Results at Rest.

Variable	R	T	S	F	Sig?	End Result
Vo_2 (ml/min)	360	281	263	243	Yes	T,S,F > R
HR (beats/min)	87.6	82.1	78.3	68.0	Yes	F > S > R and F > T
SV (ml/beat)	69	58	62	70	No	-
Q (l/min.)	5.9	4.7	4.7	4.7	Yes	T,S,F > R
$(a\text{-}v)O_2$ diff	63.3	62.7	58.5	54.4	No	-
V_E (l/min)	13.9	11.5	10.5	10.5	Yes	T,S,F > R
RR (breaths/min)	19.2	18.1	17.6	16.8	No	-
TV (l/breath)	0.78	0.68	0.67	0.68	Yes	R > T,S,F

Table 5. Summary of Results at Steady-State.

Variable	R	T	S	F	Sig?	End Result
Vo_2 (ml/min)	1632	1607	1562	1559	No	-
HR (beats/min)	150.3	143.3	140.8	143.9	Yes	T,S,F,> R
SV (ml/beat)	117	116	129	128	No	-
Q (l/min)	17.4	16.2	17.7	18.0	No	-
$(a\text{-}v)O_2$ diff	97.7	105.4	96.1	88.9	No	-
V_E (l/min)	53.0	48.1	45.9	50.6	Yes	T,S, > R and S > F
RR (breaths/min)	36.8	33.3	34.0	36.2	No	-
TV (l/breath)	1.47	1.48	1.38	1.43	No	-
Net efficiency	20.1	19.2	19.5	19.5	No	-
Gross efficiency	15.7	16.0	16.3	16.4	No	-

Oxygen consumption (Vo_2) at rest while seated in the racing posture was significantly ($\alpha = .05$) higher than for the other postures. However, steady-state results did not indicate statistical significance, although Vo_2 maintained the same status. The heart rate (HR) at rest was significantly ($\alpha = .05$) higher at R than F and S, but not with respect to T. Nonetheless, the racing posture elicited a significantly ($\alpha = .05$) higher HR at steady-state than did the other postures. Stroke volume (SV), the arterial-venous oxygen difference [$(a-v)O_2$ diff], and the respiratory rate (RR) failed to show any statistical significance ($\alpha = .05$) at both rest and steady-state conditions. The cardiac output (Q) was revealed to be significantly ($\alpha = .05$) less in R at rest only. Minute ventilation (V_E) was significantly ($\alpha = .05$) larger in R at both conditions. Finally, the tidal volume (TV) was significantly ($\alpha = .05$) larger in R while at rest, but not in a steady-state condition.

Conclusions

In a practical sense the commuter cyclist is left with three choices when the full-recumbent position is ignored. Physiologically, the steady-state results contend that the racing posture was inferior to other postures with regard to oxygen consumption, ventilation rate, and in particular, the heart rate.

The latter variable is crucial to commuters in general and to cardiac patients in particular. On the other hand, a lower oxygen uptake for a certain exercise is interpreted as requiring the consumption of fewer calories, meaning a low rate of fuel depletion. Consequently, the commuter will reach his/her destination with less need for food and drink intake. The racing crouched position was also proven to be inferior because it absorbs a larger volume of air, thereby unnecessarily taxing the respiratory system. In addition, the enjoyment of cycling is dissipated by the use of an extremely uncomfortable saddle, especially during long rides, with strain exerted on the muscles of the neck, arms, and back.

If the commuter decides to desert the racing posture in cycling, he/she should not hesitate to select the semi-recumbent posture for many of the following advantages. Although personal preference based on enjoyment may be equivalent between the touring and the semi-recumbent postures, the latter should readily grow in popularity due to higher speed achievements at the same workload output. The speed difference becomes even more significant when a streamlined enclosure is provided. This type of fairing would also offer protection from the rain, cold air, insects, and even from other running vehicles. The low center of gravity, coupled with the addition of a third wheel, would readily stabilize the man-powered recumbent vehicle.

The disadvantages of the semi-recumbent vehicles are to a large extent solvable. The relatively low height of the system causes visibility problems, but the installation of a flag would help to alert other vehicular traffic and the relatively higher cost could be reduced by mass production.

The physiological differences between the touring and the semi-recumbent postures could have been statistically significant, in favor of the latter, if the subjects used in this study had been more homogeneous. Sincere cyclists should take all of the considerations presented in this study into account and pick the more convincing posture. It is hoped that this study provides satisfactory answers to some of the questions raised by non-scientific discussions in the cycling media regarding posture.

Recommendations for Further Study

Interested researchers should find this investigation a useful basis for exploring more efficient cycle riding. The interaction among the most influential factors, such as the workload, the pedaling frequency, and the posture, should be thoroughly investigated throughout the possible ranges. Different categories of subjects, with regard to sex and age, should be tested in order to generalize the conclusions. Particularly, with reference to the semi-recumbent posture, several crank axle heights and seat adjustment designs are candidates for prospective study. Finally, comprehensive coverage of the above research areas should be approached through the related branches of science, i.e. physiology, kinesiology, and biomechanics. Moreover, human factors engineering principles would be extremely valuable in the interior design of enclosed vehicles. Special consideration should be given to the location of display and control devices, the accommodation of a cargo basket, and to the accessibility of the vehicle for easy-in and easy-out.

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APPENDICES

APPENDIX A

Definitions, Legend, Subject Information, Equations and Statistical Procedures, Computer Programs

Appendix A-1

Definition of Terms*

AEROBIC: in the presence of oxygen.

ANAEROBIC: in the absence of oxygen.

ANOVA: analysis of variance.

ARTERIOVENOUS OXYGEN DIFFERENT [(a-v)O, diff]: The difference between the oxygen content of arterial and mixed venous blood.

CARDIAC OUTPUT (Q): The amount of blood pumped by the heart in one minute.

DIASTOLE: The resting phase of the cardiace cycle.

EFFICIENCY: The ratio of work output to work input.

ELECTROCARDIOGRAM (EKG): Recording of the electrical activity of the heart.

FULL-RECUMBENT POSTURE (F): Body is completely flat, hand on grips at full stretched arms, axle at the level of the back, and face is up (supine).

GLYCOGEN: A form of glucose (sugar) stored in the body, mainly in muscles and the liver.

ISOMETRIC (STATIC) CONTRACTION: Contraction in which tension is developed, but there is no change in the length of the muscle.

LACTIC ACID: A fatiguing metabolite resulting from the incomplete breakdown of glucose.

MAXIMAL OXYGEN CONSUMPTION (Max Vo_2): The maximum rate at which oxygen can be consumed per minute; the power or capacity of the aerobic or oxygen system.

*Note: The definitions are in part taken from those provided by Fox and Mathews (1981).

METABOLISM: The sum total of the chemical changes or reactions occurring in the body.

MINUTE VENTILATION: The amount of air inspired (V_I) or expired (V_E) in one minute; usually it refers to the expired amount.

RACING POSTURE (R): Crouched body position where the back is almost horizontal, head is up, and hands on lower handlebars forming nearly 90 degrees elbow angle.

RESPIRATORY EXCHANGE RATIO (RER): The ratio of the amount of carbon dioxide produced to the amount of oxygen consumed (Vco_2/Vo_2).

SEMI-RECUMBENT POSTURE (S): Sitting on an office-like chair where the back angle is 10° from vertical, hands on grips under the seat, and pedal axle at seat level in front of subject.

STEADY-STATE: Pertaining to the time period during which a physiological function (such as VO_2 and HR) remains at a constant (steady) value.

STROKE VOLUME (SV): The amount of blood pumped by the left ventricle of the heart per beat.

SYSTOLE: Emptying phase of the cardiac cycle.

TIDAL VOLUME (TV): Volume of air inspired or expired per breath.

TOURING POSTURE (T): Regular sitting body position where the arms are fully stretched, hands on top handlebars, and torso angle is about 20 degrees.

Appendix A-2

Legend

$>$	= better than
α	= significant level = 0.05
ϵ	= backrest angle in S posture
ς	= seat pan angle in S posture
λ	= rate of transition from rest to steady-state (YP1 model)
$(a\text{-}v)O_2$ diff	= arteriovenous oxygen difference (ml/l)
A	= frontal area of cyclist and vehicle (ft^2)
AD	= air drag facing a cyclist and the vehicle (watts)
A_0	= steady-state level minus resting level (YP2 model)
B_0	= steady-state level (YP1 model)
b_0	= the intercept of regressed line with the y-axis
B_1	= negative coefficient of transition (YP2 model)
b_1	= slope of regressed line
C_D	= coefficient of air drag
C_R	= rolling resistance
D	= diameter of driven wheel (inches)
d	= seat to pedal axle variable distance in S posture
df	= degrees of freedom

E_c = caloric Equivalence of Oxygen (kilocalories)

F = full-recumbent posture

H = body height (in)

HR = heart rate (beats/min)

h_1 = backrest height in S posture

h_2 = backrest length in S posture

I = number of iterations in FITTING program

IL = inseam length (in.)

K = rate of transition from rest to steady-state (YP2 model)

$Kcal/O_2$ = conversion factor of Vo_2 to Kcal.

LL = leg length (buttock to heel length in inches)

LW = leg weight (lb.)

Max HR = maximum Heart Rate

Max Vo_2 = maximal oxygen consumption (l/min)

MCC = maximum calf muscle circumference (in)

MS = mean sum of squares

MSE = mean Squares of Error

N_1 = number of teeth in chainwheel

N_2 = number of teeth in freewheel

Net Vo_2 = oxygen cost of exercise only (l/min)

Q = cardiac output (l/min.)

r = sample correlation coefficient

R^2 = correlation coefficient for YP1 and YP2 models

R = racing posture

RD = rolling resistance (watts)

RER = respiratory exchange ratio

RR = respiratory rate (breathes/min.)

S = semi-recumbent posture

S.d. = standard deviation

S.S. = steady-state condition

sig? = significant at α = .05?

SRP = seat reference point

SS = sum of squares

SSE = sum of Squares of Error

SV = stroke volume (ml/beat)

T = touring posture

TV = tidal volume (l/breath)

UTC = upper thigh circumference (in)

V_E = exhaled (inhaled) ventilated air (l/min)

V = relative velocity of bicycle to air velocity (mph)

Vo_2 = oxygen uptake (l/min)

W = body weight (lb)

W_T = total weight of cyclist and vehicle (lb)

Appendix A-3

Subject Information Sheet

NAME: WEIGHT: lb. = kg

SUBJECT: HEIGHT: in.

AGE: INSEAM LENGTH:

SEX: UPPER THIGH CIRC. in. = cm

SMOKING: MAXIMUM CALF CIRC. in. = cm

PHONE: BUTTOCK TO HEEL LENGTH: in.

ESTIMATED LEG WEIGHT: lb. = kg.

ESTIMATED WORK CAPACITY: liters/min.

ESTIMATED MAX HR: beats/min.

TRAINING PROGRAM:

#	TYPE	DURATION (Months)	FREQUENCY (Day/Week)	INTENSITY (Min/Day)
1				
2				
3				
4				

SLEEPING HOURS: TEMPERATURE:

MODE: PRESSURE:

LAST MEAL TIME: HUMIDITY:

DATE: LOAD: 90 watts

SPEED: 60 RPM

Appendix A-4

Equations

LW	$= 0.094 \times W + 0.146 \times MCC + 0.113 \times UTC - 5.455$ in kg and linear dimensions in cm (Clauser et al., 1969)
Max HR	$= 220 - Age$
Q	$= HR \times SV$
Vo_2	$= Q \times (a\text{-}v)O_2$ diff
E_c	$= Vo_2 \times Kcal/O_2$
RER	$= Vco_2/Vo_2$
V_E	$= RR \times TV$
AD	$= 0.005093 \times C_D \times A \times V^3$ (watts)
RD	$= 1.99 \times W_T \times C_R \times V$ (watts)
V	$= (N_1/N_2) \times D \times \pi \times$ cadence/1052 mph

Latin Square Design

The model equation (Wine, 1964, p. 436) is:

$$X_{ij(k)} = \mu + \alpha_i + \beta_j + \gamma_k + \epsilon_{ij(k)}$$

$i = 1, \ldots, t;\ j = 1, \ldots, t,\ k = 1, \ldots, t$

where t = number of treatment levels;

$X_{ij(k)}$ = the observation of the k-th treatment level falling in the i-th column and j-th row;

μ = overall mean;

α_i = the effect of the i-th column;

β_j = the effect of the j-th row;

γ_k = the effect of the k-th treatment level;

$\epsilon_{ij(k)}$ = random experimental error in ij(k) cell, having a normal distribution with a mean of zero and a common variance.

The null hypothesis of this design is

$$H_o\colon \mu_R = \mu_T = \mu_S = \mu_F$$

where the subscripts denote the different postures. Alternatively, the null hypothesis could be written as

$H_o\colon \gamma_k = 0.$ For $i, \ldots t.$

The column, row, treatment, and grand totals are given by

$$T_{i..} = \sum_j X_{ij(k)},\ T_{.j.} = \sum_i X_{ij(k)},\ T_{..k} = \sum_k X_{ij(k)}$$

and $T = \sum_i \sum_j X_{ij(k)} = \sum_i \sum_k X_{ij(k)} = \sum_j \sum_k X_{ij(k)}$

The sum of squares identity is:

$$SST = SSC + SSR + SSTR + SSE$$

where $SST = \sum_i \sum_j X^2_{ij(k)} - T^2/t^2$

$SSC = \sum_i T^2_{i..}/t - T^2/t^2$

$SSR = \sum_i T^2_{.j.}/t - T^2/t^2$

$SSTR = \sum_i T^2_{..k}/t - T^2/t^2$

and SSE is found by subtraction.

The ANOVA for a single square is shown below:

Analysis of Variance for a Single Square.

Source of Variation	Sum of Variance	Degrees of Freedom	Mean Squares	F
Columns	SSC	t-1	MSC = SSC ÷ (t-1)	MSC/MSE
Rows	SSR	t-1	MSR = SSR ÷ (t-1)	MSR/MSE
Treatment	SSTR	t-1	MSTR = SSTR ÷ (t-1)	MSTR/MSE
Error	SSE	(t-1) × (t-2)	MSE = SSE ÷ [(t-1) × (t-2)]	

The sum of squares of the square is:

$SSSQ = (T_1^2 + T_2^2)/t^2 - (T_1 + T_2)^2/nt$ with one degree of freedom,

where

T_i = grand total for square i, i = 1,2;

and n = the total number of subjects.

Single Degree of Freedom Test**

$$Q^2 = \frac{\left(\sum_{i=1}^{k} m_i \; T_i\right)^2}{n \sum_{i=1}^{k} m_i^2}$$ where Q^2 is a component

of treatment sum of squares with an individual degree of freedom, T_i is the sum of physiological responses for all 8 subjects at treatment level i, and n is the sample size for each posture amounting to 8 (i = 1 to k = 4 postures).

It is to be noted that Q^2/MSE has F distribution with 1 and k(n-1) degrees of freedom. The sum of the multipliers should be zero.

$m_1 + \ldots + m_k = o$, where some $m_i \neq o$, for i = 1, ..., k.

In order to test two postures at a time to see whether a significant difference exist with respect to a certain variable, let $m_1 = 1$ and $m_2 = -1$ and calculate Q^2. The fraction Q^2/MSE has an F distribution, therefore could be compared with

$$F_{\alpha,\ 1,\ k(n-1)} = F_{.05,\ 1,\ 4\ (8-1)}$$
$$= F_{.05,\ 1,\ 28} = 4.2.$$

**Note: see Wine, 1964.

Test Procedure Used in SSTEST Program *

Test statistic: $t = \dfrac{B_1 - o}{S\sqrt{C11}}$

H_o: $B_1 = o$

H_a: $B_1 \neq o$

RR: $t > t_{\alpha/2,\ df}$

df: $n - (k+1) = n-2 = 8$

$C_{11} = \dfrac{1}{\Sigma (X_i - \overline{X})^2}$, $S = \dfrac{SSE}{n-2} = \dfrac{\Sigma (y_i - \hat{y}_i)^2}{n-2}$

$X_i = 1, 2, \ldots\ldots, 10$

$t_{\alpha/2,\ df} = t_{.025'8} = 2.306$

*Note: Mendenhall et al., 1981, p. 445

Equations to Get YP1 Model Parameters

$$YP1 = B_o + B_1 \lambda^t$$

$$Y_t = \text{observed value}$$

$$e_t = Y_t - YP1 = Y_t - B_o - B_1 \lambda^t$$

$$SSE = \sum_{t=1}^{N} e^2_t = \sum_{t=1}^{N} [Y_t - (B_o + B_1 \lambda^t)]^2$$

$$= \Sigma\ [(Y^2_t + (B_o + B_1 \lambda^t)^2 - 2 Y_t (B_o + B_1 \lambda^t)]$$

$$= \Sigma\ [Y^2_t + B_o^2 + 2 B_o B_1 \lambda^t + B_1^2 \lambda^{2t} - 2 Y_t B_o - 2Y_t B_1 \lambda^t]$$

$$= \Sigma Y_t^2 + NB_o^2 + 2 B_o B_1 \Sigma \lambda^t + B_1 \Sigma \lambda^{2t}$$
$$- 2 B_o \Sigma Y_t - 2 B_1 \Sigma Y_t \lambda^t$$

$$= \Sigma Y_t^{\ 2} + NB_o^2 + 2 B_o B_1 \Sigma \lambda^t + B_1^2 \Sigma \lambda^{2t}$$
$$-2 B_o (NB_o + B_1 \Sigma \lambda^t) - 2 B_1 (B_o \Sigma \lambda^t + B_1 \Sigma \lambda^{2t})$$

$$= \Sigma Y^2_t - NB_o^2 - 2 B_1 B_o \Sigma \lambda^t - B_1^2 \Sigma \lambda^{2t}$$

$$= \Sigma Y^2_t - NB_o^2 - 2 B_1 B_o (\Sigma Y_t - NB_o) - B_1 (\Sigma \lambda^t Y_t - B_o \Sigma \lambda^t)$$

$$= \Sigma Y^2_t - NB_o^2 - 2 B_o \Sigma Y_t - B_1 \Sigma \lambda^t Y_t + B_o (\Sigma Y_t - NB_o)$$

$$= \Sigma Y^2_t - B_o \Sigma Y_t - B_1 \Sigma \lambda^t Y_t \qquad \text{equation 1}$$

Then,

$$\frac{\partial (\Sigma e^2_t)}{\partial B_o} = \Sigma - 2 \lambda (Y_t - B_o - B_1 \lambda^t) = 0$$

$$\frac{\partial (\Sigma e^2_t)}{\partial B_1} = \Sigma -2 \lambda^t (Y_t - B_o - B_1 \lambda^t) = 0$$

Rearranging the two last equations yields:

$$\Sigma Y_t = NB_o + B_1 \Sigma\lambda^t \qquad \text{equation 2}$$

and $$\Sigma\lambda^t Y_t = B_o \Sigma\lambda^t + B_1 \Sigma \lambda^{2t} \qquad \text{equation 3}$$

equations 1, 2, and 3 are used to solve for B_o, B_1, and λ by FITTING program.

Equations To Get YP2 Model Parameters

$$YP2 = A_o\ (1-e^{-kt})$$

Y_t = observed value

$$SSE = \sum_{t=1}^{N} e^2_t = \Sigma\ (Y_t - YP2)^2$$

$$= \Sigma\ [Y_t - A_o(1-e^{-kt})]^2$$

$$= \Sigma\ [Y^2_t + A_o^2\ (1-e^{-kt})^2 - 2\ A_o\ (1-e^{-kt})\ Y_t]$$

$$= \Sigma\ Y^2_t + A_o^2\ \Sigma(1-e^{-kt})^2 - 2\ A_o\ \Sigma\ Y_t\ (1-e^{-kt})$$

equation 1

$$\text{Then } \frac{\partial(SSE)}{\partial A_o} = \Sigma -2\ [Y_t - A_o\ (1-e^{-kt})]\ (1-e^{-kt}) = 0$$

$$\text{or} \quad \Sigma\ Y_t\ (1-e^{-kt}) = A_o\ \Sigma\ (1-e^{-kt})^2$$

$$\therefore\ A_o = \Sigma\ Y_t\ (1-e^{-kt}) / \Sigma\ (1-e^{-kt})^2$$

equation 2

equations 1 and 2 are used to solve for k and A_o by FITTING program.

Appendix A-5

Computer Programs

```
1 REM -----------------------  SSTEST ----------------------------
2 REM
3 REM
10 REM THIS PROGRAM TESTS THE ACHEIVEMENT OF STEADY STATE AFTER 5 MINUTES OF
20 DIM Y(20)
30 INPUT "SUBECT # ?",S
40 INPUT "NUMBER OF DATA POINTS ?",N
50 INPUT "POSTURE ?",P$
60 INPUT "DEPENDENT VARIABLE ?",V$
70 PRINT "THE INDEPENDENT VARIABLE IS TIME SCALED TO APPEAR AS INTEGER NUMBERS
80 S0=0:S1=0:S2=0:S3=0:S4=0:S5=0:S6=0:SSE=0 :B1SIG$="NO"
90 FOR I =1 TO N
100 PRINT "Y(",I,")="
105 INPUT Y(I)
110 S0=S0+I*Y(I)
120 S1=S1+I
130 S2=S2+Y(I)
140 S3=S3+I^2
150 NEXT I
160 YBAR=S2/N
170 XBAR=S1/N
180 B1=N*S0-S1*S2/(N*S3-S1^2)
190 B0=YBAR-B1*XBAR
200 FOR I=1 TO N
210 YHAT=B0+B1*I
220 SSE=SSE+(Y(I)-YHAT)^2
230 S4=S4+(I-XBAR)^2
240 S5=S5+(I-XBAR)*(Y(I)-YBAR)
250 S6=S6+(Y(I)-YBAR)^2
260 NEXT I
270 CC=S5/SQR (S4*S6)
280 S7=SSE/(N-2)
290 C11=1/S4
300 T=B1/(S7*SQR (C11))
310 LPRINT "SUBJECT # :",S
320 LPRINT "DEPENDENT VARIABLE : ",V$
330 LPRINT "POSTURE : ",P$
340 LPRINT "B0= ",B0
350 LPRINT "B1= ",B1
360 LPRINT "DATA POINTS = ",N
370 LPRINT "AVERAGE OF DATA POINTS = ",YBAR
380 LPRINT "SSE= ",SSE
390 LPRINT "COEFFICIENT OF CORRELATION =",CC
400 LPRINT " t = ", T
410 IF T > 2.306 THEN B1SIG$="YES"
420 LPRINT " IS  B1  SIGNIFICANT ? ",B1SIG$
425 LPRINT "***************************************************************"
430 END
```

```
1 REM---------------------FITTING --------------------------------
2 REM
3 REM
4 REM THIS PROGRAM FITS THE DATA POINTS ACROSS TIME INTO TWO MODELS:
5 REM      YP1=B0+B1*ALPHA^TIME
6 REM      YP2=A0*((1-EXP(-K*TIME))
7 REM  POWEL'S SEARCH IS USED TO OPTIMIZE THE PARAMETERS OF BOTH MODELS
10 DIM Y(40),NETY(40),YP1(40),YP2(40)
20 INPUT "SUBJECT # ?",S
30 INPUT "POSTURE ? ",P$
40 INPUT"AVERAGE HR  CALCULATED FROM LAST 10 POINTS ?",V0210
50 INPUT " HR   AT REST ?",REST
55 FOR I=1 TO 7
56 LPRINT
57 NEXT I
60 LPRINT "SUBJECT # : ",S,"      POSTURE : ",P$,"     "," HR AT REST :",REST
70 INPUT "TOLERANCE=",D
90 FOR I =1 TO 40
100 INPUT "Y=",Y(I)
110 NETY(I)=Y(I)-REST
130 IF Y(I)=9999 THEN N=I-1 : GOTO 160
140 NEXT I
160 LPRINT"------------------------------------------------------------"
170 FOR J=1 TO 2
180 X1=.6:X2=.7:X3=.8
190 IT=0
200 A=X1
210 ON J GOSUB 690,880
220 Y1=S6
230 A=X2
240 ON J GOSUB 690,880
250 Y2=S6
260 A=X3
270 ON J GOSUB 690,880
280 Y3=S6
290 IT=IT+1
300 X4=((X2^ 2-X3^ 2)*Y1+(X3^ 2-X1^ 2)*Y2+(X1^ 2-X2^ 2)*Y3)
305 X4=X4/(2*((X2-X3)*Y1+(X3-X1)*Y2+(X1-X2)*Y3))
310 IF X4>.999 THEN X4=.999
320 IF X4<.001 THEN X4=.001
330 A=X4
340 ON J GOSUB 690,880
350 IT=IT+1
360 Y4=S6
370 IF Y3<Y2 THEN 420
380 IF Y2<Y1 THEN 400
390 GOTO 430
400 X1=X2 : Y1=Y2
410 GOTO 430
420 X1=X3:Y1=Y3
430 X2=X4:Y2=Y4
440 IF ABS(X1-X2)<D THEN 520
450 IF IT> 30 THEN 520
460 IF Y2<Y1 THEN 480
470 X3=X1:Y3=Y1:X1=X2:Y1=Y2:X2=X3:Y2=Y3
```

```
480 X3=2*X2-X1
490 IF X3>.999 THEN X3=.999
500 IF X3<.001 THEN X3=.001
510 GOTO 260
520 A=X2
530 ON J GOSUB 690,880
535 PRINT"----------------------------------------------------------------"
540 NEXT J
545 LPRINT "YP1=B0+B1*ALPHA^t"
550 LPRINT "SSE=",SSE1,"ALPHA=";ALPHA;"B0=";B0;"B1=";B1;"R2=";R2;
552 LPRINT "ITERATIONS=",I1
554 D1=CINT(B0-V0210)
555 LPRINT "DIFFERENCE BETWEEN PREDICTED AND CALCULATED VO2 AT STEADY STATE=",D1
560 FOR I=0 TO N
570 YP1(I)=B0+B1*ALPHA^I
580 NEXT I
590 LPRINT"----------------------------------------------------------------------"
595 LPRINT"YP2=A0*(1-EXP(-K*t))+RESTING VALUE"
600 LPRINT "SSE=",SSE2,"K=",K,"A0=",A0,"R2=",R4,"ITERATIONS=",I2
604 D2=CINT((A0+REST)-V0210)
605 LPRINT "DIFFERENCE BETWEEN PREDICTED AND CALCULATED VO2 AT STEADY STATE=",D2
610 FOR I=0 TO N
620 YP2(I)=A0*(1-EXP(-K*I))+REST
630 NEXT I
640 LPRINT"----------------------------------------------------------------------"
645 LPRINT "  t              Y              YP1              YP2"
646 LPRINT " ---            ---             ---              ---"
650 FOR I=1 TO N
660 LPRINT I,Y(I),CINT(YP1(I)),CINT(YP2(I))
670 NEXT I
680 LPRINT"&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&"
685 FOR I=1 TO 7
686 LPRINT
687 NEXT I
690 REM SUBROUTINE SUM OF SQUARES FOR Y=B0+B1*ALPHA^t
700 ALPHA=A : I1=IT
710 S1=0:S2=0:S3=0:S4=0:S5=0:SSE1=0
720 FOR I=M+1 TO N
740 S1=S1+Y(I)
750 S2=S2+Y(I)^ 2
760 S3=S3+ALPHA^I
770 S4=S4+Y(I)*ALPHA^ I
780 S5=S5+ALPHA^ (2*I)
790 NEXT I
800 B1=(N*S4-S1*S3)/(N*S5-S3^ 2)
810 B0=(S1-B1*S3)/N
820 SSE1=S2-B0*S1-B1*S4
830 S6=SSE1
840 R1=S2-S1^ 2/N
850 R2=(R1-SSE1)/R1
860 PRINT " ALPHA=",ALPHA,"SSE=",SSE1,"I1=",I1
870 RETURN
880 REM SUBROUTINE SUM OF SQUARES FOR Y=A0*(1-EXP(-K*t))
890 K=A :I2=IT
900 S7=0:S8=0: S9=0:S11=0:SSE2=0
```

```
910 FOR I=M+1 TO N
930 E=1-EXP(-K*I)
940 S7=S7+NETY(I)*E
950 S8=S8+E*E
960 S11=S11+NETY(I)^2
970 SSE2=S11+A0*A0*S8-2*A0*S7
980 S9=S9+NETY(I)
990 NEXT I
1000 A0=S7/S8
1010 S6=SSE2
1020 R3=S11-S9^2/N
1030 R4=(R3-SSE2)/R3
1040  PRINT "K=",K,"SSE=",SSE2,"I2=",I2
1050 RETURN
1060 END
```

```
1 REM-----------------ANOVA ---------------------------
2 REM
3 REM
4 REM THIS PROGRAM PERFORMS AN ANALYSIS OF VARIANCE FOR TWO LATIN SQUARES.
5 REM
10 DIM X(4,4,2),P$(4,4,2),TR(2,8),TC(2,8),TT(2,8),T(2),SST(2),SSC(2),SSR(2)
12 DIM SSTR(2),SSE(2),MSC(2),MSR(2),MSTR(2),MSE(2),FC(2),FR(2),FTR(2),D(2)
15 PRINT"!!! ADJUST DIGIT FIELDS IN STATMENT # 410,420,430,440,AND 500 !!!"
20 LPRINT "SEQUENCE OF  POSTURES FOR ALL 8 SUBJECTS"
30 LPRINT "----------------------------------------"
40 FOR L=1 TO 2
50 FOR I=1 TO 4
60 FOR J=1 TO 4
70  PRINT "P(",I,J,L,")"
80  INPUT P$(I,J,L)
90 LPRINT P$(I,J,L),"   ";
100 NEXT J
110 LPRINT
120 NEXT I
130 NEXT L
140 PRINT"VARIABLE ?"
150 INPUT VAR$
160 LPRINT VAR$
170 LPRINT"--------------------"
180 FOR L=1 TO 2
190 FOR I=1 TO 4
200 FOR J=1 TO 4
210 PRINT "X(",I,J,L,")"
220 INPUT X(I,J,L)
230 NEXT J
240 NEXT I
250 NEXT L
260 FOR L=1 TO 2
270 FOR I=1 TO 4
280 FOR J=1 TO 4
290 TR(L,I)=TR(L,I)+X(I,J,L)
300 TC(L,I)=TC(L,I)+X(J,I,L)
310 IF P$(I,J,L) ="R" THEN TT(L,1)=TT(L,1)+X(I,J,L)
320 IF P$(I,J,L) ="T" THEN TT(L,2)=TT(L,2)+X(I,J,L)
330 IF P$(I,J,L) ="S" THEN TT(L,3)=TT(L,3)+X(I,J,L)
340 IF P$(I,J,L) ="F" THEN TT(L,4)=TT(L,4)+X(I,J,L)
350 NEXT J
360 NEXT I
370 NEXT L
380 LPRINT
390 LPRINT"  AVERAGE VALUES OF ALL 8 SUBJECTS"
400 LPRINT"-----------------------------------"
410 LPRINT USING" RACING :              #.###";(TT(1,1)+TT(2,1))/8
420 LPRINT USING" TOURING :             #.###";(TT(1,2)+TT(2,2))/8
430 LPRINT USING" SEMI-RECUMBENT :      #.###";(TT(1,3)+TT(2,3))/8
440 LPRINT USING" FULL RECUMBENT :      #.###";(TT(1,4)+TT(2,4))/8
450 LPRINT"-----------------------------------"
455 LPRINT
460 LPRINT "AVERAGE VALUES OF ALL 4 POSTURES FOR EACH SUBJECT"
470 LPRINT"-------------------------------------------------"
```

```
480 FOR L=1 TO 2
490 FOR I=1 TO 4
500 LPRINT USING " #.###";TR(L,I)/4 ;
510 NEXT I
520 NEXT L
530 LPRINT"---------------------------------------------------------"
540 FOR L=1 TO 2
550 T1=0:T2=0:T3=0
560 FOR I=1 TO 4
570 T1=T1+TR(L,I)
580 T2=T2+TC(L,I)
590 T3=T3+TT(L,I)
600 NEXT I
610 T(L)=T1
620 TGRAND=TGRAND+T(L)
630 D(L)=T(L)^2/16
640 NEXT L
650 FOR L=1 TO 2
660 FOR I=1 TO 4
670 FOR J=1 TO 4
680 SST(L)=SST(L)+X(I,J,L)^2
690 NEXT J
700 SSC(L)=SSC(L)+TC(L,I)^2/4
710 SSR(L)=SSR(L)+TR(L,I)^2/4
720 SSTR(L)=SSTR(L)+TT(L,I)^2/4
730 NEXT I
740 SST(L)=SST(L)-D(L)
750 SSC(L)=SSC(L)-D(L)
760 SSR(L)=SSR(L)-D(L)
770 SSTR(L)=SSTR(L)-D(L)
780 SSE(L)=SST(L)-SSC(L)-SSR(L)-SSTR(L)
790 NEXT L
800 FOR L=1 TO 2
810 MSC(L)=SSC(L)/3
820 MSR(L)=SSR(L)/3
830 MSTR(L)=SSTR(L)/3
840 MSE(L)=SSE(L)/6
850 NEXT L
860  FOR L=1 TO 2
870 FC(L)=MSC(L)/MSE(L)
880 FR(L)=MSR(L)/MSE(L)
890 FTR(L)=MSTR(L)/MSE(L)
900 NEXT L
910 FOR L= 1 TO 2
920 LPRINT
930 LPRINT " LATIN SQUARE # ",L
940 LPRINT "-----------------------------------------------------------------------"
950 FOR I=1 TO 4
960 FOR J=1 TO 4
970 LPRINT X(I,J,L),"   ";
980 NEXT J
990 LPRINT
1000 NEXT I
1010 LPRINT
1020 LPRINT "--------------------------------------------------------------------"
```

```
1030 LPRINT"                    SS           df                 MS                F"
1040 LPRINT"--------------------------------------------------------------------"
1050 LPRINT"TREATMENT" ,SSTR(L),3,MSTR(L),FTR(L)
1060 LPRINT"SUBJECTS ",SSR(L),3,MSR(L),FR(L)
1070 LPRINT"SEQUENCE ",SSC(L),3,MSC(L),FC(L)
1080 LPRINT"ERROR    ",SSE(L),6,MSE(L)
1090 NEXT L
1100 LPRINT
1110 LPRINT
1120 LPRINT "COMBINED LATIN SQUARES"
1130 LPRINT "-----------------------------------------------------------------------"
1140 SSTR2=SSTR(1)+SSTR(2)
1150 SSR2=SSR(1)+SSR(2)
1160 SSC2=SSC(1)+SSC(2)
1170 SSSQ=(T(1)^2+T(2)^2)/16-TGRAND^2/32
1180 SSE2=SSE(1)+SSE(2)
1190 MSTR2=SSTR2/6
1200 MSR2=SSR2/6
1210 MSC2=SSC2/6
1220 MSSSQ=SSSQ/1
1230 MSE2=  SSE2/12
1240 FTR2=MSTR2/MSE2
1250 FR2=MSR2/MSE2
1260 FC2=MSC2/MSE2
1270 FS=MSSSQ/MSE2
1280 LPRINT"                    SS           df                 MS                F"
1290 LPRINT"--------------------------------------------------------------------"
1300 LPRINT"TREATMENT",SSTR2,6,MSTR2,FTR2
1310 LPRINT"SUBJECTS ",SSR2,6,MSR2,FR2
1320 LPRINT"SEQUENCE ",SSC2,6,MSC2,FC2
1330 LPRINT"SQUARES  ",SSSQ,1,MSSSQ,FS
1340 LPRINT"ERROR    ",SSE2,12,MSE2
1380 END
```

APPENDIX B

Tables

Table 1. Anthropometric, Physical, and Physiological Characteristics of Subjects.

Subj. #	H (in)	W (in)	LL (in)	LW (lb)	IL (in)	UTC (in)	MCC (in)
1	71.1	190	44.6	34.7	34.7	25.5	15.6
2	67.7	130	42.5	23.1	34.0	20.0	12.5
3	69.6	148	43.3	27.0	33.5	21.0	14.5
4	68.0	168	42.5	31.0	33.5	23.0	15.5
5	68.5	168	42.5	30.7	32.0	24.1	14.2
6	63.6	148	40.0	28.5	31.0	23.5	14.3
7	64.0	135	39.5	24.9	30.0	21.0	13.3
8	67.7	150	42.0	28.2	33.0	22.0	14.8
Mean	67.5	154.6	42.1	28.5	32.7	22.5	14.4
+/- s.d.	2.6	19.7	1.6	3.7	1.6	1.9	1.0

Subj. #	Age	Smoker	Max. HR	% Max HR	Max Vo_2	% Max Vo_2	Physical Fitness	Cycling
1	30	-	190	61	4.60	37	Excellent	-
2	22	-	198	75	2.40	66	Moderate	-
3	21	-	199	71	2.90	61	Moderate	-
4	29	-	191	84	2.35	75	Low	-
5	22	-	198	68	3.27	50	Moderate	-
6	23	10*	197	88	1.70	83	Low	-
7	23	-	197	77	1.98	68	Moderate	10+
8	28	12*	192	69	3.13	52	Moderate	-
Mean	24.8			74	2.79	61.5		
+/- s.d.	3.6							

* cigarettes per day
\+ minutes per day in touring posture

Table 1 (Continued).

Chest Circumference at Rest

Subj. #	R	T	S	F	Average
1	39.0	37.0	39.0	38.5	38.4
2	33.5	31.5	31.0	32.5	32.1
3	35.0	34.0	33.5	34.0	34.1
4	38.5	37.0	37.0	36.5	37.3
5	36.3	34.0	35.3	35.0	35.1
6	35.0	34.3	34.0	33.5	34.2
7	35.5	34.0	35.0	34.5	34.8
8	34.5	33.3	33.0	33.5	33.6
Average	35.9	34.4	34.7	34.7	

Table 2: Vo_2 at Rest

#	R	T	S	F	Mean
1	442	399	334	321	374
2	358	258	215	187	255
3	280	249	240	211	245
4	364	320	322	263	317
5	497	256	343	295	348
6	341	241	247	200	257
7	269	189	201	232	223
8	328	337	202	238	276
Mean	360	281	263	243	

Table 3: ANOVA for Vo_2 at Rest

Source of Variation	SS	df	MS	F
Treatment	65,769.8	6	10,961.6	5.92
Subjects	76,730.8	6	12,788.5	6.90
Sequence	7,410.8	6	1,235.1	0.67
Squares	3,762.8	1	3,762.8	2.04
Error	22,240.3	12	1,853.4	

Table 4. Single Degree of Freedom Test on Vo_2 at Rest

MSE = 1853.4

T_R = 2879.2 T_T = 2248.8

T_S = 2104.0 T_F = 1947.2

H_o	Multi- pliers	Q2	F	F.05, 1, 28	SIG. ?	Result
$\mu_T-\mu_R=0$	1, -1	24,837.8	13.4	4.2	Yes	Reject H_o
$\mu_T-\mu_S=0$	1, -1	1,310.4	0.7	4.2	No	
$\mu_T-\mu_F=0$	1, -1	5,685.2	3.07	4.2	No	
$\mu_R-\mu_S=0$	1, -1	37,558.4	20.3	4.2	Yes	Reject H_o
$\mu_R-\mu_F=0$	1, -1	54,289	29.3	4.2	Yes	Reject H_o
$\mu_F-\mu_S=0$	1, -1	1,536.6	0.83	4.2	No	

Table 5: Vo_2 at Steady-State

#	R	T	S	F	Mean
1	1754	1694	1671	1641	1690
2	1581	1584	1621	1590	1594
3	1623	1758	1531	1612	1631
4	1890	1759	1670	1687	1752
5	1717	1654	1607	1631	1652
6	1441	1424	1537	1610	1503
7	1630	1339	1490	1492	1488
8	1419	1641	1368	1206	1409
Mean	1632	1607	1562	1559	

Table 6: ANOVA for Vo_2 at Steady-State

Source of Variation	SS	df	MS	F
Treatment	34,460	6	5,743.3	0.45
Subjects	181,440	6	30,240.0	2.57
Sequence	57,340	6	9,556.7	0.81
Squares	188,952	1	188,952.0	16.03
Error	141,460	12	11,788.3	

Table 7: Vo_2/Weight at Steady-State

#	R	T	S	F	Mean
1	9.23	8.92	8.79	8.64	8.89
2	12.16	12.18	12.47	12.23	12.26
3	10.97	11.88	10.34	10.89	11.02
4	11.25	10.47	9.94	10.04	10.43
5	10.22	9.85	9.57	9.71	9.84
6	9.74	9.62	10.39	10.88	10.16
7	12.07	9.92	11.04	11.05	11.02
8	9.46	10.94	9.12	8.04	9.39
Mean	10.64	10.47	10.21	10.18	

Table 8: ANOVA for Vo_2/Weight at Steady-State

Source of Variation	SS	df	MS	F
Treatment	1.32	6	0.22	0.40
Subjects	29.13	6	4.85	8.78
Sequence	2.47	6	0.41	0.74
Squares	2.41	1	2.41	4.36
Error	6.64	12	0.553	

Table 9: Net Vo_2

#	R	T	S	F	Mean
1	1312	1295	1337	1320	1316
2	1223	1326	1406	1403	1340
3	1343	1509	1290	1401	1386
4	1526	1439	1348	1424	1434
5	1220	1398	1264	1336	1305
6	1100	1183	1296	1410	1247
7	1361	1150	1289	1260	1265
8	1091	1304	1166	968	1132
Mean	1272	1326	1300	1315	

Table 10: ANOVA for Net Vo_2

Source of Variation	SS	df	MS	F
Treatment	17,938	6	2,989.7	0.21
Subjects	98,540	6	16,423.3	1.14
Sequence	30,520	6	5,086.7	0.35
Squares	138,600	1	138,600	9.63
Error	172,614	12	14,384.5	

Table 11: HR at Rest

#	R	T	S	F	Mean
1	80.3	78.0	74.4	65.6	74.6
2	98.9	93.0	90.3	75.1	89.3
3	77.8	71.6	71.2	72.6	73.3
4	87.8	96.3	91.0	81.6	89.2
5	90.6	70.5	72.0	54.9	72.0
6	111.3	98.5	95.0	65.8	92.7
7	89.0	88.7	67.1	70.1	78.7
8	65.2	60.1	65.0	58.4	62.2
Mean	87.6	82.1	78.3	68.0	

Table 12: ANOVA for HR at Rest

Source of Variation	SS	df	MS	F
Treatment	1,852.4	6	308.7	5.71
Subjects	2,905.9	6	484.3	8.96
Sequence	273.5	6	45.6	0.84
Squares	216.8	1	216.8	4.01
Error	648.5	12	54.04	

Table 13. Single Degree of Freedom Test on HR at Rest

MSE = 54.04

T_R = 700.8 T_S = 626.4

T_T = 656.8 T_F = 544.0

H_o	Multi-pliers	Q2	F	F.05, 1, 28	SIG. ?	Result
$\mu_T-\mu_R=0$	1, -1	121.0	2.24	4.2	No	
$\mu_T-\mu_S=0$	1, -1	57.76	1.07	4.2	No	
$\mu_T-\mu_F=0$	1, -1	795.24	14.7	4.2	Yes	Reject H_o
$\mu_R-\mu_S=0$	1, -1	345.96	6.4	4.2	Yes	Reject H_o
$\mu_R-\mu_F=0$	1, -1	1536.64	28.4	4.2	Yes	Reject H_o
$\mu_F-\mu_S=0$	1, -1	424.36	7.85	4.2	Yes	Reject H_o

Table 14: HR at Steady-State

#	R	T	S	F	Mean
1	123.1	111.2	111.8	118.0	116.0
2	155.0	149.7	147.7	139.9	148.1
3	142.6	142.0	138.0	140.8	140.9
4	167.2	160.4	152.1	158.4	159.5
5	143.2	129.2	129.4	134.5	134.1
6	178.9	171.2	170.5	171.9	173.1
7	156.4	151.9	141.4	156.7	151.6
8	136.2	130.9	135.7	130.9	133.4
Mean	150.3	143.3	140.8	143.9	

Table 15: ANOVA for HR at Steady-State

Source of Variation	SS	df	MS	F
Treatment	411.8	6	68.6	3.56
Subjects	8,270.0	6	1,378.3	71.41
Sequence	51.1	6	8.5	0.44
Squares	385.1	1	385.1	19.95
Error	231.63	12	19.30	

Table 16. Single Degree of Freedom Test on HR at Steady-State

MSE = 19.3

T_R = 1202.4 T_S = 1126.4

T_T = 1146.4 T_F = 1151.2

H_o	Multi-pliers	Q2	F	F.05, 1, 28	SIG. ?	Result
$\mu_T-\mu_R=0$	1, -1	196	10.2	4.2	Yes	Reject H_o
$\mu_T-\mu_S=0$	1, -1	25	1.3	4.2	No	
$\mu_T-\mu_F=0$	1, -1	1.44	0.07	4.2	No	
$\mu_R-\mu_S=0$	1, -1	361	18.7	4.2	Yes	Reject H_o
$\mu_R-\mu_F=0$	1, -1	163.8	8.5	4.2	Yes	Reject H_o
$\mu_F-\mu_S=0$	1, -1	38.4	2.0	4.2	No	

Table 17: SV at Rest

#	R	T	S	F	Mean
1	51	56	74	64	61
2	58	46	50	59	53
3	69	78	67	73	72
4	56	44	52	65	54
5	105	78	90	127	100
6	61	50	26	49	47
7	57	56	70	63	62
8	92	58	68	58	69
Mean	69	58	62	70	

Table 18: ANOVA for SV at Rest

Source of Variation	SS	df	MS	F
Treatment	1,084.8	6	180.8	1.20
Subjects	6,965.8	6	1,161.0	7.71
Sequence	713.8	6	119.0	0.79
Squares	666.1	1	666.1	4.42
Error	1,806.5	12	150.54	

Table 19: SV at Steady-State

#	R	T	S	F	Mean
1	141	142	182	167	158
2	113	183	179	181	164
3	117	105	136	121	120
4	110	93	78	88	92
5	93	118	108	119	110
6	68	60	63	109	75
7	168	82	154	103	127
8	127	146	135	133	135
Mean	117	116	129	128	

Table 20: ANOVA for SV at Steady-State

Source of Variation	SS	df	MS	F
Treatment	1,839.8	6	306.6	0.44
Subjects	22,215.8	6	3,702.6	5.36
Sequence	2,779.8	6	463.3	0.67
Squares	3,828.1	1	3,828.1	5.54
Error	8,296.5	12	691.4	

Table 21: Q at Rest

#	R	T	S	F	Mean
1	4.1	4.4	5.1	4.2	4.5
2	5.7	4.3	4.5	4.4	4.7
3	5.4	5.6	4.8	5.3	5.3
4	4.9	4.2	4.7	5.3	4.8
5	9.5	5.5	6.5	7.0	7.1
6	6.8	4.9	2.6	3.2	4.4
7	5.1	5.0	4.7	4.4	4.8
8	6.0	3.5	4.4	3.4	4.3
Mean	5.9	4.7	4.7	4.7	

Table 22: ANOVA for Q at Rest

Source of Variation	SS	df	MS	F
Treatment	15.74	6	2.62	3.54
Subjects	22.63	6	3.77	5.08
Sequence	2.25	6	0.38	0.51
Squares	0.98	1	0.98	1.32
Error	8.90	12	0.742	

Table 23: Single Degree of Freedom Test on Q at Rest

MSE = 0.7419

T_R = 47.2

T_T = 37.6

T_S = 37.6

T_F = 37.6

H_o	Multi-pliers	Q^2	F	F.05, 1, 28	SIG. ?	Result
$\mu_R-\mu_T=0$ $\mu_R-\mu_S=0$ $\mu_R-\mu_F=0$	1, -1	5.76	7.8	4.2	Yes	Reject H_o

Table 24: Q at Steady-State

#	R	T	S	F	Mean
1	17.3	15.8	20.1	19.7	18.2
2	17.5	27.4	26.4	25.3	24.2
3	16.7	14.9	18.7	17.1	16.9
4	18.4	14.9	11.9	13.9	14.8
5	13.3	15.2	14.0	16.0	14.6
6	12.2	10.2	10.7	18.8	13.0
7	26.2	12.4	21.7	16.1	19.2
8	17.3	19.1	18.3	17.4	18.0
Mean	17.4	16.2	17.7	18.0	

Table 25: ANOVA for Q at Steady-State

Source of Variation	SS	df	MS	F
Treatment	31.81	6	5.30	0.35
Subjects	295.33	6	49.21	3.27
Sequence	61.48	6	10.25	0.68
Squares	42.09	1	42.09	2.80
Error	180.59	12	15.05	

Table 26: $(a-v)O_2$ Diff. at Rest

#	R	T	S	F	Mean
1	107.8	90.7	65.5	76.4	85.1
2	62.8	60.0	47.8	42.5	53.3
3	51.9	44.5	50.0	39.8	46.6
4	74.3	76.2	68.5	49.6	67.1
5	52.3	46.5	52.8	42.1	48.4
6	50.1	49.2	95.0	62.5	64.2
7	52.7	37.8	42.8	52.7	46.5
8	54.7	96.3	45.9	70.0	66.7
Mean	63.3	62.7	58.5	54.4	

Table 27: ANOVA for $(a-v)O_2$ Diff. at Rest

Source of Variation	SS	df	MS	F
Treatment	1,272.5	6	212.1	0.90
Subjects	4,799.4	6	799.9	3.40
Sequence	807.2	6	134.5	0.57
Squares	343.9	1	343.9	1.46
Error	2,825.1	12	235.4	

Table 28: $(a-v)O_2$ Diff. at Steady-State

#	R	T	S	F	Mean
1	101.4	107.2	83.1	83.3	93.8
2	90.3	57.8	61.4	62.8	68.1
3	97.2	118.0	81.8	94.3	97.8
4	102.7	118.1	140.3	121.4	120.6
5	129.1	108.8	114.8	101.9	113.7
6	118.1	139.6	143.6	85.6	121.7
7	62.2	108.0	68.7	92.7	82.9
8	82.0	85.9	74.8	69.3	78.0
Mean	97.9	105.4	96.1	88.9	

Table 29: ANOVA for $(a-v)O_2$ Diff. at Steady-State

Source of Variation	SS	df	MS	F
Treatment	1,363.0	6	227.2	0.68
Subjects	11,289.5	6	1,881.6	5.61
Sequence	1,173.4	6	195.6	0.58
Squares	128.0	1	128.0	0.38
Error	4,027.9	12	335.66	

Table 30: V_E at Rest

#	R	T	S	F	Mean
1	17.2	16.7	13.6	14.8	15.6
2	16.9	10.6	11.1	8.1	11.6
3	12.0	11.3	10.4	9.6	10.8
4	12.6	12.9	10.1	12.4	12.0
5	15.7	10.2	12.1	11.9	12.5
6	14.0	10.6	10.2	8.6	10.9
7	11.5	8.1	8.9	9.6	9.5
8	11.2	11.6	8.0	9.0	10.0
Mean	13.9	11.5	10.5	10.5	

Table 31: ANOVA for V_E at Rest

Source of Variation	SS	df	MS	F
Treatment	63.29	6	10.55	3.74
Subjects	73.57	6	12.26	4.35
Sequence	9.35	6	1.56	0.55
Squares	26.10	1	26.10	9.25
Error	33.85	12	2.82	

Table 32. Single Degree of Freedom Test on V_E at Rest

MSE = 2.821

T_R = 111.2 T_S = 84.0

T_T = 92.0 T_F = 84.0

H_o	Multi-pliers	Q2	F	F.05, 1, 28	SIG. ?	Result
$\mu_T-\mu_R=0$	1, -1	23.04	8.2	4.2	Yes	Reject H_o
$\mu_T-\mu_S=0$	1, -1	4.0	1.4	4.2	No	
$\mu_T-\mu_F=0$	1, -1	4.0	1.4	4.2	No	
$\mu_R-\mu_S=0$	1, -1	46.24	16.4	4.2	Yes	Reject H_o
$\mu_R-\mu_F=0$	1, -1	46.24	16.4	4.2	Yes	Reject H_o
$\mu_F-\mu_S=0$	1, -1	0	0	4.2	No	

Table 33: V_E at Steady-State

#	R	T	S	F	Mean
1	50.7	49.5	46.7	49.5	49.1
2	49.4	45.4	47.1	48.4	47.6
3	55.2	51.5	45.4	52.7	51.2
4	83.5	68.0	54.6	65.5	67.9
5	50.8	41.7	42.8	49.3	46.2
6	48.3	48.4	48.0	53.0	49.4
7	45.1	39.8	43.2	45.9	43.5
8	41.2	40.2	39.1	40.8	40.3
Mean	53.0	48.1	45.9	50.6	

Table 34: ANOVA for V_E at Steady-State

Source of Variation	SS	df	MS	F
Treatment	317.4	6	52.9	3.41
Subjects	1,245.0	6	207.5	13.36
Sequence	96.2	6	16.0	1.03
Squares	661.6	1	661.6	42.60
Error	186.4	12	15.53	

Table 35. Single Degree of Freedom Test on V_E at Steady-State

MSE = 15.53

T_R = 424.0 T_S = 367.2

T_T = 384.8 T_F = 404.8

H_o	Multi-pliers	Q2	F	F.05, 1, 28	SIG. ?	Result
$\mu_T-\mu_R=0$	1, -1	96.04	6.2	4.2	Yes	Reject H_o
$\mu_T-\mu_S=0$	1, -1	19.36	1.3	4.2	No	
$\mu_T-\mu_F=0$	1, -1	25.00	1.6	4.2	No	
$\mu_R-\mu_S=0$	1, -1	201.6	13.0	4.2	Yes	Reject H_o
$\mu_R-\mu_F=0$	1, -1	23.04	1.5	4.2	No	
$\mu_F-\mu_S=0$	1, -1	88.36	5.7	4.2	Yes	Reject H_o

Table 36: RR at Rest

#	R	T	S	F	Mean
1	13.5	13.8	9.7	12.4	12.4
2	28.6	17.8	18.8	12.0	19.3
3	18.8	19.6	16.0	15.6	17.5
4	18.0	23.3	17.0	18.6	19.2
5	20.8	19.3	22.3	25.0	21.9
6	18.0	17.5	21.8	18.0	18.8
7	18.8	16.0	18.5	18.0	17.8
8	17.1	17.2	16.5	14.5	16.3
Mean	19.2	18.1	17.6	16.8	

Table 37: ANOVA for RR at Rest

Source of Variation	SS	df	MS	F
Treatment	83.28	6	13.88	1.88
Subjects	193.69	6	32.28	4.37
Sequence	55.45	6	9.24	1.25
Squares	20.80	1	20.80	2.82
Error	88.59	12	7.38	

Table 38: RR at Steady-State

#	R	T	S	F	Mean
1	28.9	27.8	30.3	32.2	29.8
2	43.1	38.9	43.9	45.3	42.8
3	37.8	31.5	28.8	33.2	32.8
4	57.3	50.2	37.8	45.3	47.7
5	33.6	27.6	32.4	35.4	32.3
6	34.6	36.6	41.0	39.0	37.8
7	29.4	27.3	27.7	30.3	28.7
8	29.7	26.6	30.1	28.5	28.7
Mean	36.8	33.3	34.0	36.2	

Table 39: ANOVA for RR at Steady-State

Source of Variation	SS	df	MS	F
Treatment	128.1	6	21.4	2.27
Subjects	1,061.2	6	176.9	18.80
Sequence	107.7	6	17.9	1.91
Squares	328.3	1	328.3	34.86
Error	113.0	12	9.42	

Table 40: TV at Rest

#	R	T	S	F	Mean
1	1.51	1.30	1.53	1.33	1.42
2	0.59	0.64	0.61	0.73	0.64
3	0.66	0.58	0.65	0.62	0.63
4	0.69	0.56	0.59	0.66	0.63
5	0.76	0.54	0.56	0.49	0.59
6	0.78	0.62	0.47	0.48	0.59
7	0.61	0.52	0.48	0.53	0.53
8	0.66	0.67	0.49	0.62	0.61
Mean	0.78	0.68	0.67	0.68	

Table 41: ANOVA for TV at Rest

Source of Variation	SS	df	MS	F
Treatment	0.115	6	1.92E-02	3.32
Subjects	1.865	6	0.311	53.65
Sequence	0.019	6	3.20E-03	0.55
Squares	0.493	1	0.493	85.00
Error	6.95E-02	12	5.795E-03	

Table 42. Single Degree of Freedom Test on TV at Rest

MSE = 0.005795

T_R = 6.24 T_S = 5.36

T_T = 5.44 T_F = 5.44

H_o	Multi-pliers	Q2	F	F.05, 1, 28	SIG. ?	Result
$\mu_T-\mu_R=0$	1, -1	0.04	6.9	4.2	Yes	Reject H_o
$\mu_T-\mu_S=0$	1, -1	0.0004	0.07	4.2	No	
$\mu_T-\mu_F=0$	1, -1	0	0	4.2	No	
$\mu_R-\mu_S=0$	1, -1	0.0484	8.4	4.2	Yes	Reject H_o
$\mu_R-\mu_F=0$	1, -1	0.04	6.9	4.2	Yes	Reject H_o
$\mu_F-\mu_S=0$	1, -1	0.0004	0.07	4.2	No	

Table 43: TV at Steady-State

#	R	T	S	F	Mean
1	1.76	1.82	1.55	1.56	1.67
2	1.17	1.17	1.08	1.07	1.12
3	1.50	1.64	1.58	1.59	1.58
4	1.46	1.36	1.46	1.46	1.44
5	1.52	1.53	1.33	1.40	1.45
6	1.40	1.33	1.17	1.36	1.32
7	1.54	1.47	1.57	1.53	1.53
8	1.40	1.52	1.31	1.44	1.42
Mean	1.47	1.48	1.38	1.43	

Table 44: ANOVA for TV at Steady-State

Source of Variation	SS	df	MS	F
Treatment	5.66E-02	6	9.443E 03	2.71
Subjects	0.785	6	0.131	37.62
Sequence	7.21E-02	6	1.20E-02	3.45
Squares	5.24E-03	1	5.24E-03	1.51
Error	4.17E-02	12	3.478E-03	

Table 45: Caloric Equivalence of Oxygen (E_c)

Latin Square Design #1

Sub. #	Posture	Vo_2 (Rest)	Vo_2 (S.S.)	RER (rest)	RER (S.S.)	$KCal/O_2$ (rest)	$Kcal/O_2$ (S.S.)	E_c (rest)	E_c (S.S.)	Net E_c
1	T	399	1694	1.00*	1.00*	5.047	5.047	2.014	8.550	6.536
	R	442	1754	1.00*	1.00*	5.047	5.047	2.231	8.852	6.621
	S	334	1671	1.00*	1.00*	5.047	5.047	1.686	8.434	6.748
	F	321	1641	1.00*	1.00*	5.047	5.047	1.620	8.282	6.662
2	F	187	1590	0.85	100*	4.862	5.047	0.909	8.025	7.116
	T	258	1584	0.81	1.00*	4.813	5.047	1.242	7.994	6.752
	R	358	1581	1.00*	1.00*	5.047	5.047	1.807	7.974	6.167
	S	215	1621	1.00*	1.00*	5.047	5.047	1.085	8.181	7.096
3	S	240	1530	0.99	1.00*	5.035	5.047	1.208	7.722	6.514
	F	211	1612	1.00*	1.00*	5.047	5.047	1.065	8.136	7.071
	T	249	1758	0.84	1.00*	4.850	5.047	1.208	8.873	7.665
	R	280	1623	0.94	1.00*	4.973	5.047	1.392	8.871	6.679
4	R	364	1890	0.87	1.00*	4.887	5.047	1.779	9.539	7.760
	S	322	1670	0.73	1.00*	4.714	5.047	1.518	8.428	6.910
	F	263	1687	1.00*	1.00*	5.047	5.047	1.327	8.514	7.187
	T	320	1759	0.82	1.00*	4.825	5.047	1.544	8.878	7.334

Table 45 (continued).

Latin Square Design #2

Sub. #	Posture	Vo_2 (Rest)	Vo_2 (S.S.)	RER (rest)	RER (S.S.)	$KCal/O_2$ (rest)	$Kcal/O_2$ (S.S.)	E_c (rest)	E_c (S.S.)	Net E_c
5	R	497	1717	0.94	1.00*	4.973	5.047	2.472	8.666	6.194
	S	343	1607	0.86	1.00*	4.875	5.047	1.672	8.111	6.438
	T	256	1654	0.82	0.95	4.825	4.985	1.235	8.245	7.010
	F	295	1631	0.89	1.00*	4.911	5.047	1.449	8.232	6.783
6	F	172	1610	0.95	1.00*	4.985	5.047	0.857	8.126	7.269
	T	241	1424	0.81	1.00*	4.813	5.047	1.160	7.187	6.027
	R	341	1441	0.90	1.00*	4.924	5.047	1.679	7.273	5.594
	S	247	1537	0.73	0.94	4.714	4.973	1.164	7.644	6.480
7	S	201	1490	0.97	1.00*	5.010	5.047	1.007	7.520	6.513
	R	269	1630	1.00*	1.00*	5.047	5.047	1.358	8.227	6.869
	F	232	1492	0.97	1.00*	5.010	5.047	1.162	7.530	6.368
	T	189	1339	0.92	1.00*	4.948	5.047	0.935	6.758	5.823
8	T	337	1641	0.86	0.93	4.875	4.961	1.643	8.141	6.498
	F	238	1206	0.99	1.00*	5.035	5.047	1.198	6.087	4.889
	S	202	1368	0.84	1.00*	4.850	5.047	0.980	6.904	5.924
	R	328	1419	0.94	1.00*	4.973	5.047	1.631	7.162	5.531

NOTES:
1. $Kcal/O_2$ = Kcalories consumed per one liter of O_2 uptake
2. RER values are taken from reference Fox and Mathews, 1981, p. 61.
3. Asterisks (*) indicate rounding off RER values exceeding units.
4. E_c = Energy consumption in Kcal./min. = $\frac{Vo_2 * Kcal/O_2}{1000}$

Table 46: E_c at Rest

#	R	T	S	F	Sum
1	2.231	2.014	1.686	1.620	1.888
2	1.807	1.242	1.085	0.909	1.261
3	1.392	1.208	1.208	1.065	1.218
4	1.779	1.544	1.518	1.327	1.542
5	2.472	1.235	1.672	1.449	1.707
6	1.679	1.160	1.164	0.857	1.215
7	1.358	0.935	1.007	1.162	1.116
8	1.631	1.643	0.980	1.198	1.363
Sum	1.794	1.373	1.290	1.198	

Table 47: ANOVA for E_c at Rest

	SS	df	MS	F
Treatment	1.731	6	0.289	5.52
Subjects	1.950	6	0.325	6.23
Sequence	0.153	6	2.54E-02	0.49
Square	0.129	1	0.129	2.47
Error	0.626	12	5.219E-02	

Table 48: Single Degree of Freedom Test on E_c at Rest

MSE = .0522

T_R = 14.352 T_S = 10.320

T_T = 10.984 T_F = 9.584

H_o	Multi-pliers	Q2	F	F.05, 1, 28	SIG. ?	Result
$\mu_T-\mu_R=0$	1, -1	0.71	13.6	4.2	Yes	Reject H_o
$\mu_T-\mu_S=0$	1, -1	0.028	0.5	4.2	No	
$\mu_T-\mu_F=0$	1, -1	0.123	2.3	4.2	No	
$\mu_R-\mu_S=0$	1, -1	1.02	19.5	4.2	Yes	Reject H_o
$\mu_R-\mu_F=0$	1, -1	1.42	27.2	4.2	Yes	Reject H_o
$\mu_F-\mu_S=0$	1, -1	0.034	0.65	4.2	No	

Table 49: E_c at Steady-State

#	R	T	S	F	Mean
1	8.852	8.550	8.434	8.282	8.530
2	7.974	7.994	8.181	8.025	8.044
3	8.071	8.873	7.722	8.136	8.200
4	9.539	8.878	8.428	8.514	8.840
5	8.666	8.245	8.111	8.232	8.313
6	7.273	7.187	7.644	8.126	7.558
7	8.227	6.758	7.520	7.530	7.509
8	7.162	8.141	6.904	6.087	7.074
Mean	8.221	8.078	7.868	7.867	

Table 50: ANOVA for E_c at Steady-State

Source of Variation	SS	df	MS	F
Treatment	0.844	6	0.141	0.50
Subjects	4.691	6	0.782	2.77
Sequence	1.389	6	0.231	0.82
Square	4.993	1	4.993	17.66
Error	3.392	12	0.283	

Table 51: Net Efficiency

#	R	T	S	F	Mean
1	19.3	19.6	18.9	19.2	19.3
2	20.7	18.9	18.0	18.0	18.9
3	19.1	16.7	19.6	18.1	18.4
4	16.5	17.4	18.5	17.8	17.5
5	20.6	18.2	19.9	18.8	19.4
6	22.9	21.2	19.7	17.6	20.4
7	18.6	22.0	19.6	20.1	20.1
8	23.1	19.7	21.6	26.1	22.6
Mean	20.1	19.2	19.5	19.5	

$$\text{Net efficiency} = \frac{\text{90 watts}}{\text{net } E_c} = \frac{\text{1.278 Kcal/min.}}{\text{net } E_c}$$

Table 52: ANOVA for Net Efficiency

Source of Variation	SS	df	MS	F
Treatment	4.61	6	0.77	0.21
Subjects	30.31	6	5.05	1.36
Sequence	9.49	6	1.58	0.42
Squares	34.86	1	34.86	9.35
Error	44.72	12	3.73	

Table 53: Gross Efficiency

#	R	T	S	F	Mean
1	14.4	15.0	15.2	15.4	15.0
2	16.0	16.0	15.6	15.9	15.9
3	15.8	14.4	16.6	15.7	15.6
4	13.4	14.4	15.2	15.0	14.5
5	14.8	15.5	15.8	15.5	15.4
6	17.6	17.8	16.7	15.7	17.0
7	15.5	18.9	17.0	17.0	17.1
8	17.8	15.7	18.5	21.0	18.3
Mean	15.7	16.0	16.3	16.4	

$$\text{Grosss Efficiency} = \frac{90 \text{ watts}}{E_c(\text{S.S.})} = \frac{1.278 \text{ Kcal/min.}}{E_c \text{ (steady-state)}}$$

Table 54. ANOVA for Gross Efficiency.

SS	df	MS	F
3.34	6	0.56	0.37
21.08	6	3.51	2.33
7.14	6	1.19	0.79
22.44	1	22.44	14.88
18.10	12	1.51	

Table 55. Correlation Coefficient (r) between Vo_2 and HR for Male Subjects.

Reference	Subjects	Load (watts)	Posture	r	Z	n
current study	normal	90	R	-0.11	-.25	8
		90	T	-.43	-1.03	8
		90	S	-.14	-.32	8
		90	F	+.21	.48	8
Holmgren et al., (1960)	normal	49	F	-.50	-1.8	14
		98	F	-.43	-1.5	14
		147	F	+.23	.62	10
Bevegard et al., (1963)	well-trained athletes	131	T	+.36	.75	7
		262	T	+.26	.60	8
		131	F	+.59	1.52	8
		262	F	-.21	-.48	8
Bevegard et al., (1966)	normal	82	T	+.32	.57	6
		164	T	+.53	1.00	6
		82	F	-.47	-.88	6
		164	F	+.62	1.26	6

$$z = 1/2 \ln \left(\frac{1 + r}{1 - r}\right) \div \frac{1}{\sqrt{n-3}}$$ n = number of subjects

H_o: ρ = o, H_a: ρ = o
Rejection Region: $Z > |Z_{.05}| = 1.96$

Table 56 : Summary of Racing VO_2 Data (8 subjects)

Subject/ Time	1	2	3	4	5	6	7	8	Avg
4	808	657	585	962	926	733	722	744	767
5	1316	1006	677	1156	1255	1081	903	700	1012
6	1330	1191	995	1264	1284	1155	999	1058	1160
7	1301	1385	1123	1164	1316	1228	1181	1299	1250
8	1992	1476	1435	1371	1590	1264	1318	1348	1474
9	1426	1161	1631	1465	1578	1421	1480	1463	1453
10	1940	1675	1540	1329	1328	1404	1426	1367	1501
11	1566	1603	1604	1611	1325	1302	1584	1500	1512
12	1764	1449	1402	1642	1700	1390	1571	1316	1529
13	1667	1513	1681	1547	1595	1380	1553	1421	1545
14	1591	1567	1516	1876	1733	1425	1610	1661	1622
15	1781	1518	1775	1729	1740	1365	1584	1499	1624
16	1710	1667	1472	1712	1509	1426	1584	1408	1561
17	1544	1439	1526	1804	1368	1185	1694	1424	1498
18	1544	1656	1588	1757	1553	1400	1443	1447	1549
19	1880	1607	1722	1776	1703	1532	1541	1449	1651
20	1791	1619	1735	1785	1724	1353	1535	1220	1595
21	1670	1496	1591	1821	1693	1482	1686	1509	1619
22	1637	1615	1382	1764	1764	1431	1703	1310	1576
23	1858	1554	1730	1902	1833	1224	1523	1583	1651
24	1746	1654	1593	1798	1564	1509	1758	1459	1635
25	2071	1304*	1565	1824	1514	1566	1836	1386	1680
26	1748	494*	1493	1905	1917	1418		1403	
27	1687	1026*	1794	1874	1941	1490		1410	
28	1539	1519	1254	1955	1517	1402		1462	
29	1792			1934					
30				1887					
31				2055					

* Artifacts not considered in computation

Table 57: Summary of Touring VO_2 Data (8 subjects)

Subject/ Time	1	2	3	4	5	6	7	8	Avg
4	954	321	593	853	638	700	621	554	654
6	1217	547	888	841	1127	902	731	691	868
7	1507	776	940	1056	962	1067	813	1194	983
8	1425	1110	1255	1210	1323	1168	1048	1086	1203
9	1584	1237	1511	1507	1535	1367	1193	1415	1423
10	1754	1492	1627	1503	1416	1453	1311	1462	1502
11	1825	1524	1522	1617	1444	1288	1220	1410	1481
12	1674	1454	1580	1790	1478	1420	1152	1482	1504
13	1665	1500	1834	1519	1530	1385	1430	1435	1537
14	1913	1320	1499	1721	1544	1346	1340	1494	1522
15	1600	1816	1730	1495	1485	1424	1361	1537	1556
16	1595	1643	1665	1568	1325	1351	1205	1534	1486
17	1587	1362	1958	1692	1565	1376	1328	1484	1544
18	1755	1540	1663	1775	1704	1372	1373	1760	1618
19	1622	1651	1760	1680	1498	-	1316	1605	1590
20	1646	1656	1667	1642	1532	-	1423	1586	1593
21	1638	1638	1760	1728	1622	-	1360	1660	1629
22	1936	1536	1902	1822	1581	1521	1271	1654	1653
23	1439	1600	1665	1715	1596	1418	1330	1670	1554
24	1949	1562	1743	1640	1838	1382	1256	1622	1624
25	1751	1558	1460	1869	1562	1446	1331	1600	1572
26	1588	1710	1944	1624	1635	1326	1419	1637	1610
27	1751	1404	1802	1782	1716	1544	1301	1674	1622
28	1624	1625	1874	1924	1848	1425	1333	1715	1671
29		1483		1653	1513	1302	1348	1678	
30		1738		1832	1629	1499	1439	1504	
		1624							

Table 58: Summary of Semi-Recumbent Vo_2 Data (8 subjects)

Subject/ Time	1	2	3	4	5	6	7	8	Avg
4	968	710	479	707	604	514	323	459	596
5	1175	897	595	707	909	689	603	688	783
6	1509	976	496	864	959	794	617	757	872
7	1578	1168	750	1038	1098	995	835	996	1057
8	1532	1293	1199	1215	1248	1159	1076	1128	1231
9	1757	1349	1117	1415	1515	1256	1175	1336	1365
10	1492	1476	1335	1479	1412	1329	1210	1272	1376
11	1651	1508	1265	1529	1463	1382	1355	1269	1428
12	1617	1465	1605	1596	1426	1256	1241	1213	1427
13	1953	1395	1417	1421	1622	1466	1306	1404	1498
14	1504	1720	1512	1557	1471	1216	1338	1303	1453
15	1789	1520	1456	1517	1710	1568	1478	1329	1546
16	1369	1600	1378	1533	1539	1379	1315	1265	1422
17	1724	1673	1499	1796	1571	1484	1399	1406	1569
18	1601	1420	1499	1447	1564	1506	1299	1254	1449
19	1764	1734	1548	1591	1665	1474	1499	1435	1589
20	1646	1505	1550	1550	1544	1592	1508	1333	1528
21	1546	1630	1419	1720	1767	1573	1384	1432	1559
22	1817	1604	1504	1607	1373	1443	1435	1323	1513
23		1636	1542	1603	1673	1465	1483	1296	1528
24		1550	1628	1681	1548	1484	1492	1303	1526
25		1632	1420	1665	1613	1630	1555	1428	1563
26		1593	1536	1706	1666	1595	1501	1392	1570
27		1673	1661	1751	1664	1596	1550	1308	1600
28		1656		1753	1564	1516	1488	1430	
29				1667	1656				
30									

Table 59: Summary of Full-Recumbent Vo_2 Data (8 subjects)

Subject/ Time	1	2	3	4	5	6	7	8	Avg
4	473	592	562	657	416	567	592	296	519
5	1155	688	664	1043	730	796	731	411	777
6	1155	770	874	961	701	764	837	559	828
7	1389	1173	1183	1258	823	968	1105	851	1094
8	1637	1256	1224	1367	1270	1222	1175	897	1256
9	1445	1405	1368	1476	1258	1143	1250	1039	1298
10	1725	1147	1483	1395	1245	1344	1316	972	1328
11	1250	1483	1407	1665	1396	1364	1264	1187	1377
12	1569	1456	1251	1537	1499	1280	1456	1025	1384
13	1739	1445	1684	1491	1428	1348	1299	1140	1447
14	1557	1599	1436	1538	1499	1414	1283	1144	1434
15	1786	1460	1660	1734	1496	1463	1436	1094	1517
16	1502	1536	1492	1365	1651	1330	1300	1034	1401
17	1326	1583	1658	1758	1393	1508	1516	1273	1502
18	1665	1599	1612	1483	1659	1509	1311	1180	1502
19	1712	1608	1478	1659	1609	1622	1447	1121	1532
20	1566	1521	1642	1653	1504	1508	1560	1124	1510
21	1607	1516	1658	1600	1579	1531	1417	1110	1502
22	1608	1636	1447	1717	1699	1450	1312	1264	1517
23	1673	1634	1680	1796	1697	1691	1568	1180	1615
24	1568	1312	1752	1703	1654	1565	1440	1158	1519
25	1537	1757	1669	1839	1560	1736	1575	1282	1619
26	1861	1644	1614	1533	1804	1566	1560	1162	1593
27	1609	1604	1568	1653	1550	1786	1482	1332	1573
28		1669		1716	1654	1642	1554	1239	
29								1211	
30									

Table 60: Summary of Racing HR Data For All 8 Subjects

Subject/ Time	1	2	3	4	5	6	7	8	Avg
Rest	80	99	78	88	91	111	83	65	88
1	93	118	105	110	109	115	107	93	106
2	89	120	115	120	110	120	110	93	110
3	91	115	100	121	110	140	108	94	110
Exercise									
4	98	126	105	128	122	137	114	107	117
5	105	138	122	126	134	150	129	118	128
6	111	135	121	129	130	160	138	124	131
7	109	142	124	128	132	160	138	128	133
8	112	139	130	138	131	160	144	129	135
9	113	144	135	143	133	166	147	130	139
10	110	144	135	147	128	167	147	131	139
11	115	142	133	197*	131	171	145	130	138
12	110	144	137	150	137	166	147	133	140
13	114	147	137	153	137	172	146	133	142
14	113	146	142	154	138	171	147	134	143
15	114	146	138	156	139	173	147	132	143
16	115	149	136	159	137	174	150	133	144
17	118	150	136	162	138	174	148	134	145
18	111	147	139	212*	139	175	149	135	142
19	116	153	141	162	143	177	157	135	148
20	113	150	144	165	142	176	160	138	149
21	119	156	142	161	142	179	162	132	149
22	119	151	141	163	144	179	163	133	149
23	127	156	142	166	140	176	158	136	150
24	129	154	142	166	141	180	160	137	151
25	127	153	143	167	145	181	157	136	151
26	123	157	143	168	146	180		139	151
27	122	158	143	169	145	181		139	151
28	124	162	145	172	144	180		137	152
29	128								

* Artifacts not considered in computation

Table 61: Summary of Touring HR Data for All 8 Subjects

Subject/ Time	1	2	3	4	5	6	7	8	Avg
Rest	78	93	72	96	71	99	89	60	82
1	89	92	98	109	87	113	104	74	96
2	82	103	101	112	99	117	108	82	101
3	92	108	99	153*	103	118	103	85	101
Exercise									
4	102	108	104	114	102	119	139	93	110
5	103	120	120	123	113	138	120	111	119
6	105	122	123	173*	116	145	127	116	122
7	104	127	128	135	118	151	132	120	127
8	105	134	131	144	119	154	137	120	131
9	110	136	129	144	124	156	141	120	133
10	109	140	133	149	118	162	138	121	134
11	115	140	135	150	121	160	-	121	135
12	109	142	135	150	121	165	145	123	136
13	113	140	136	150	126	163	149	125	138
14	114	145	138	152	117	163	-	123	136
15	109	143	141	154	122	167	144	126	138
16	111	145	136	156	123	169	195*	201*	140
17	110	141	139	155	123	169	149	188*	141
18	114	146	138	156	127	170	145	126	140
19	109	145	139	159	127	170	150	128	141
20	112	148	144	156	120	168	148	131	141
21	112	145	141	158	128	168	150	130	142
22	111	148	144	157	134	168	149	132	143
23	111	147	140	159	127	172	154	133	143
24	116	148	145	160	130	172	153	132	144
25	111	150	143	162	130	173	149	132	144
26	108	151	141	164	128	171	153	175*	145
27	108	151	145	161	128	173	155	128	144
28		152		163	135	174	153	130	
		155		164	132	173	155	130	

* Artifacts not considered in computation

Table 62: Summary of Semi-recumbent HR Data for All 8 Subjects

Subject/ Time	1	2	3	4	5	6	7	8	Avg
Rest	74	90	71	91	72	95	67	65	78
1	87	110	85	103	100	107	81	98	96
2	93	109	91	103	95	108	83	84	96
3	90	110	95	106	102	111	87	89	99
Exercise									
4	98	112	98	104	104	117	88	90	101
5	105	125	97	111	111	130	99	115	112
6	107	131	105	120	114	138	106	121	118
7	109	133	112	126	117	144	114	125	123
8	111	134	118	133	120	150	118	126	126
9	113	139	122	139	124	155	123	130	131
10	114	138	127	142	127	155	124	131	132
11	106	146	130	142	129	159	127	132	134
12	116	142	131	143	130	162	130	134	136
13	112	135	135	145	127	161	132	135	135
14	106	142	134	147	129	161	132	135	136
15	113	143	133	145	134	163	136	134	138
16	108	144	135	147	129	168	134	132	137
17	107	144	135	145	127	166	137	135	137
18	110	144	134	152	132	168	132	138	139
19	115	141	136	119*	131	167	135	137	137
20	111	138	138	150	123	169	138	139	138
21	117	146	134	152	122	171	139	135	139
22	119	148	136	151	126	172	143	136	141
23		149	139	155	129	169	143	136	
24		152	139	153	135	171	141	138	
25		147	140	152	131	172	143	136	
26		154	141	152	126	170	144	136	
27		152	143	77*	132	172	143	132	
28		150		104*	136	172	145	132	
				152	134				

* Artifacts not considered in computation

Table 63: Summary of Full-recumbent HR Data for All 8 Subjects

Subject/ Time	1	2	3	4	5	6	7	8	Avg
Rest	66	75	73	82	55	66	70	58	68
1	80	90	88	97	76	94	99	73	87
2	84	92	93	101	83	97	97	80	91
3	85	101	101	104	88	98	98	83	95
Exercise									
4	91	107	105	114	91	104	105	79	100
5	95	112	112	119	102	114	119	101	109
6	103	114	119	127	112	124	128	109	117
7	102	119	121	131	112	137	130	112	121
8	100	127	126	138	113	142	132	116	124
9	107	129	126	136	119	148	141	118	128
10	109	127	132	139	117	151	142	116	129
11	107	134	130	141	119	154	140	119	131
12	107	128	131	144	122	155	141	121	131
13	110	131	132	144	126	155	144	124	133
14	111	134	136	147	127	158	146	125	136
15	109	133	135	146	125	157	146	122	134
16	111	134	137	148	128	160	151	125	137
17	110	134	137	152	126	161	150	127	137
18	115	136	135	153	129	167	149	127	139
19	113	137	134	153	125	166	150	126	138
20	113	137	141	153	130	167	154	127	140
21	114	136	138	157	134	166	153	128	141
22	116	142	139	158	138	170	154	131	143
23	114	141	140	158	129	174	158	129	143
24	118	134	144	159	138	174	158	130	144
25	122	146	144	160	141	176	160	128	147
26	129	137	146	160	133	174	159	131	146
27	126	146	147	163	138	176	160	132	148
28		143		163	139	176	161	138	
								135	

Table 64. Parameters of the Regression Equation ($Vo_2 = B_0 + B_1 \times HR$) for the average values of all 8 subjects timewise.

Posture	r	B_0	B_1	n	SSE
R	.93	-2080.1	25.19	22	144,265.6
T	.96	-2432.8	28.58	24	119,866.2
S	.98	-2172.0	26.72	19	67,955.0
F	.96	-1665.7	22.72	24	136,329.3

Table 65. Resting Periods After Each Trial in Minutes.

Subject	After 1st Trial	After 2nd Trial	After 3rd Trial
1	20	25	27
2	25	28	21
3	23	53*	24
4	26	33	24
5	33	73*	67**
6	27	34	40
7	27	37	26
8	27	22	22
Average:		27.5	

* equipment failure
** operator tied-up in emergency

Table 66: Comparisons Between YP1 and YP2 Models Based on Average Values of all 8 Subjects

	Posture	SSE (YP1)	SSE (YP2)	S.S.	B_o	A^o + rest	R2 (YP1)	R2 (YP2)	I (YP1)	I (YP2)
HR	R	437.0	765.0	150.3	151.8	149.2	0.94	0.90	8.3	22.0
	T	354.2	582.4	143.3	144.1	143.9	0.95	0.92	6.8	23.8
	S	429.9	983.8	140.8	145.0	140.5	0.94	0.89	8.3	21.3
	F	354.8	650.8	143.9	146.4	143.3	0.97	0.95	8.8	24.5
	AV.	394.0	745.5				0.95	0.92	8.1	22.9
Vo_2	R	323,825	397,593	1632	1631	1608	0.77	0.72	5.5	14.8
	T	258,870	320,666	1607	1604	1582	0.85	0.82	4.5	12.0
	S	189,596	223,915	1562	1571	1556	0.89	0.87	4.0	14.3
	F	233,914	288,584	1559	1565	1537	0.89	0.86	5.5	15.3
	AV.	251,551	307,690				0.85	0.82	4.9	14.1

Table 67 : Summary of SSTEST Program to Test Steady-State Achievement

Subject #	Posture	Variable	b_o	b_1	t
1	T	Vo_2	1699	-0.76	-2.5E-4
	R		1748	1.10	4.3E-4
	S		1666	0.96	2.6E-4
	F		1644	-0.57	-5.1E-4
	T	HR	111	0.09	0.10
	R		125	-0.28	-7.3E-2
	S		113	-0.25	-8.8E-2
	F		120	-0.44	-7.4E-2
2	F	Vo_2	1607	-2.99	-1.6E-3
	T		1595	-2.08	-1.6E-3
	R		1595	-1.08	-1.1E-3
	S		1624	-0.47	-9.4E-4
	F	HR	141	-0.21	-7.8E-2
	T		151	-0.23	-0.15
	R		156	-0.24	-0.11
	S		150	-0.36	-0.08
3	S	Vo_2	1543	-2.30	-2.9E-3
	F		1623	-1.99	-1.8E-3
	T		1773	-2.72	-1.1E-3
	R		1551	6.41	1.6E-3
	S	HR	139	-0.24	-0.15
	F		143	-0.37	-9.9E-2
	T		143	-0.13	-0.14
	R		143	-0.07	-0.28
4	R	Vo_2	1922	-5.89	-4.9E-3
	S		1691	-3.77	-5.5E-3
	F		1691	-0.75	-7.5E-4
	T		1768	-1.62	-1.2E-3
	R	HR	169	-0.31	-0.11
	S		152	-7.14	-0.12
	F		160	-0.30	-0.13
	T		162	-0.24	-0.15
5	R	Vo_2	1717	0.09	3.1E-5
	S		1617	-1.80	-1.2E-3
	T		1659	-0.92	-5.8E-4
	F		1644	-2.30	-2.2E-3
	R	HR	144	-0.09	-0.17
	S		131	-0.35	-8.3E-2
	T		130	-0.21	-8.2E-2
	F		136	-0.32	-7.5E-2

Table 67 (Cont.)

Subject #	Posture	Variable	b_o	b_1	t
6	F	Vo_2	1637	-5.01	-3.1E-3
	T		1424	-3.3E-3	-4.1E-6
	R		1442	-0.26	-2.1E-4
	S		1547	-1.81	-3.0E-3
	F	HR	174	-0.35	-0.10
	T		172	-0.18	-0.18
	R		180	-0.13	-0.21
	S		171	-0.10	-0.22
7	S	Vo_2	1500	-1.90	-5.5E-3
	R		1664	-6.2	-2.8E-3
	F		1508	-2.96	-2.9E-3
	T		1352	-2.46	-5.2E-3
	S	HR	143	-0.24	-0.14
	R		159	-0.37	-7.3E-2
	F		158	-0.31	-0.12
	T		153	-0.18	-0.15
8	T	Vo_2	1669	-4.9	-1.3E-2
	F		1136	12.7	2.74
	S		1371	-0.59	-1.3E-3
	R		1385	6.2	5.0E-3
	T	HR	132	-0.22	-0.73
	F		126	0.92	1.86
	S		139	-0.53	-1.65
	R		134	0.42	0.89

Table 68 : Parameters of YPl Model on Vo_2 at R

Subject #	B_o	B_1	λ	SSE	R^2	I
1	1726.9	-1494.2	0.596	666,741	.61	4
2	1576.8	-1380.2	0.654	202,086	.84	4
3	1599.3	-1655.5	0.683	473,560	.80	6
4	1933.5	-825.0	0.863	137,765	.87	10
5	1691.8	-835.8	0.799	524,036	.60	4
6	1410.7	-1042.5	0.620	174,766	.76	6
7	1658.3	-1256.0	0.772	154,316	.91	6
8	1446.4	-1269.3	0.646	257,326	.78	4
Average	1630.5	-1219.8	0.704	323,824.5	.77	5.5

Table 69: Parameters of YPl Model on Vo_2 at T

Subject #	B_o	B_1	λ	SSE	R^2	I
1	1703.0	-1269.2	0.596	364,148	.67	2
2	1595.5	-1952.9	0.704	333,535	.90	2
3	1770.8	-1647.8	0.739	361,892	.87	6
4	1751.9	-1297.8	0.776	279,487	.86	4
5	1616.2	-1219.1	0.735	337,761	.79	6
6	1415.2	-1150.7	0.646	103,209	.88	4
7	1351.0	-1093.8	0.724	128,304	.89	6
8	1629.0	-1476.2	0.741	162,623	.92	6
Average	1604.0	-1388.4	0.708	258,869.9	0.85	4.5

Table 70: Parameters of YP1 Model on Vo_2 at S

Subject #	B_o	B_1	λ	SSE	R^2	I
1	1663.7	-1299.6	0.555	328,426	.65	6
2	1637.7	-1168.2	0.797	142,035	.92	2
3	1567.5	-1542.4	0.802	294,930	.90	4
4	1678.7	-1359.5	0.803	200,297	.92	4
5	1618.1	-1339.0	0.760	190,410	.90	4
6	1544.7	-1319.9	0.800	143,027	.93	4
7	1491.2	-1479.5	0.798	107,367	.96	4
8	1363.6	-1313.0	0.717	110,279	.93	4
Average	1570.7	-1352.6	0.754	189,596.4	.89	4.0

Table 71 : Parameters of YP1 Model on Vo_2 at F

Subject #	B_o	B_1	λ	SSE	R^2	I
1	1604.9	-1991.4	0.547	441,193	.77	6
2	1609.1	-1378.9	0.789	254,519	.89	4
3	1628.9	-1451.9	0.776	226,829	.90	4
4	1673.5	-1261.1	0.771	282,685	.85	6
5	1647.2	-1569.3	0.804	204,201	.93	4
6	1665.9	-1236.4	0.862	168,400	.93	10
7	1485.4	-1147.6	0.792	163,974	.90	6
8	1202.3	-1261.8	0.759	129,508	.92	4
Average	1564.7	-1412.3	0.760	233,913.6	.89	5.5

Table 72: Parameters of YPl Model on HR at R

Subject #	B_o	B_1	λ	SSE	R^2	I
1	124.9	-45.5	0.897	493.2	.88	8
2	156.0	-58.7	0.869	387.5	.93	10
3	143.3	-67.6	0.844	590.8	.92	10
4	175.8	-86.1	0.907	352.4	.97	8
5	142.5	-56.3	0.831	353.2	.93	10
6	176.8	-95.6	0.797	437.6	.96	4
7	158.9	-83.2	0.851	562.3	.95	10
8	136.2	-86.9	0.783	318.7	.96	6
Average	151.8	-72.5	0.847	437.0	0.94	8.3

Table 73 : Parameters of YPl Model on HR at T

Subject #	B_o	B_1	λ	SSE	R^2	I
1	112.4	-42.5	0.804	250.8	.90	2
2	151.9	-73.8	0.872	220.2	.98	10
3	143.0	-78.9	0.831	326.5	.96	10
4	159.2	-86.8	0.799	362.0	.96	4
5	127.6	-66.0	0.798	412.6	.93	4
6	174.0	-90.1	0.859	352.9	.97	10
7	154.2	-74.3	0.853	626.5	.93	10
8	130.4	-90.9	0.802	281.9	.97	4
Average	144.1	-75.4	0.827	354.2	.95	6.8

Table 74 : Parameters of YP1 Model on HR at S

Subject #	B_o	B_1	λ	SSE	R^2	I
1	112.9	-50.5	0.754	299.0	.89	4
2	149.2	-64.7	0.856	467.9	.93	10
3	148.3	-79.7	0.906	338.8	.97	6
4	159.1	-78.7	0.894	376.3	.96	12
5	130.8	-65.2	0.810	501.2	.92	6
6	174.8	-96.3	0.872	297.8	.98	10
7	147.1	-91.0	0.888	240.1	.98	10
8	137.4	-85.8	0.816	917.8	.91	8
Average	145.0	-76.5	0.850	429.9	0.94	8.3

Table 75 : Parameters YP1 Model on HR at F

Subject #	B_o	B_1	λ	SSE	R^2	I
1	121.1	-55.7	0.888	370.3	.93	8
2	141.2	-75.1	0.855	248.2	.97	10
3	143.0	-78.9	0.856	164.4	.98	10
4	163.7	-88.2	0.892	139.3	.99	10
5	136.1	-87.5	0.860	367.4	.97	10
6	177.5	-122.1	0.882	487.6	.98	8
7	159.9	-95.4	0.873	432.2	.97	10
8	128.7	-95.5	0.804	629.2	.95	4
Average	146.4	-87.3	0.864	354.8	0.97	8.8

Table 76 : Parameters of YP2 Model on Vo_2 at R

Subject #	A_o	K	SSE	R^2	I
1	1282.9	0.647	755,048	.56	8
2	1187.0	0.655	376,384	.71	8
3	1328.9	0.308	515,352	.78	16
4	1461.7	0.459	350,208	.68	14
5	1144.6	0.439	575,868	.56	20
6	1068.3	0.495	174,880	.76	16
7	1394.1	0.311	165,984	.90	16
8	1114.7	0.419	267,016	.78	20
Average	1247.7	0.467	397,592.5	0.72	14.8

Table 77 : Parameters of YP2 Model on Vo_2 at T

Subject #	A_o	K	SSE	R^2	I
1	1299.7	0.554	364,128	0.67	18
2	1334.3	0.280	516,824	0.84	12
3	1472.5	0.379	487,456	0.82	10
4	1434.8	0.267	292,928	0.86	16
5	1309.2	0.363	342,952	0.79	14
6	1144.8	0.655	178,876	0.80	6
7	1130.3	0.461	183,716	0.84	10
8	1278.6	0.299	198,448	0.91	10
Average	1300.5	0.407	320,666.0	0.82	12.0

Table 78: Parameters of YP2 Model on Vo_2 at S

Subject #	A_o	K	SSE	R^2	I
1	1324.9	0.629	329,548	.65	10
2	1404.3	0.287	160,376	.90	8
3	1272.1	0.250	430,932	.85	20
4	1349.3	0.226	202,064	.91	24
5	1255.9	0.300	212,104	.89	10
6	1277.4	0.268	177,444	.92	12
7	1274.7	0.220	151,916	.94	20
8	1183.7	0.265	126,936	.92	10
Average	1292.8	0.306	223,915.0	0.87	14.3

Table 79: Parameters of YP2 Model on Vo_2 at F

Subject #	A_o	K	SSE	R^2	I
1	1298.1	0.403	506,432	.73	24
2	1386.6	0.289	282,264	.88	12
3	1388.7	0.287	252,296	.89	12
4	1392.3	0.312	292,776	.85	8
5	1290.5	0.256	376,648	.88	20
6	1419.0	0.219	218,160	.91	16
7	1221.2	0.300	181,816	.89	10
8	956.6	0.243	198,276	.88	20
Average	1294.1	0.289	288,583.5	0.86	15.3

Table 80 : Parameters of YP2 Model on HR at R

Subject #	A_o	K	SSE	R^2	I
1	41.7	0.141	566.4	0.86	26
2	52.3	0.206	713.0	0.88	20
3	62.7	0.207	757.6	0.90	20
4	77.5	0.148	734.3	0.94	24
5	49.9	0.208	464.4	0.90	20
6	70.1	0.135	618.4	0.94	26
7	70.5	0.209	1105.2	0.89	20
8	68.0	0.305	1161.3	0.87	20
Average	61.6	0.195	765.0	0.90	22

Table 81 : Parameters of YP2 Model on HR at T

Subject #	A_o	K	SSE	R^2	I
1	33.7	0.209	346.1	0.86	20
2	58.3	0.121	622.4	0.93	28
3	68.5	0.208	589.6	0.93	20
4	67.5	0.137	411.7	0.96	24
5	56.5	0.207	487.8	0.92	26
6	75.6	0.130	651.8	0.95	26
7	65.4	0.143	729.5	0.92	26
8	68.8	0.208	820.6	0.92	20
Average	61.8	0.170	582.4	0.92	23.8

Table 82 : Parameters of YP2 Model on HR at S

Subject #	A_o	K	SSE	R^2	I
1	39.8	0.211	367.3	0.86	16
2	55.3	0.205	851.1	0.88	20
3	67.4	0.150	703.3	0.94	26
4	54.1	0.221	2373.5	0.76	18
5	58.2	0.230	564.7	0.91	20
6	76.1	0.141	1066.1	0.93	24
7	76.1	0.126	690.4	0.95	26
8	70.8	0.207	1253.6	0.88	20
Average	62.2	0.186	983.8	0.89	21.3

Table 83: Parameters of YP2 Model on HR at F

Subject #	A_o	K	SSE	R^2	I
1	54.1	0.126	377.9	0.93	30
2	66.9	0.137	334.6	0.96	24
3	70.7	0.138	253.3	0.97	24
4	75.4	0.142	610.7	0.95	24
5	75.1	0.206	1110.7	0.91	20
6	104.1	0.151	1441.2	0.94	26
7	89.3	0.134	494.5	0.97	24
8	75.1	0.136	583.7	0.95	24
Average	76.3	0.146	650.8	0.95	24.5

Table 84: ANOVA for λ values of V_{O_2}

Source of Variation	SS	df	MS	F
Treatment	2.8E-2	6	4.7E-3	1.9
Subject	0.11	6	1.90	7.8
Sequence	3.2E-2	6	5.3E-3	2.2
Squares	7.0E-3	1	3.5E-3	1.4
Error	2.94E-2	12	2.4E-3	

Table 85: ANOVA for λ values of HR

Source of Variation	SS	df	MS	F
Treatment	1.1E-2	6	1.8E-3	1.3
Subjects	1.3E-2	6	2.2E-3	1.6
Sequence	6.7E-3	6	1.1E-3	0.8
Squares	3.7E-3	1	3.7E-3	2.8
Error	1.6E-2	12	1.3E-3	