A CALORIMETRIC ANALYSIS OF ECCENTRIC AND CONCENTRIC BICYCLE ERGOMETRY

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A Calorimetric Analysis of Eccentric and Concentric Bicycle Ergometry

By

© Robert Thomas Christopher Farrell, B.Sc.(Hons)

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Abstract

Phase I of this study entailed a verification of the relationship between oxygen consumption and both concentric and eccentric workrate on the bicycle ergometer constructed for the whole - body human calorimeter. This series of exercise experiments, carried out without calorimetry, included a range of pedaling speeds and brakeforces, but also "idling", i.e. pedaling only against the frictional resistance of the ergometer transmission and passively "being pedaled" by the electric motor of the eccentric exercise ergometer. It also included experimentation with the brake on the flywheel, by substituting the von Döblen brake on the monarch ergometer by a known weight suspended from the brake belt. Only one subject was employed for the total of 36 experiments.

Phase II was carried out on six subjects, who performed a total of 79 experiments with concentric and eccentric exercise at a range of pedaling speeds and brakeforces in the calorimeter. All experiments were carried out at a calorimeter temperature of 32.36 + 0.06°C and a dew point temperature of less than 6°C. Each experiment lasted about 50 minutes, or until the various monitored variables, sensible and insensible heat exchange, heart rate and body core temperature (tympanic or esophageal) showed a steady state as judged by visual inspection. Immediately prior to this state metabolic heat production was determined in duplicate from the measurement of oxygen consumption and respiratory quotient. Near the end of the experiment the subject reported his perceived exertion on the Borg scale.

Phase I, which was intended to familiarise the author with the various methods, did not reveal anything that was not yet known from the current literature. The net mechanical efficiency of exercising on the calorimeter ergometer was 18.6% for concentric work and -100.4% for eccentric work. There was little to be gained by modifying the braking mechanism.

In Phase II the energy balance was analysed by adding algebraically all heat

gains and heat losses during the apparent caloric and thermal steady state. Suprisingly, there was usually a small positive heat storage which was most closely related to the concentric or eccentric workrate applied, and to a lesser extent to the metabolic heat production.

Conclusions

1. With direct calorimetry one can detect rates of heat storage which cannot be detected by thermometry at the conventional body sites. After 50 minutes of continuous exercise, either concentric or eccentric, there was a small amount of heat storage, which was associated with the workrate (0.5 W storage per applied workrate in watts), but not with metabolic heat production. The average heat storage was small at 33 watts for all experiments. A heat storage rate of 33 watts converts, in a 70 kg subject, to a rise in average body temperature of 0.008 ^{o}C/min. This may well go undetected by observing the eardrum and mean skin temperature, if the storage takes place in peripheral body regions such as the exercising muscle.

2. It is not possible to quantitate internal work thermodynamically as the energy required to overcome these forces must ultimately be derived from aerobic metabolism and thus would show up as heat.

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Chapter 1

Overview

1.1. Theory

1.1.1. Heat Balance Equation

Man produces heat as a result of complex biochemical reactions whereby energy is made available to metabolically active tissue. The overall metabolic heat production, M can be calculated from an individual's oxygen consumption. This procedure relies on the stoichiometric relationship between the combusted energy source, the oxygen required for the process and the carbon dioxide produced. The consumption of 1 liter of oxygen liberates anywhere from 19.33 to 20.24 kJ of heat, depending on the energy source utilized (Carpenter, 1939). In keeping with the basic laws of thermodynamics, during any period of sustained activity, M should equal the total heat lost by the individual plus or minus the work imposed. For this to be true, body heat storage (S) must equal zero. During the initial stages of exercise, the rate of heat dissipation does not match the rate of heat production and this leads to heat storage and a subsequent rise in body temperatures (Nielsen, 1938). When they have risen enough to elicit heat dissipating mechanisms sufficiently to bring heat loss into balance with heat production, the rate of heat storage becomes zero and the temperatures reach a plateau. Radiative, conductive and convective heat loss (Sensible Heat Exchange,***SHE***) and evaporative heat loss (Insensible Heat Exchange,***IHE***) are the two major modes of heat transfer between man and his environment. Deviations in body temperatures whether due to exercise or varying environmental temperatures lead to modifications in ***SHE*** and ***IHE*** to allow for effective dissipation of heat produced and/or gained. On a conventional bicycle ergometer the exercising subject performs external work i.e. the caloric equivalent of the external work has to be subtracted from the metabolic rate (concentric work). Approximately 80% of the energy liberated at the tissue shows up as heat, the remaining 20% being used to produce the mechanical work performed on the braking mechanism (Shephard, 1982). As will be described in detail later, it is also technically possible to do work on stimulated muscles. In this case, mechanical work, which ultimately degenerates into heat, is delivered to the body. The caloric equivalent of this mechanical work ~~has to be~~ added to the metabolic rate (eccentric work). The first law of thermodynamics can thus be stated in the above mentioned physiological units (Bligh and Johnson, 1973).

All components are expressed in power units, rather than energy units:

$$S = M + E + R + C + K + W \qquad [\mathrm{W/m^2}] \text{ or } [\mathrm{W}] \qquad \textit{Eq. 1}$$

in which

S = Rate of storage of body heat

M = Metabolic heat production

E = Evaporative heat transfer

R = Radiant heat transfer

C = Convective heat transfer

K = Conductive heat transfer

W = Workrate

The convention has been followed that all heat gains by the body get a positive sign and vice versa. Thus, M is always positive, E almost always negative, whereas S, R, C, K and W can assume either a positive or negative sign. See also definition of terms, 1.3.

1.1.2. The mechanical workrate term

During bicycle ergometry, with the help of a motorized ergometer, the work performed by an individual can be of an eccentric or concentric nature. The terms eccentric and concentric exercise are explained in the attached Definition of Terms, and by figure 1.1. In addition to this applied work (***Wa***), energy is expended by the individual to increase respiration and cardiac output, in raising and lowering limb segments, in maintaining posture and in overcoming elastic and viscous forces in the muscles and joints. These forces, whether gravitational or frictional, occur within the body and are distinctly different from the forces applied via the bicycle ergometer. The work required to overcome these forces is known as internal work (***Wi***). Additional force is also required to overcome frictional resistance within the ergometer itself (***Wf***). The manual accompanying all Monark ergometers indicates that friction in the transmission, chain and bearings increases the workrate by approximately 9%. This work component, while internal to the ergometer, is external to the body and is therefore an integral part of the applied work component of exercise. Thus the total work performed while exercising can be considered to be the sum of three separate work components:

$$W = Wi + Wa + Wf \qquad \textit{Eq. 2}$$

where ***W*** is the total work performed; ***Wa*** is the applied work component; ***Wi*** is the internal work component; and ***Wf*** is the work required to overcome frictional forces within the ergometer. Collectively ***Wa*** and ***Wf*** are referred to as the external work component of exercise, ***We***.

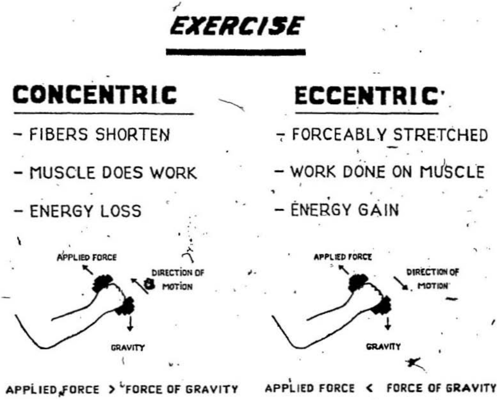

Figure 1-1: Eccentric and Concentric Exercise

1.1.2.1. Internal Work as a Component of Total Work

When assessing energy balance during exercise it is critical to have an accurate measure of the total work performed by the subject. *Wa* of the external work component is applied work and can be easily measured. *Wf* is also easily determined using foil strain gauges on the cranks (Daly and Cavanagh, 1976) or, in the case of the eccentric ergometer, with the calibration procedure described by Snellen and Chang (1981), and utilized for the calibration of the eccentric ergometer used in this study. This procedure will be discussed later. The internal work component, on the other hand, cannot be measured directly and has to be calculated through indirect means.

1.1.2.2. Historical Aspect of Internal Work

The concept that extra energy is used in moving the limbs and overcoming resistance within the joints and muscles has been recognized for many years (Chauveau, 1896 , as cited by Asmussen, 1953; Abbott, Bigland and Ritchie, 1952). These studies, as well as recent investigations (Whipp and Wasserman, 1969; Linnarsson, 1974; Hesser, Linnarsson and Bjurstedt, 1977), have shown that oxygen uptake during pedaling without any external load is significantly higher than at rest and that zero load pedaling does require energy expenditure by the subject. It seems likely that much of the additional energy expenditure associated with loadless pedaling is used mainly in overcoming internal work (Abbott and Bigland, 1953; Asmussen, 1952; Aastrand, 1960). In this respect the study by (Bigland, Graichen and Woods, 1973)is most intriguing. They confirmed the results observed by the above authors with pedaling rates up to 120 RPM, but observed that there was only a marginal rise when the legs were "being pedaled" by the eccentric ergometer motor. The assumption here is that the eccentric ergometer motor supplies the energy to overcome the internal work which is normally supplied by the subject in zero load concentric pedaling. They also report that the subjects had to be trained for this passive exercise in light of the fact that the uninitiated would have trouble relaxing the leg muscles.

1.1.2.3. Techniques to Méasure Internal Work

To date, a variety of methods have been used to calculate the internal work component of different types of exercise mainly using biomechanical techniques. Invariably these techniques involve calculating energy changes in the body during exercise. The most popular of these is cinematographical analysis (in more than one plane) of accelerations and decelerations of centres of gravity of a large number of body segments. In one study of over-ground level walking, the average internal work per unit body mass per unit distance walked was determined to be 1.09 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ (Winter, 1979). The relative contribution of eccentric and concentric muscle activity was not assessed. In another study the energy required to move the legs during eccentric and concentric bicycle ergometry at different pedaling frequencies and brakeforces was calculated from segmental energy changes in the body using cinematography (Wells, Morrisey and Hughson, 1986). The mean internal work calculated at speeds of 30, 60 and 90 revolutions per minute (RPM) were 11.5, 20 and 62 watts respectively. Unfortunately, in using cinematography to establish values for internal work, it is not possible to measure energy expended to overcome frictional and viscous resistance in the muscles and joints.

1.2. Purpose

Apart from the obvious biomechanical differences between eccentric and concentric exercise, the physiological responses observed to occur during these types of exercise are vastly different. It is thought that these differences might in part be attributable to the internal work component of exercise. This study was carried out to assess this possibility. The purpose of this study is:

1. To evaluate the aerobic cost of eccentric exercise and to evaluate systematically the calorimeter ergometer using physiological variables. So far, the calorimeter ergometer had only been described technically (Snellen and Chang, 1981). This part is referred to as Phase I.

2. To compare estimates of *M* during eccentric and concentric exercise at various brakeforces and pedaling speeds, as made through indirect calorimetry, to that of heat losses measured through direct calorimetry.

3. To determine the relationship between an individual's perceived exertion and exercise intensity, heart rate and oxygen uptake for both eccentric and concentric exercise.

4. To evaluate the time period required to reach steady state oxygen consumption during eccentric exercise.

1.3. Limitations

There are a number of inherent limitations in this study;

1. When calculating M, a non-protein R.Q. is used to determine the calorific equivalent of a liter of oxygen. Here we assume that no protein is metabolized during the exercise. The actual energy contribution of protein metabolism in short term, submaximal exercise of this nature is questionable but quite possibly a factor. Previous studies indicate that for exercise of short duration, energy requirements can be easily met by glycogen and fatty acid breakdown (McGilvery, 1973) but as work duration increases, amino acid metabolism may become increasingly important (Felig and Wahren, 1973).

2. We also assume that ATP and CP stores are maintained and that there is no anaerobic metabolism. Anaerobic processes give rise to a production of lactic acid. In light and moderate work the lactate concentration remains at resting levels, or it may even decrease slightly. At higher workrates, lactate concentration increases steeply with load (Asmussen, 1965). In this study, *M* is calculated on the basis of aerobic metabolism. This is more warranted since all exercise R.Q.'s observed in this study were around an expected "aerobic" value of 0.9. In support of this observation is the fact that the highest % of VO_2max used in Phase II was 57% and in fact only four of the 79 experiments showed values above 50%.

3. The results in this study rely heavily on the manufacturer's assurance (Applied Electrochemistry Inc., AEI) that calibration of the oxygen analyser with standard air is sufficient. Newfoundland outdoor air and calorimeter inlet air is standard, i.e. 20.94 % O_2, 0.03 % CO_2 (unpublished results with Haldane analysis).

1.4. Definition of Terms

Before attempting an explanation of the theory behind a thermodynamic approach to this problem it will be of some advantage to review a few of the relevent terms used in thermal physiology:

1. Concentric Exercise, W_{con} (fig 1-1): Exercise during which active muscle fibers undergo shortening and perform external work, e.g., running uphill. In terms of the Heat Balance Equation, W_{con} is the transfer of energy from the body to an external system and is therefore a loss of energy. [W/m^2] or [W]

2. Conductive Heat Transfer, K: The net rate of heat transfer by conduction between an organism and its environment, usually expressed in terms of unit area of the total body surface. The quantity K in the Heat Balance Equation in which $+K$ = heat gain, and $-K$ = heat loss. [W/m^2] or [W]

3. Core Temperature, T_c: The mean temperature of the tissue at a depth below that which is affected directly by a change in the temperature

gradient through peripheral tissues. Mean core temperature cannot be measured accurately and is generally represented by a specified core temperature, e.g., that of the esophagus.[° C]

4. Convective Heat Transfer, C: The net rate of transfer by convection between an organism and its environment, usually expressed in terms of unit area of the total body surface; the quantity C in the body Heat Balance Equation in which $+ C =$ heat gain and $- C =$ heat loss. [W/m^2] or [W]

5. Direct calorimetry: All processes occuring in the body ultimately result in the production of heat. Direct calorimetry is a procedure whereby the heat dissipated by an individual can be measured directly in an appropriately insulated calorimeter via differential thermometry and hygrometry.

6. Eccentric Exercise, W_{ecc} (fig 1-1): Exercise during which the muscle fibers are forcibly stretched while being stimulated and work is done on the muscles e.g., running downhill. In terms of the Heat Balance Equation, W_{ecc} is the transfer of energy from an external system to the body and is therefore a gain of energy. [W/m^2] or [W]

7. Evaporative Heat Transfer, E: The rate of heat transfer by evaporation from or condensation on the skin and the surfaces of the

respiratory tract, usually expressed in terms of unit area of total body surface. E is calculated by multiplying the calorimetrically observed total water vapor loss per minute by the heat of vaporisation (2.44kJ/g). In the Heat Balance Equation, evaporation and heat loss from the body are indicated by $-E$, condensation and heat gain by the body by $+E$. [W/m^2] or [W]

8. Indirect calorimetry: As energy metabolism in the body depends on the utilization of oxygen, it is possible to obtain an indirect estimate of energy metabolism by measuring a persons oxygen consumption, either at rest or under steady state exercise conditions. This form of calorimetry assumes anaerobic energy yield to be negligible.

9. Radiant Heat Transfer, R: The net rate of heat exchange by radiation between an organism and its environment, usually expressed in terms of unit area of the total body surface. The quantity R in the Heat Balance Equation where $+R$ = heat gain and $-R$ = heat loss. [W/m^2] or [W]

10. Rate of Body Heat Storage, S: The rate of increase or decrease in the heat content of the body, as reflected by body temperatures, caused by an imbalance between heat production and heat loss, usually expressed per unit total body surface area. The quantity S in the Heat Balance Equation. [W/m^2] or [W]

11. Temperature Regulation: The maintenance of the temperature or temperatures of a body within a restricted range under conditions involving variable internal and/or external thermal loads. Biologically, the existence of some degree of body temperature regulation by autonomic or behavioral means.

Chapter 2

Methods

2.1. Calorimeter

2.1.0.1. Technique to Assess Total Heat Loss

Total heat loss was assessed using a whole-body air calorimeter which measures sensible and insensible heat exchange directly and continuously. A technical description and the performance characteristics of the calorimeter have been presented in detail elsewhere (Snellen, Chang and Smith, 1983). Figure 2-1 is a picture of the calorimeter with the control panel and computer terminal in the foreground.

2.1.0.2. Technical Description of the Calorimeter

The calorimeter is a double walled, cylindrical climatic chamber with an internal diameter of 1.52 meters and a height of 1.57 meters. Dew point temperature and air temperature are the only two climatic variables controlled. Part of the conditioned air ($t_{air} \pm 0.02°C$, $t_{dew} \pm 0.15°C$) is injected tangentially into the calorimeter through six inlet slots located in the radiation shield in the calorimeter (about 12.5 m^3/min). The other part of the same air is diverted into the outer jacket surrounding the calorimeter to eliminate any thermal gradient over the calorimeter wall. The innermost wall acts as a radiation shield. The

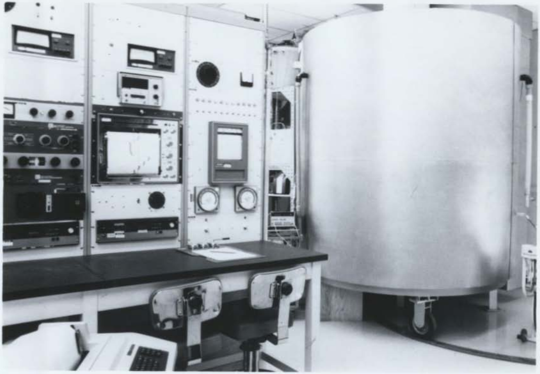

Figure 2-1: Whole-Body Human Calorimeter

temperature of this air can be adjusted and controlled accurately from about 12°C to 50 °C and the dew point temperature from about 4 °C to 28 °C. A quartz crystal thermometer (H-P 18111 A) positioned between the radiation shield and the calorimeter wall displays air temperature to three decimals and varies less than a few hundredths of a degree over several hours. In the absence of any thermal gradient across the cylinder wall, all heat absorbed or dissipated by a subject inside the vessel can be measured by differential thermometry and hygrometry between the inlet and outlet air. ***SHE*** and ***IHE*** as well as tympanic or esophageal temperatures are recorded on two micrograph BD6 recorders (Kipp and Zonen) which are in turn connected to a PDP 11-10 computer with 16 A/D channels (Digital Equipment Corporation). When a channel is addressed the computer returns a value between 2048 and 4096, corresponding to the pen position of the appropriate recorder. A program has been written in Focal to sample each of the active A/D channels 220 times a minute and to print out the average every 60 seconds. These averages are then stored in a file on a floppy disc for future processing. Programs have also been written to convert computer counts per minute (CPM) into ***SHE***, ***IHE*** and temperature using the calculated calibration equations. The procedure for establishing calibration equations to convert CPM's into ***SHE***, ***IHE*** and temperature will be discussed below.

2.2. Calorimeter Calibration

2.2.0.1. Introduction to Calibration Procedure

The calibration procedure for both ***IHE*** and ***SHE*** readings are similar in that, in both, water vapor and heat respectively are injected into the calorimeter at known rates. Pen positions, as received by the computer from the Kipp recorders, are converted to net deflections from the baseline and plotted against heat exchange. ***IHE*** and ***SHE*** calibrations were carried out each day an experiment was run.

2.2.0.2. Insensible Heat Exchange Calibration

In the case of ***IHE***, a continuous infusion pump (Sage Instruments model 220) with 50 ml. syringes delivers accurately measured volumes of water (g/min) into a small electric furnace (Sybron Thermolyne 1300) set at about 500 °C. Here the water is vaporized and injected into the calorimeter through a heavily insulated

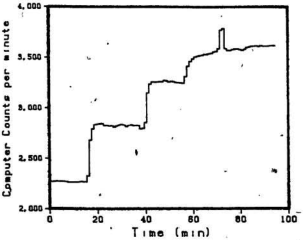

Figure 2-2: Water vapor loss calibration as recorded by the Kipp recorder

tube. Figure 2-2 shows on a reduced scale the same recording as the Kipp recorder shows when steam is injected into the calorimeter at a rate of 0, 4, 8 and 12 g/min. Figure 2-3 shows the last 10 computer readings at each flow rate in net deflections (dependent variable) plotted against steam injection in g/min. The relationship is not linear but parabolic. The graph presents the dependent variable (CPM) as a function of the flowrate of water injected. The equation, however, gives the prediction of water loss per minute from the meter deflection (CPM), i.e. the inverse of $y = f(x)$. The exceedingly high correlation coefficient indicates that $y = f(x)$ is virtually the same as $x = f(y)$. The resolution of the calorimeter for water vapor loss on this day is 0.226 g/min which, when multiplied by the heat of vaporization of water, is equivalent to about 0.55 kJ/min, which in turn equals

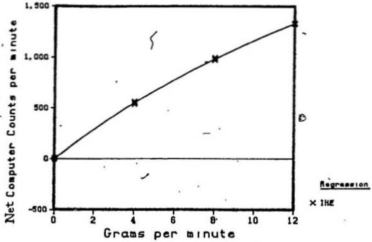

Figure 2-3: Calibration of computer counts per minute (CPM) for IHE

$x = 0.009931 + 0.0059105 \cdot CPM + 0.000002320 \cdot CPM^2$

$r = 0.9998$ $\quad s_{xyy}2 = 0.2256$

approximately 9 watts. When the subject is the source of water vapor which results in the deflections he has provided the heat of vaporization. Thus, ***IHE*** (in watts) is the subject's deflections (in g/min), multiplied by 2.44 kJ/g, and divided by 60.

2.2.0.3. Sensible Heat Exchange Calibration

For the ***SHE*** calibration, a YEW type 2504 Wattmeter measures heat dissipation to the nearest 0.1 watt through a bare spiralised resistance wire (total length about 6 meters) stretched out over the whole height of the calorimeter inside the radiation shield. A typical calibration for ***SHE*** is shown in figure 2-4. Again, figure 2-4 shows the same recording as the Kipp recorder shows when 0,

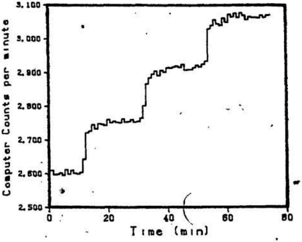

Figure 2-4: SHE calibration as recorded by the Kipp recorder

20, 40 and 60 watts heat dissipation is applied. Figure 2-5 shows the last 10 readings at each heat load as recorded by the computer, plotted against the wattage applied. The calibration is linear and for this particular experimental day, each CPM of ***SHE*** above or below the baseline equals 0.1392 watts. The standard error is 0.797 watts which represents the resolution of the calorimeter for ***SHE*** on that day.

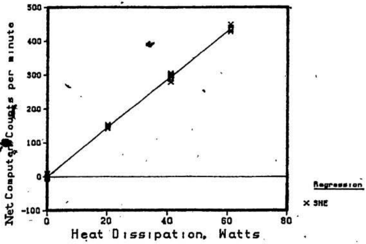

Figure 2-5: Calibration of computer counts per minute (CPM) for SHE

$$SHE \Rightarrow 0.0467 + 0.1392 \cdot CPM$$

$$r = 0.9988 \quad s_{yx} = .7973$$

2.3. Ergometer

2.3.0.1. Technical Description of Ergometer

The ergometer used in this study is the one described by Snellen and Chang(1981). To simulate eccentric exercise a 3 H.P. motor with variable transmission drives the flywheels of two bicycle ergometers which are connected to each other by a Datsun 510 differential gear box (figure 2-6).

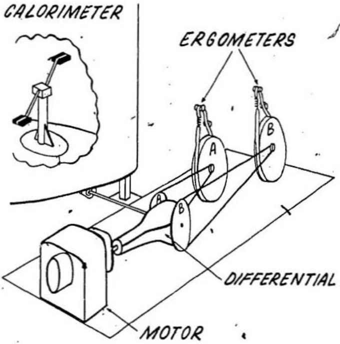

Figure 2-6: Eccentric Ergometer

Since heat sources in the calorimeter should be kept to a minimum the motor and ergometers are mounted outside the calorimeter. Inside the calorimeter is an open weave, steel frame chair in which the subject sits while exercising. The chair is

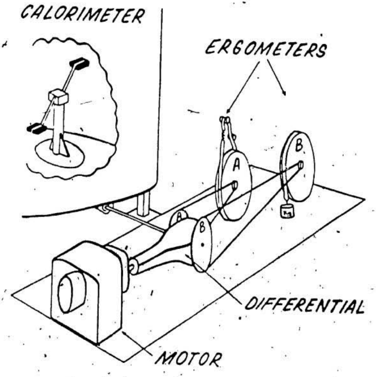

Figure 2-7: Eccentric Ergometer showing modification to flywheel B

situated so that the person sits more nearly level with the pedals and with the legs extended forward, rather than downward. The armchair was employed so as to minimize the energy contribution of sitting and the movements of balance and body fixation. The pedals are mounted on a pedestal inside the calorimeter and are connected to the outside ergometers via a series of axles, mitred gears and air-tight bearings. The outgoing shaft of the electric motor and the two outgoing shafts of the differential are all equipped with stroboscopic discs, drawn to indicate six speeds (40-90 RPM in increments of 10). One RPM is equivalent to the distance one point on the circumference of the wheel travels in one minute. In our ergometer this is six meters. Workrate is a function of RPM and brakeforce, i.e. at 80 RPM and 20 N brakeforce, workrate is equal to 20 N x 6.0 m/rev. x 80 RPM, which equals 9600 $N{\cdot}m/min$. Workrates are usually expressed in Watts. One $N{\cdot}m/min$ equals approximately 0.016 Watt.

2.3.0.2. Use of Ergometer in Concentric and Eccentric Exercise

During conventional concentric exercise the motor is not used. The brakeforce is set on flywheel A which is connected directly to the pedals inside the calorimeter. When the subject pedals, the two flywheels A and B run at the same speed but flywheel B runs in reverse. For eccentric brakeforces the brakeband of flywheel A is first maximally tightened. Next the motor is engaged and the predetermined pedaling rate is selected using the stroboscopic disc on the driveshaft. The desired brakeforce is then set on flywheel B which is spinning twice as fast when flywheel A is not running. By slowly releasing the brakeband of flywheel A the pedals inside the calorimeter will begin to move forward. When the brakeforce on both flywheels are equal the subject's legs will be moved passively. By completely releasing the brake on flywheel A an eccentric workrate will be imposed on the subject. Contrary to concentric exercise where the subject must generate the force required to turn the flywheels, the subject must resist the force generated by the motor and maintain a particular RPM. In other words, he takes over the function of the brake on flywheel A. A metronome is used to set the RPM. For instance, at 80 RPM and a force of 15 N the subject has to apply a force to the pedals equal to 15 N at a pedaling rate of 80 RPM in order to keep the pedals from speeding up. The eccentric workrate is thus equal to the product of the circumferential velocity of flywheel A and the brakeforce on flywheel B when the subject pedals at the selected pedaling rate. Figure 1-1 illustrates the direction of the various forces during concentric and eccentric exercise.

2.3.0.3. Ergometer Modification

Initially the calorimeter ergometer to be used was the one described above (Snellen and Chang, 1981), but in preliminary studies it was evident that the brake belt had a tendency to change its length as exercise progressed and that this subsequently changed the magnitude of the applied brake force. This requires constant vigilance and frequent adjustments. As this force component is critical in the calculation of workrate and ultimately affects oxygen consumption, the set-up was modified to overcome the problem. Instead of using the original device on the bicycle ergometer to apply force (von Döblen, 1954), fixed, constant weights were used. Figure 2-7 shows the modification to flywheel B. The brakeband was attached at one end to a block of wood which was bolted to the floor. A hook was attached to the free end of the brakeband on which weights (1.0, 1.5 and 2.0 Kg) could be hung so that the brake force would remain constant. Once this had been done it was necessary to recalibrate the ergometer to determine what force a particular weight hung over flywheel B would impose on the subject. The calibration procedure follows. The braking device on flywheel A was not modified since during eccentric exercise the subject replaces this brake.

2.4. Procedure for Calibrating Ergometer

The calibration procedure for this set-up was similar to that described by Snellen and Chang(1981) for the original ergometers. The desired RPM was first selected on the variable speed transmission and weights hung over flywheel

B. Next, brakeforces were applied to flywheel A to balance the brakeforce on flywheel B and to keep both shafts at the same RPM. The required brakeforces on flywheel A were determined at all combinations of 40-80 RPM (in increments of 10) with the exception of 70, and weights of 1.0 - 5.0 kg in five equal increments.

As was reported in the above-mentioned paper, it was found that the required brakeforce on flywheel A varied depending on whether flywheel A was either maximally tightened and the tension released slowly or minimally tightened and the tension increased slowly. The maximum and minimum brakeforces on flywheel A were determined for all brakeforces on flywheel B and an average of these two values was taken. In the course of the calibration it was found that this discrepancy could be reduced by avoiding overtightening and overreleasing as error appears to be introduced by successive tightening and loosening of the band of flywheel A to establish the correct force. It is worth mentioning that this set-up produced a brakeforce about half of that of the original set-up, the brakeband only covering one half of the wheel circumference as compared to more than three quarters in the original. Averages of the various brakeforces were plotted against the weight needed to counteract each brakeforce at each of the RPM assessed. Linear least square fits were then calculated for each RPM (Figure 2-8). The author is aware that the S.I. unit of force is the Newton. Since in this calibration section kg weights were used, and the force scales on the ergometer are given in kiloponds (to indicate kg force) he left it at that, without multiplying each value by 9.81. Workrates are given in Watts ($N{\cdot}m/sec$) throughout.

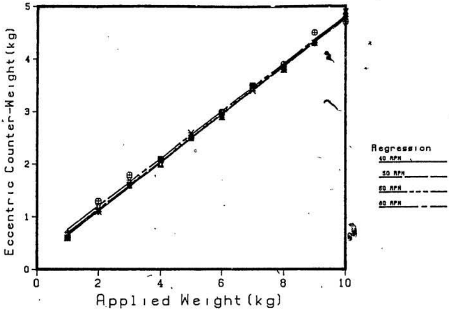

Figure 2-8: Regression Analysis at various RPM

40 RPM $y = 0.183 + 0.464x$ $s_{yx} = 0.0642$

50 RPM $y = 0.230 + 0.456x$ $s_{yx} = 0.0679$

60 RPM $y = 0.233 + 0.457x$ $s_{yx} = 0.0465$

80 RPM $y = 0.323 + 0.451x$ $s_{yx} = 0.1006$

Where y = brakeforce on flywheel A

x = brakeforce on flywheel B

An analysis of covariance showed that there was no difference between slopes of the four lines and so the common slope was adopted for all four regression lines. Next the Y-intercepts were plotted against RPM (figure 2-9). A direct relationship was found between these two variables. The intercept is taken to be the internal resistance of the system i.e. the force required on flywheel B to keep both outgoing shafts at the same RPM when the brakeband of flywheel A is completely removed. From figure 2-9 it appears that as the RPM increases so does the internal resistance, linearly. A regression line was drawn through the points and from the regression equation new intercepts were generated . So now, with a common slope and new intercepts, values for 70 RPM could be generated. Although the analysis of covariance showed no difference between Y intercepts a common Y-intercept was not taken as it was felt that the increase in internal resistance with RPM (approximately .13 kg over a span of 40 RPM) was meaningful in our determination of Wf and subsequently Wi.

2.5. Use of Thermocouples

Body core temperature was measured using either an esophageal or tympanic thermocouple probe. Core temperature was one of the parameters used to establish that subjects were in caloric equilibrium at the end of the 50 minute exercise period, i.e. that the term S in the heat balance equation was indeed close to zero.

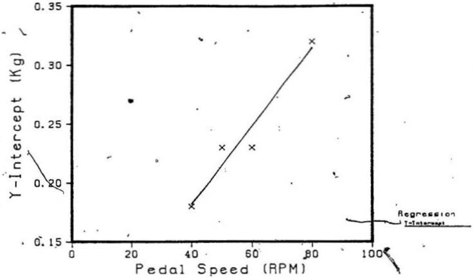

Figure 2-9: Regression Analysis of Y-intercepts

$$y = 0.0503 + 0.0033x$$

$$s_{yx} = 0.0158$$

2.5.1. Technical Description of Tympanic Thermocouple

Owing to the inability or unwillingness of subjects to insert the esophageal probe for core temperature, a tympanic thermocouple probe was made to accommodate all but one of the 6 subjects. The thermocouple was fabricated using a muscle thermocouple catheter (Ellab, Denmark) consisting of insulated copper and constantan wire (diameter 0.02 cm) encased in a flexible nylon sheathing. Approximately 60 cm of the total 325 cm of the nylon sheathing was stripped and the two wires coiled in a tight spiral (diameter 0.13 cm). The insulation of the tips of both wires was then scraped off, the tips twisted together and fashioned into a closed circle at the end of the spiral. The tip was then soldered with a minimum of solder, closing the circle into a disk. Finally the tip of the spiral was dipped in a insulating compound, INSL-X (INSL-X Products Corp.) to insulate the solder and bare section of the copper and constantan wires. A connector (Omega Engineering) with copper and constantan pins was connected to the free end. The connector fits into a selected receptacle in a bank of 18 such receptacles attached to the steel chair inside the calorimeter. The reference junction of the thermocouple was kept at 0°C in an Ice-Point Cell (Omega Engineering).

2.5.1.1. Thermocouple Modification

Although the disk of the tip of the probe was designed to lie directly on the tympanic membrane little success was met in early trial runs using this set-up. Artifacts from a number of sources made readings of the thermocouple microvoltage impossible. All subjects found the tympanic thermocouple painful or uncomfortable. Subsequently the design was modified to monitor the temperature of the external ear canal. The external ear canal has become a popular site for measuring core temperature since the original use of the ear drum by Benzinger (1959), as it is easily measured without discomfort or danger. It has been shown that changes in temperature in the external auditory canal reflect quite accurately central temperature changes although absolute temperature levels are probably of little value (Cooper, Cranston and Snell, 1964). As we were interested only in relative changes in central temperature this method of monitoring *Tc* was felt to be an adequate substitute for more central methods. The design used is the one suggested by the above authors. A soft, rubber stopper about the diameter of the outer ear canal was drilled out just enough to let the spiral travel through its centre. The soldered tip of the thermocouple was allowed to protrude through the opening by just a fraction and was insulated to the level of the tip with the Insl-X compound to provide support. The same was done at the opposite end of the rubber stopper. All but the last 50 cm of the thermocouple probe was then further enclosed in latex tubing (diameter 0.32 cm) to give additional support and flexibility. After the subject inserted the plug a large insulating pad made of cotton was applied over the ear and the side of the head to eliminate draughts and to reduce possible heat exchange with the environment. The design proved superior to the initial set-up giving smooth readings on the Kipp recorder. Because the thermocouple had only one connector and because the Kipp recorder was connected to a different receptacle than the K-5 potentiometer, it was necessary for the subject to periodically change the connector from the Kipp input to the potentiometer input to allow microvoltages to be measured, thus interrupting the continuous computer recording. These voltages were later used to generate regression equations whereby CPM could be converted to microvoltages.

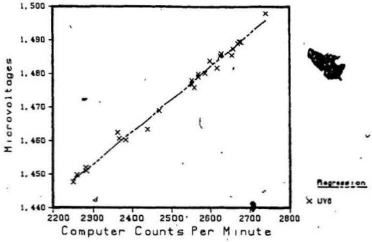

Figure 2-10: Regression for conversion of CPMs to microvoltages
y=1228.75+0.0975·*CPM*
$r = 0.9910 \quad s_{yx} = 1.4127$

Figure 2-10 is a typical calibration equation. Changes in these voltages reflect changes in temperature in the outer ear canal.

2.5.2. Technical Description of Esophageal Thermocouple

One of the best measures of core temperature is given by a properly positioned sensor in the esophagus (Saltin and Hermansen, 1966; Cooper and Kenyon, 1957). The design of this esophageal thermocouple probe was far superior to the above ear canal probe in that two muscle thermocouple catheters, with the manufacturer's copper-constantan junction still intact, were threaded through a single plastic catheter (diameter 0.2 cm). The two thermocouples were electrically separated. Omega connectors were used to plug into pre-selected receptacles. They had their reference junction in the Ice-Point Cell. One was connected to a BD6 Kipp recorder via a bias supply of 1.5mV and the other to the K5 potentiometer. This eliminated the problem of having to switch one plug from channel to channel. The tips of the muscle catheters were embedded in epoxy and surrounded by a stainless steel ferrule inside the plastic catheter. Total length was 1.6 meters. The probe was inserted to the level of T10 as determined by x-ray examination. A copper-constantan thermocouple with its reference junction at 0 ^{o}C produces a thermal EMF of 1.5mV at about 37.5 ^{o}C, i.e. about 40 μV per degree. With a bias supply of 1.5 mV the recorder can be set at a sensitivity of 100 μV full scale, thus covering a span of about 2.5 ^{o}C. The recorder is scanned by the computer in the same way as the recorder for ***IHE*** and ***SHE***, converting pen position to CPM. A number of μV readings are made at different pen positions. Computer counts are then converted to microvoltage with calibration equations (see below). These microvoltages are then converted to temperature using equations generated from calibration of the probes. The calibration procedure is discussed below.

2.5.2.1. Calibration procedure

The tympanic and esophageal thermocouples were calibrated separately using a standard calibration technique. The thermocouple was first immersed in a glass pipette (internal diameter 0.5 cm) flamed closed at one end and half filled with liquid paraffin (Saybolt Viscosity 125/135). The paraffin acts as a thermal insulator and slows the rate at which the temperature of the thermocouple changes, making the set-up less sensitive to fluctuations in external temperature. The glass tube was then bound to a quartz crystal thermometer (H.P. 18112A) using elastic bands and immersed in a pyrex test tube (internal diameter 1.8 cms) filled again with paraffin oil. The test tube was sealed with cotton and surgical tape and further immersed in a thermos flask with a rubber stopper. This stopper was perforated in the center to accommodate the stem of the quartz thermometer and the wires of the thermocouple. The wires were pulled through and secured in place with surgical tape. The test tube was set to rest approximately 5 cm above the bottom of the thermos and close to the center so as not to touch the adjacent walls. The calibration procedure involved filling the thermos with water at different temperatures and measuring, by means of the K5 potentiometer, voltages generated by the thermocouple. A typical calibration at any one temperature took approximately 45 minutes. This was necessary to allow the temperature of the oil to stabilize. The thermocouple microvoltage was displayed on the Kipp recorder to serve as a visual aid in determining whether the temperature in the innermost paraffin tube had stabilized. When steady state was reached, the microvoltage and corresponding temperature were recorded. The water was then changed and the procedure repeated at a different temperature.

The water temperature ranged from 27.5 to 38.6 °C. Microvoltages and temperatures were plotted against each other to yield calibration equations which convert microvoltages into temperatures. Copper-constantan thermocouples are known to have a curvilinear relationship between microvoltage and temperature. Depending on the range a quadratic, cubic or even higher order equation is commonly used. Figures 2-11 and 2-12 represent the regression equations of the tympanic and esophageal thermocouples.

2.6. Oxygen Consumption and Metabolic Heat Production

2.6.0.1. Method of Collection of Expired Air

In this study oxygen consumption was measured using Douglas bags and an AEI oxygen analyser. The subject put on a nose clip and inserted a mouthpiece attached to a three way valve. The tube for the expired air was thermally insulated, to prevent any heat loss in the calorimeter. The Douglas bags were connected to the other end of this tube outside the calorimeter and timed volumes of expired air were collected. After the gas analysis (see below) the bags were evacuated in a calibrated Tissot Spirometer to the same negative pressure as before filling. Before use the Douglas bags are always "rinsed" with expired air and then evacuated with the Tissot. In this study all volumes are corrected to O°C and 100 kPa.

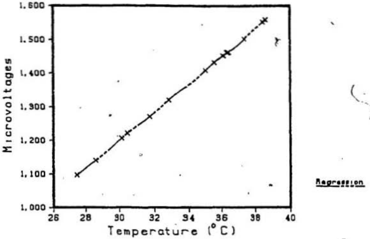

Figure 2-11: Tympanic thermocouple calibration

$$Temp = 0.0259 + 0.1024 \cdot \mu V - 0.000000657 \cdot \mu V^2$$

$$r = 0.9999 \qquad s_{xyy}^2 = 0.0097$$

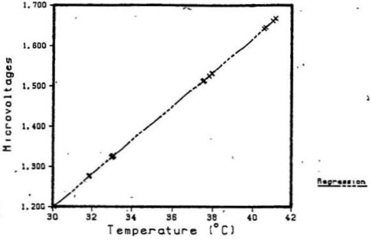

Figure 2-12: Esophageal thermocouple calibration

$Temp = 0.8345 + 0.02464 \cdot \mu V - 0.000000264 \cdot \mu V^2$

$r = 0.9999 \qquad s_{xyy}2 = 0.0040$

2.6.0.2. Method of Gas Analysis

The oxygen analyser (model S 3-A) has two independent analysis cells. At each air inlet port the sample is dried with silica-gel. One port is directly connected to the Douglas bag, the other via a CO_2 absorbing agent (soda lime). With a selector switch the analyser displays the outputs of Cell I and Cell II to two decimals, and the difference between the two to three decimals. This allows the calculation of the CO_2 concentration in the Douglas bag as well. If the composition in the Douglas bag is a% O_2, b% CO_2 and c% N_2 (i.e. "physiological" N_2, a mixture of N_2 and all other biologically inert gases), a and c will rise when CO_2 is removed, in proportion to the percentages of the other two gases:

a becomes $a+b\cdot\frac{a}{(a+c)}$

and c becomes $c+b\cdot\frac{c}{(a+c)}$

The difference between the outputs of Cell I and Cell II will be ;

$d=a-(a+b\cdot\frac{a}{a+c})$ and thus

$d=-b\cdot\frac{a}{(a+c)}$ or since

a + c = 100 - b, then $d=-b\cdot\frac{a}{(100-b)}$

solving for b gives; $b=\frac{100\cdot d}{d-a}$

Before any analysis, the output of Cell I was dialed to read 20.94 (standard air) and the difference to read -0.006 (CO_2 free standard air). A sampling pump draws the samples through the two cells. The outlet of the sampling pump is connected to a wet gasmeter, in order to measure the gas volume taken from the Douglas bag for analysis. This volume is added to the Douglas bag before any further calculations are made (the volume of CO_2 removed from half the sampled volume is smaller than the accuracy with which the Douglas bag volume can be determined; this small error is ignored.). The time required to obtain stable readings is long, because the volume displacement of the sampling pump is small and the samples for the two cells have to pass one or two rather large absorption vessels respectively. Typically 60 minutes was allowed for one analysis, with a sample volume of about 12 liters. Once the Douglas bag volume, filling time, correction factor to 0 °C and 100 kPa and the gas analysis were obtained, the calculation of R.Q. and oxygen consumption (liters/min) is classical (Carpenter, 1939).

The calorific value of one liter of oxygen is linearly dependent on the non-protein R.Q. :

$$kcal/liter = 3.817 + 1.2297 \cdot R.Q.$$

In this equation a liter (1 dm^3) contains a gas volume reduced to 0 °C and 760 mm Hg. The volume at 0 °C and 100 kPa is slightly larger (760/750.059). The equation was modified to S.I. units taking this new definition of STPD into account (1 kcal = 4.186 kJ):

$$kJ/liter = 15.769 + 5.0799 \cdot R.Q.$$

2.7.15 - Graded Borg Perceived Exertion Test

In Phase II of this study subjects were asked to rate their level of exertion on a 15-graded scale perceived exertion chart once during the course of each experiment. For the sake of convenience the scale used is given below in Table 2-1. Borg first introduced this scale in 1962 as a 21-graded scale (Borg, 1962) but later changed it to a 15-graded scale (Borg, 1970) with values from 6-20 to match the variation in heart rate from 60-200 beats/minute. The original scale functioned well and high correlations (.80-.90) with heart rates were found when subjects were tested on a bicycle ergometer. The new scale for ratings of perceived exertion, the RPE-Scale or " Borg-Scale", has now been used in many different studies in many countries with similar success (Borg and Noble, 1974; Henriksson, Knuttgen and Bonde Petersen, 1972; Pandolf, Kamon and Noble, 1978). The test was not administered in Phase I of this study.

Table 2-1: Borg rating scale for perceived exertion

6	-	
7	-	very, very light
8	-	
9	-	very light
10	-	
11	-	fairly light
12	-	
13	-	somewhat hard
14	-	
15	-	hard
16	-	
17	-	very hard
18	-	
19	-	very, very hard
20	-	

Chapter 3
Phase I

3.1. Procedure

3.1.0.1. Pre-Experimental Protocol

All experiments in Phase 1 of this study were performed using the modified exercise facility of the calorimeter (figure 2-6). As these experiments did not involve whole-body calorimetry the door of the calorimeter was left open. One subject was recruited for the total of 36 experiments carried out in this phase. His anthropometric data is included in table 4-1 (subject D) as he also took part in Phase II of this study. Since eccentric work with the legs is an unusual form of exercise, the subject had a number of practice runs at various workrates. Prior to each experiment the subject was also asked to observe a number of conditions: to do no strenuous exercise for 24 hours; to get a normal nights sleep; to eat a moderate breakfast; and to avoid alcohol and xanthine derivatives for at least 24 hours prior to each experiment. The subject was informed of the total procedure and was requested to sign a consent form (Appendix A) before being allowed to participate in the study. This procedure was also followed for the subjects in Phase II of this study. The protocol for this study (Appendix B) was approved by the Human Investigation Committee of the Faculty of Medicine, Memorial University, St. John's, Newfoundland.

3.1.0.2. Experimental Protocol

The experiments were carried out under a variety of conditions for eccentric exercise ranging from 40-80 RPM's and 0.0-24.6 N. Only one series of experiments was carried out for concentric exercise at 60 RPM. At the start of each experiment the subject sat down in the open weave steel chair inside the calorimeter and immediately began to exercise at the designated workrate. The speed and brakeforce were assigned randomly. After seven minutes of exercise the subject was instructed to put on a nose clip and breathe through a respiration valve connected to a Douglas bag (capacity 150 L) via a heavily insulated tube. Following a three minute period for flushing the dead space in the system, two Douglas bags were filled for a time period ranging from 2-10 minutes, depending on the intensity of the exercise. Once the expired volumes were collected the workrate was changed and the procedure repeated at another brakeforce and/or RPM. Not more than 3 experiments were conducted per session. During each run heart rate was monitored continuously using a General Electric EKG monitor. All expired air samples were analyzed using an S-3A Oxygen Analyzer, Applied Electrochemistry Inc., and volumes were determined using a calibrated Tissot Spirometer.

3.2. Results

3.2.0.1. Data Presentation

The results obtained for oxygen consumption and heart rate at the various work intensities for eccentric workrates (W_{ecc}) and concentric workrates (W_{con}) are presented graphically. All R.Q.'s were below 1.0 indicating that there was no anaerobic metabolism. The subject found the range of workrates evaluated in this phase well within his physical capabilities. A period of 2 - 3 days of leg muscle soreness did follow the practice runs but no further soreness was experienced by the subject during the remainder of the study.

3.2.0.2. Oxygen Consumption Data

In figure 3-1 values for oxygen consumption are plotted against workrate at five different RPM during W_{ecc}. Traditionally the relationship between oxygen consumption and conventional concentric workrate has been given in the upper right quadrant of rectangular coordinates. When eccentric exercise was added, it was only natural to plot the results in the upper left quadrant, giving the eccentric workrate a negative sign. "Eccentric work" is synonymous with "Negative work". This leads only to confusion with respect to the heat balance equation where eccentric workrate has a positive sign. Graphs 3-1, 3-2, 4-3, 4-6 and 4-8 are presented , however, in the traditional way.

The results show a positive relationship between oxygen consumption and W_a for W_{ecc}. At lower workrates the increase in oxygen consumption appears to be dependent on RPM. For example, at 40 RPM an increase in work intensity from 0 to -150 watts results in a corresponding increase in oxygen consumption of

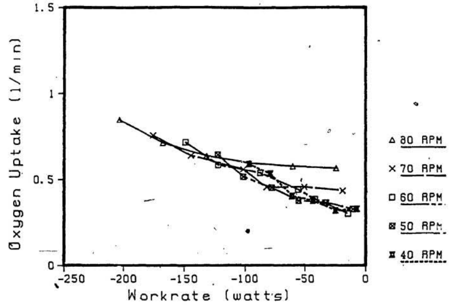

Figure 3-1: Oxygen consumption at various workrates

approximately 0.47 liter per minute while at 80 RPM an increase in work intensity of the same magnitude results in only a 0.23 liter per minute increase in oxygen consumption. At higher pedaling speeds, additional increases in work intensity elicit smaller responses in terms of oxygen consumption than at lower speeds. A subsequent analysis of covariance, however, showed no significant difference between slopes or Y-intercepts for the five different lines ($p<0.05$) and so this RPM effect must be considered negligible.

The slope of the relationship between workrate and oxygen consumption decreases with increasing RPM, but is probably only significant above 60 RPM.

3.2.0.3. Comparison of Eccentric and Concentric Exercise

A positive relationship similar to that observed for W_{ecc} is observed between oxygen consumption and workrate for W_{con} at 60 RPM. In Figure 3-2 oxygen consumption is plotted against workrate for both types of exercise at 60 RPM. The actual rate of increase in oxygen consumption with increasing workrate is considerably greater in W_{con} than W_{ecc} at 60 RPM. A 150 watt increase in work intensity results in an increase in oxygen consumption of 0.435 liters and 2.460 liters respectively for W_{ecc} and W_{con}. A regression analysis of the points in figure 3-2 results in the two following regression equations:

$$60 \text{ RPM } W_{con} \quad y=0.3631+0.0164\cdot x \qquad s_{yx} = 0.076$$

$$60 \text{ RPM } W_{ecc} \quad y=0.2659-0.0029\cdot x \qquad s_{yx} = 0.023$$

As the point of intersection with the ordinate can be interpreted to represent the oxygen consumption (y) of idling, the actual energy expenditure in pedaling the ergometer is represented by the slope of the equation times the workrate (x). The

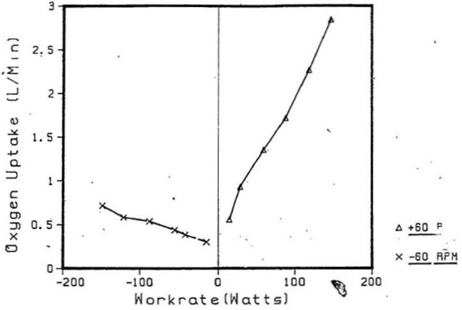

Figure 3-2: Oxygen consumption for eccentric and concentric exercise at 60 RPM

ratio of W_{con} to W_{ecc} is 0.0164 : 0.0029 or 5.7. Thus, in terms of energy cost, eccentric exercise is approximately six times cheaper than an equivalent amount of concentric exercise.

3.2.0.4. Net Mechanical Efficiency Calculation

Net mechanical efficency was calculated by taking the reciprocal of the slope of the regression lines obtained by graphing oxygen consumption against workrate for both W_{ecc} and W_{con} at 60 RPM after converting oxygen consumption to watts. Efficiency was calculated at 18.6 and -100.4% for concentric and eccentric exercise, respectively.

3.2.0.5. Heart Rate Data

In figure 3-3, heart rates were plotted against oxygen consumption for W_{ecc} only. In general, the higher the rate of oxygen consumption, the higher the heart rate, with pedaling frequency having little influence on this relationship. An analysis of co-variance didn't show any difference between slopes but did show a significant difference between y-intercepts ($P<0.05$). This was subsequently shown to be due to the data at 80 RPM i.e. a re-analysis of the data omitting the 80 RPM data showed no significant difference between y-intercepts.

In figure 3-4 the same variables were plotted for both W_{ecc} and W_{con} at 60 RPM. The regression of heart rate on oxygen uptake was linear in both instances, but the slope of the line for W_{ecc} was significantly steeper as determined by a student's t-test of slopes ($p<0.05$). It can be seen that heart rates in W_{ecc} exceed to some extent those obtained in W_{con} at similar oxygen uptake.

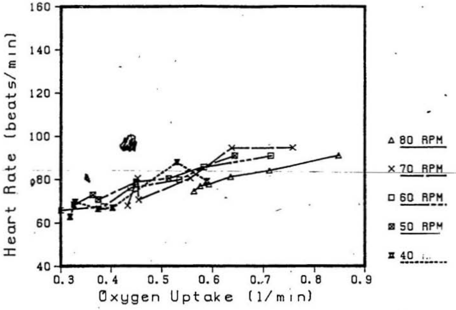

Figure 3-3: Heartrate response at various levels of oxygen consumption for W_{ecc}

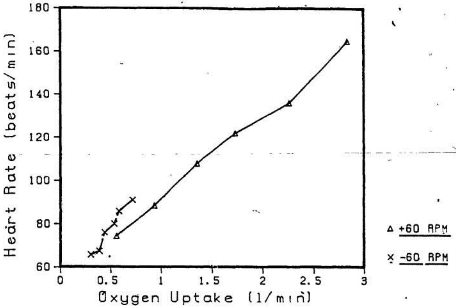

Figure 3-4: Heart rate response at various levels of oxygen consumption for eccentric and concentric exercise at 60 RPM

60 RPM W_{ecc} $y=45.31+65.71 \cdot x$ $s_{yx} = 2.30$

60 RPM W_{con} $y=53.50+38.55 \cdot x$ $s_{yx} = 3.01$

3.3. Discussion

3.3.0.1. Net Mechanical Efficiency

The oxygen consumption and heart rate data obtained in Phase I of this study are comparable to the results of previous investigators (Abbott and Bigland, 1953; Abbott, Bigland and Ritchie, 1952; Asmussen, 1952; Knuttgen, Bonde Petersen and Klausen, 1971), although their subjects rode proper bicycle ergometers and/or rode real bicycles with blocked freewheels downhill on treadmills (to simulate eccentric exercise). This difference is reflected in the lower mechanical efficiencies found in this study when compared to previous studies in which the net mechanical efficiency of cycling has been estimated at approximately 22% for concentric and -120% for eccentric exercise (Margaria, 1968; Gaesser and Brooks, 1975). The lower efficiency noted in this study is attributed to the less favorable body posture of subjects sitting in a chair and pedaling semi-reclined. As Bigland *et al*(1973) argue, a chair allows the subject to spend less energy on maintaining posture, so that only the relevant muscle groups are involved. The difference in mechanical efficiency is felt to have little effect on the results of this study.

3.3.0.2. Oxygen Consumption Data

It is commonly agreed and confirmed in this study that in light and moderate cycle ergometer exercise, steady state oxygen consumption increases linearly with the ergometric load (for review see Asmussen,1965). A number of recent studies, however, have indicated that the relationship may in fact be quadratic (Hesser, Linnarsson and Bjurstedt, 1977; Croisant and Boileau, 1984). Hesser *et al* showed that during concentric exercise in the range of 0 - 147 W the relationship between oxygen consumption and ergometric load were quadratic rather than linear.

During eccentric work (range 16 - 147), however, no such relationship could be demonstrated. The results on eccentric exercise in Phase I support these findings. Section 4.3.0.8 deals with this concept further in relation to the results of Phase II. The observation that oxygen consumption rose at a much slower rate in eccentric than in concentric exercise also confirms earlier findings. These results are generally explained in terms of the different number of actively contracting muscle fibers noted in both types of exercise (Bigland-Ritchie and Woods, 1976; Abbott and Bigland, 1953). It has been shown that each individual muscle fiber can exert a greater force while being stretched than while shortening (Katz, 1939; Asmussen, 1965; Komi, 1973) and so fewer muscle fibers are required to do eccentric exercise than to do an equivalent amount of concentric exercise. In this study the ratio of the oxygen cost of the two types of work was approximately 6.0 at 60 RPM, which is in close agreement with values obtained by the above mentioned authors.

3.3.0.3. Heart Rate Data

During eccentric exercise, heart rate increased linearly with oxygen consumption and did not vary considerably across the RPM evaluated. There is an indication that for increases in RPM above 60 the same heart rate can deliver more oxygen. Whether this is an observed physiological phenomena or an error in experimentation awaits further studies. The range of RPM looked at in this study is not sufficiently high enough to evaluate this problem properly. In physiological terms, there doesn't seem to be any clear cut reason as to why at higher pedaling rates, more oxygen can be delivered at the same heart rate. There is no reason to assume that the relationship is any different from that observed to occur in concentric exercise. During eccentric exercise, however, heart rate has been found to be higher than in concentric exercise at similar oxygen uptakes (Thomson, 1971; Knuttgen, Bonde Petersen and Klausen, 1971; Nielsen, Nielsen and Bonde Petersen, 1972) and even to increase more steeply for a given increase in oxygen uptake. Our results confirm these findings. It is proposed that this dissimilarity is related to stroke volume which has been shown to decrease in eccentric exercise when compared to concentric exercise. It has also been noted that the change in the distribution of cardiac output during eccentric exercise may be a contributing factor: Nielsen et al. (1972) have shown that the higher heat production in the muscles during eccentric exercise necessitates an increase in skin blood flow in order to maintain heat balance. In both cases, the observed physiological changes would result in higher heart rates. Similar observations have been made in subjects working in both hot and cold environments (Williams, et al., 1962; Hesser, Linnarsson and Bjurstedt, 1977).

3.3.0.4. Ergometer Performance

The close correlation between the observed physiological responses and previous studies testifies to the appropriateness of the modified bicycle ergometer in simulating eccentric exercise. Of note is the fact that the brakeband hung over the flywheel contacted only 50% of the flywheel surface and so the forces generated were only one-half of the applied weight. It was also found that the brakeband had a tendency to wear faster as the force exerted was applied to a smaller surface area. For these reasons and due to the fact that this set-up showed no real advantage over the original set-up, the original eccentric ergometer was choosen for phase II of this study.

Chapter 4
Phase II

4.1. Procedure

4.1.0.1. Anthropometric Data

A total of 6 healthy male subjects volunteered for the 70 experiments carried out in Phase II of this study. Their anthropometric data including the modified Dubois body surface area (Mitchell, Strydom, van Graan, and van der Walt, 1971) and maximal VO_2's are listed in Table 4-1. Maximal VO_2's were obtained using a standard continuous VO_2max procedure on a motor driven treadmill (Washburn and Montoye, 1984). As in Phase I subjects were informed of the total procedure involved and were required to sign a consent form (Appendix A) before being allowed to participate in the study.

4.1.0.2. Calorimeter Conditions

All experiments were carried out at a calorimeter temperature of 32.36 ± 0.06 °C, which is a considerable heat load for an exercising individual. The dew point temperature was below 5 °C and air flow through the calorimeter was about 12 m^3/min. As mentioned previously, the ergometer used in this phase was the original ergometer described by Snellen and Chang (1981).

Subject	# of Expts.	Body Wt.(Kg)	Body Ht.(cm)	Surface Area(m^2)	VO_2max (ml/kg/min)
A	11	78.4	184.0	2.11	57.5
B	12	75.7	182.7	2.10	46.1
C	12	65.6	172.3	1.89	43.6
D	24	67.8	174.5	1.92	62.6
E	12	76.6	183.6	2.09	54.3
F	8	78.9	176.6	2.06	55.0

Table 4-1: Anthropometric data

4.1.0.3. Pre-Experimental Protocol

As with the subject in phase I, all subjects in phase II were required to perform practice runs with eccentric exercise on three separate occasions. Subjects were also asked to observe the same conditions prior to each experiment as was the subject in phase I.

4.1.0.4. Experimental Protocol

Each experiment lasted approximately 50 minutes or until stable readings were obtained for ***SHE***, ***IHE*** and T_c. Pedaling speeds and brakeforces were assigned randomly, ranging from 40 - 80 RPM and 0.0 - 19.6 N respectively. Zero brakeforce during concentric exercise represents freewheeling, with only ***Wf*** as external work. During eccentric exercise it represents "being pedaled" by the motor. A 5 minute warm-up on the treadmill at approximately 60 % of VO_2max

preceeded each experiment. Then the subject, clad in only shorts and sneakers, entered the calorimeter and following a short hook-up and systems check immediately began pedaling. For eccentric exercise the subject's feet were taped to the pedals with masking tape. At all times subject and experimenter were able to communicate with each other via an intercom system. ***SHE***, ***IHE***, heart rate and either tympanic or esophageal temperature were monitored continuously. Two Douglas bags were filled between minutes 25-35, following which five consecutive, one minute heart rate readings were taken and the Borg Perceived Exertion Test (Borg, 1970) was administered (Table 2-1). The experiment was usually terminated 12-20 minutes following the expired air collection or when the measured physiological variables were steady as determined from the Kipp chart recorders and/or the computer readouts. The number of experiments per subject per day was limited to one but as many as three separate experiments were carried out on some days, depending on the availability of subjects. In table 4-2 the protocol for a typical experiment is summarized in tabular form.

4.2. Results

4.2.1. Subjective Evaluation

As with the subject in phase I of this study, all subjects experienced a 2-3 day period of muscle soreness following the first practice run but again no further muscle soreness was experienced over the remainder of the study. Also, in no instance was an experiment terminated due to an inability or refusal of the subject to maintain the workrate for the required time period.

Time(min)	0	5	10	35	45	47	50	60
Warm-up (treadmill)	<------>							
Enter calorimeter (hook-up)		<------>						
Exercise			<-->					
SHE IHE T_c			<-->					
Oxygen Consumption 2x				<------>				
Perceived Exertion					<-->			
Heart Rate 5x					<-------------->			

Table 4-2: Protocol for typical experiment

4.2.2. Experimental Data for One Experiment

The results for a typical experiment are presented graphically in figure 4-1 and 4-2 showing the monitored variables plotted against time. At this environmental temperature and range of workrates evaluated, ***IHE*** represents over 90 % of the total heat loss in the majority of cases. ***SHE*** rarely contributed more than 25 watts to the total heat loss but in a few isolated cases it was noted to be positive i.e. heat was actually being gained through ***SHE***. Since ***SHE*** is among other factors proportional to the difference between calorimeter air and mean skin temperature, these results indicate that mean skin temperature was slightly above calorimeter air temperature in most cases (heat loss), but occasionally somewhat below (heat gain).

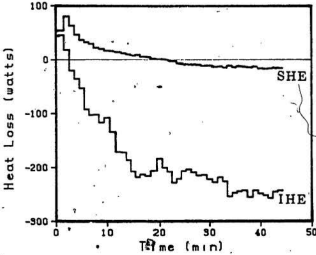

Figure 4-1: Continuous ***SHE*** and ***IHE*** readings over the duration of a typical experiment

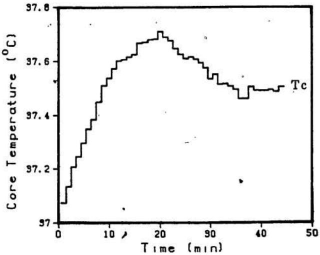

Figure 4-2: Continuous core temperature readings over the duration of a typical experiment

4.2.3. Oxygen Consumption Data

4.2.3.1. Relationship of Oxygen Consumption to Workrate

The relationship between oxygen uptake and external workrate (*We*) for all subjects during W_{ecc} and W_{con} is shown in figure 4-3. As was noted in Phase I of this study, a positive relationship exists between oxygen consumption and the external workrate. An analysis of covariance showed no effect of RPM on oxygen consumption ($p < 0.05$) during either eccentric and concentric exercise, and so all the data points were pooled for the respective type of exercise. The ratio of W_{con} to W_{ecc} is 0.0133 : 0.0017, or 7.8. This is not significantly higher (student's t-test, $p<0.05$) than 5.7 as estimated from phase I of this study. As was found in phase I, in spite of large increases in *We* during eccentric exercise, oxygen

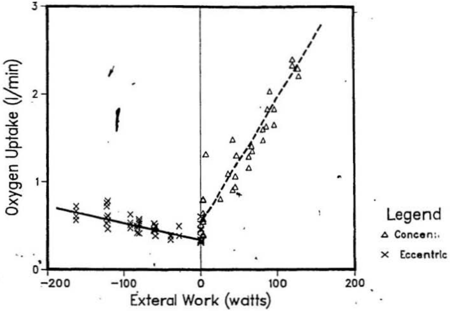

Figure 4-3: Oxygen consumption at various levels of external workrate for all RPM

W_{ecc} $y = 0.3701 - 0.0017 \cdot x$

W_{con} $y = 0.5739 + 0.0133 \cdot x$

consumption increased only marginally. The converse is true for concentric exercise.

4.2.3.2. Physiological Minimum Load Estimation

The physiological minimum load i.e. lowest steady state exercise oxygen consumption, was also estimated from the data in figure 4-3. This was done by assuming that the minimum load equals the point of intersection of the regression lines relating oxygen consumption to the measured ergometric loads in concentric and eccentric exercise. This value corresponds to an oxygen consumption of 0.3930 L/min and to an eccentric workload of -13.6 watts, a decrease of 0.1809 L/min from freewheeling oxygen uptake, or approximately 1/3 thereof. This physiological minimum oxygen uptake is only 0.0016 L/min different from that of "being pedaled". This difference is statistically not significant.

4.2.3.3. Comparison of Oxygen Uptake at 10 and 25 minutes

A student's T-test was performed to determine whether oxygen uptake values differed significantly for eccentric exercise between phase I and II. The results obtained in phase I were based on 30 observations on one subject within 10 minutes of the exercise period whereas the results obtained in phase II were based on 47 observations on 6 subjects and collected after 25 minutes of exercise. The slopes of the regression lines of oxygen consumption at various workrates of eccentric exercise in both phase I and II were found not to be significantly different ($p < 0.05$).

4.2.3.4. Heart Rate Data

A positive relationship was noted between heart rate and oxygen consumption for both eccentric and concentric exercise (Figure 4-4). Contrary to what was found in Phase I and earlier studies (Hesser, Linnarsson and Bjurstedt, 1977; Knuttgen, Bonde Petersen and Klausen, 1971; Henriksson, Knuttgen and Bonde Petersen, 1972), at any level of oxygen consumption heart rate was found to be greater in concentric than eccentric exercise, the difference between the lines being statistically significant at a probability level of $p < 0.05$ using the student's t-test. Plotting heart rate against % of maximal oxygen uptake did not change this relationship but did reduce the standard error (s_{yx}) from 9.0 down to 8.6 for eccentric exercise and from 7.2 to 6.8 for concentric exercise. In figure 4-5 oxygen consumption was plotted against heart rate for the only subject completing a series of both eccentric and concentric exercise (Subject D). In this instance the results agree with these earlier studies and the results of Phase I (figure 3-4) that at any level of oxygen consumption, heart rate is greater in eccentric than concentric exercise.

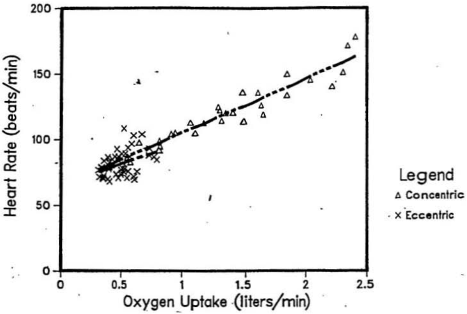

Figure 4-4: Combined data relating oxygen consumption to heart rate for eccentric and concentric exercise for all RPM

W_{ecc} $y{=}65.4{+}32.4{\cdot}x$ $s_{yx} = 9.0$

W_{con} $y{=}64.2{-}41.1{\cdot}x$ $s_{yx} = 7.1$

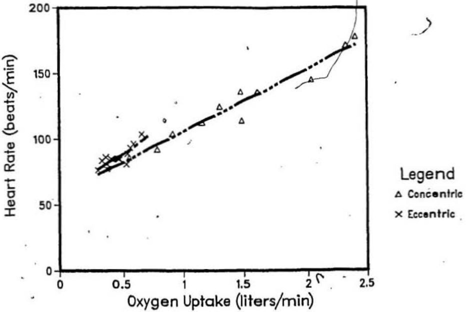

Figure 4-5: Subject D - Data relating oxygen consumption to heart rate for eccentric and concentric exercise for all RPM

$$W_{ecc} \quad y=58.0+61.4\cdot x \quad s_{yx} = 4.4$$

$$W_{con} \quad y=58.7-47.1\cdot x \quad s_{yx} = 6.8$$

4.2.4. Evidence For Near Zero Heat Storage

Although core temperature is the major indicator of caloric equilibrium, steady state conditions are also reflected in sensible and insensible heat exchange. Below are the slopes of regression lines for ***SHE***, ***IHE*** and T_c plotted against time during the last ten minutes of each experiment taking all data for all subjects:

SHE y = -0.0170 t ± 0.2396 watts

IHE y = -0.0877 t ± 1.2687 watts

T_c y = +0.0016 t ± 0.0109 °C

These results indicate that subjects did indeed reach a caloric equilibrium with negligible body heat storage within the experimental time frame. A stable ***SHE*** indicates no change in mean skin temperature. Since the contribution of mean skin temperature to average body temperature is between 10 - 15 % in the present experimental conditions (Snellen, 1966), one can safely say that with a negligible change in ***SHE*** at least 10 % of the body has zero heat storage. A rise of 0.0016 °C/min in T_c represents, even when one would consider the whole body of a 75 Kg subject to rise by this amount, 75 x 3474 x 0.0016/60 = 6.9 watts (3474 is the specific heat of the body, in J $kg^{-1}C^{-1}$). This value is already close to the resolution of the calorimeter. Since the assumption that the whole body has this rise of temperature is unrealistic, the actual rate of heat storage is negligibly small, and cannot invalidate the results of the present study.

4.2.5. Internal Work Calculation

Using a whole-body human calorimeter it is possible to measure SHE and IHE directly. Due to the construction of the calorimeter, radiation, conduction and convection are measured together as sensible heat exchange (see section 2.1). By establishing values for M, SHE and IHE using a combination of indirect and direct calorimetry it is possible, at zero heat storage, to rearrange the Heat Balance Equation (equation 1) and solve for W:

$$W = SHE + IHE - M \qquad Eq.\ 3$$

By inserting W into equation 2 (page 4) it should be possible to solve for Wi. For each experiment the heat balance equation was solved for total workrate, (W). These estimates of the total workrate performed by the subjects were plotted against We (figure 4-6). Any deviation from the line of identity represents the difference between W and We, ΔW. An analysis of covariance showed no effect of RPM on ΔW ($p < .05$) during either eccentric or concentric exercise and so all data points were pooled for the respective types of exercise. Values of W at zero load for concentric exercise (freewheeling) and eccentric exercise (passively "being pedaled") were estimated at +15.7 and +8.8 watts respectively, and may well represent the work required to overcome elastic and viscous resistance in joints and muscles, Wi. It is suprising that these values (with reversed signs) are very close to the physiological minimum load.

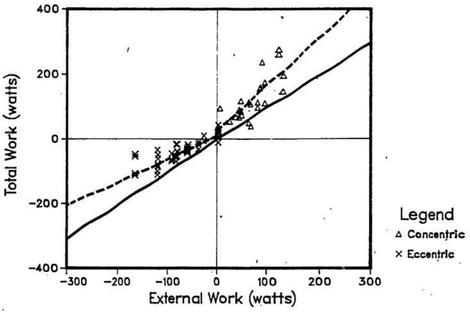

Figure 4-6: Comparison of ***We*** to ***W*** calculated from the heat balance equation

W_{ecc} $y=8.81+0.65\cdot x$ $\quad s_{yx} = 19.6$

W_{con} $y=15.75+1.51\cdot x$ $\quad s_{yx} = 41.5$

4.2.6. Perceived Exertion

In figures, 4-7, 4-8, and 4-9 mean values for perceived exertion determined after approximately 30 minutes of exercise are plotted against *We*, M and HR respectively for both eccentric and concentric exercise. In each case, the lines represent least square fit. Again, an analysis of covariance showed no effect of RPM on the relationship between perceived exertion and the three variables examined. When the regression lines for concentric exercise are compared to eccentric exercise, the perceived exertion for eccentric exercise is greater at similar levels of M and HR when compared to concentric exercise i.e. the line for eccentric exercise falls above that for concentric exercise on the graph. This is not so at similar levels of *We* where the perceived exertion for concentric exercise is seen to exceed that for eccentric exercise. Also of note is the fact that the slopes of the two lines are quite different ($p<0.05$) and a similar increase in either M or HR is associated with a greater rate of increase in perceived exertion for eccentric than for concentric exercise. Again the converse is true in the case of *We*. To test the significance of the relationship between perceived exertion and *We*, M and HR for both W_{con} and W_{ecc} Spearmans Rank Correlation was performed. Table 4-3 contains the ρ values for the three variables observed for both types of exercise.

At $p < 0.05$, all variables showed a significant correlation with perceived exertion, the correlation being much stronger for concentric exercise than for eccentric exercise in terms of HR and M and approximately equal for *We*. These results indicate a substantial relationship between ratings of perceived exertion and all the variables measured, especially for concentric exercise. In both types of

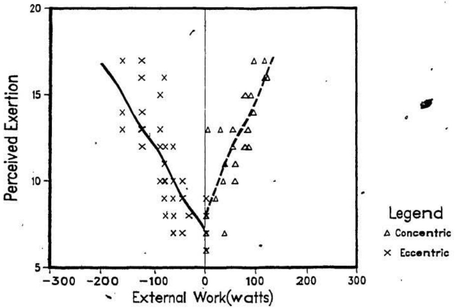

Figure 4-7: PE at various levels of external work for eccentric and concentric exercise

$$W_{ecc} \quad y = 6.99 - 0.050 \cdot x \qquad s_{yx} = 1.79$$

$$W_{con} \quad y = 7.36 + 0.072 \cdot x \qquad s_{yx} = 1.67$$

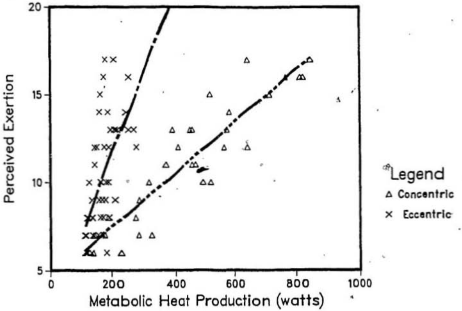

Figure 4-8: PE at various levels of metabolic heat production M for eccentric and concentric exercise

W_{ecc} $y = 2.64 + 0.045 \cdot x$ $s_{yx} = 2.86$

W_{con} $y = 4.55 + 0.015 \cdot x$ $s_{yx} = 1.58$

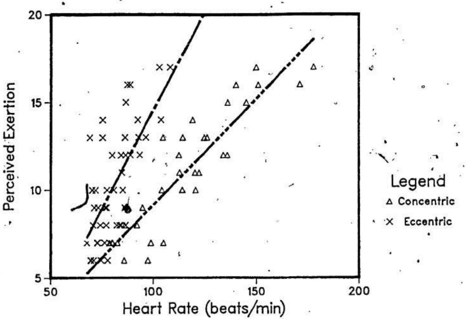

Figure 4-9: PE at various heart rates for eccentric and concentric exercise

$$W_{ecc} \quad y = -8.04 + 0.226 \cdot x \qquad s_{yx} = 2.42$$

$$W_{con} \quad y = -2.97 + 0.121 \cdot x \qquad s_{yx} = 1.69$$

Table 4-3: Spearman's rank correlation coefficients of perceived exertion and various physiological parameters for eccentric and concentric exercise

	Eccentric Exercise	Concentric Exercise
We	0.8831	0.8773
MHP	0.6478	0.8936
HR	0.6560	0.8868

exercise *We* shows the strongest correlation indicating that group ratings of perceived exertion were able to accurately reflect the work performed by the subjects in both concentric and eccentric exercise.

4.3. Discussion

4.3.1. Oxygen Consumption Data

4.3.1.1. Relationship of Oxygen Consumption to Workrate

The ratio of the metabolic cost of concentric to eccentric exercise was found to be somewhat higher in this phase of the study compared to phase I, concentric exercise costing 8 times the equivalent amount of eccentric exercise. This is still within the range of reported values given by the studies mentioned earlier in the discussion of the results from phase I. The discrepancy is quite possibly due to the variation in leg length between subjects and the distance from the pedals while exercising. Asmussen(1952) showed that the ratio of the metabolic cost of concentric to eccentric exercise increases with increasing middle length of the muscles (seat to pedals). In this study pedaling frequency was found not to have an effect on the metabolic cost of exercise. This is probably due to the fact that only lower pedaling speeds were evaluated. Asmussen(1952) noted that between 45 and 85 RPM the ratio of the metabolic cost of concentric to eccentric exercise increased between 5.9 and 13.7 while increasing the rate of pedaling from 92 to 102 RPM increased the ratio from 44.5 to 125. The range of RPM evaluated in this study was between 40 and 80 RPM and thus one would expect a ratio between 5.9 and 13.7, which was what was found. The range of RPM looked at here was probably not large enough to elicit a significant effect.

4.3.1.2. Comparison of Oxygen Uptake at 10 and 25 minutes

In the present study no substantial differences were found between oxygen consumption data taken at ten and twenty-five minutes of eccentric exercise indicating that oxygen consumption reaches steady state in a time frame similar to that for concentric exercise. These results are contrary to a recent study that shows oxygen consumption increases more than 25% in the tenth to the last minute of 25 - 50 minutes of eccentric cycling (Knuttgen, Nadel, Pandolf and Patton, 1982). The difference between our results and those of the above mentioned paper could be due to the lower exercise intensities used in this study. At lower exercise intensities, other studies have also found no such difference between oxygen uptakes at five and 20 minutes of exercise (Pimental, Shapiro and Pandolf, 1982). These results also support the concept that the original ergometer and the modified ergometer are functionally equivalent and do not yield different physiological results.

4.3.1.3. The Quadratic Relationship between Workrate and Oxygen Consumption

In support of Phase I and previous studies (Hesser, Linnarsson and Bjurstedt, 1977; Croisant and Boileau, 1984) the relationship between oxygen consumption and eccentric work was found to increase linearly with ergometric load. In contrast to these previous studies, this study found the relationship to be linear for concentric work as well. These authors proposed that oxygen consumption did not increase linearly because of the metabolic cost of unmeasured (internal) work, suggesting that the internal work does not change in proportion to the changes in the external work output. Regardless of how the internal work component changes with changes in external work or its absolute value, it seems logical to assume that it would change in proportion during eccentric and concentric work Although this study cannot comment on how the internal work changes at higher workloads, the results are consistent with the concept that it changes proportionally during increasing eccentric and concentric workloads.

4.3.1.4. Physiological Minimum Load

In this study the point of physiological minimum load was determined at -13.6 watts, less than 5.0 watts different from that noted by Hesser *et al*(1977). The procedure used to estimate this point is the one described in section 4.2.0.5. Hesser *et al* argue that the difference between the oxygen consumption at the point of physiological minimum load and the oxygen consumption in concentric exercise at zero load represents the oxygen consumption to overcome elastic and viscous resistances in the moving legs, ***Wi***. It seems logical to assume that at the point of physiological minimun load the eccentric ergometer is supplying the energy to overcome *Wi* and that the oxygen consumption drops from that seen at concentric zero load pedaling by a value equal to the oxygen consumed in overcomming *Wi*. At this point the estimated oxygen consumption is approximately 0.181 L/min lower than zero load concentric pedaling and only minimally different from the oxygen consumption at "being pedaled" (0.0016 L/min), where the provision of the energy to overcome *Wi* by the ergometer definitely applies. Unfortunately, resting oxygen uptakes were not taken and so the difference in oxygen consumption between zero load pedaling and resting i.e. net oxygen consumption was not determined. From other studies, the net oxygen consumed during zero pedaling has been found to average 0.17 L/min at 50 RPM (Aastrand, 1960), and 0.26-0.30 L/min (Whipp and Wasserman, 1969) and 0.22 L/min (Hesser, Linnarsson and Bjurstedt, 1977) at 60 RPM. If we estimate the net oxygen consumption to be approximately 0.20 L/min, it follows from this study that up to 90.0% of the net oxygen cost of zero load pedaling i.e. 0.181 L/min of the total 0.20 L/min can be attributed to overcoming *Wi*. This is considerably greater than the 33% estimated by Hesser *et al.*. They found 0.075 L/min of the total net oxygen consumption of 0.220 L/min attributable to internal work. In essence Hesser *et al.* are saying that approximately 2/3 of the oxygen cost of zero load concentric pedaling is expended on processes other than internal work yet he does not speculate where this extra energy is being expended. As well, an internal work component overcome by the energy generated from the combustion of 0.075 L/min of oxygen would be less than 5 watts. A recent cinematographical analysis of internal work (Wells, Morrisey and Hughson, 1986) showed mean internal workrates of 11.5, 20.0 and 52.0 watts at pedal frequencies of 30, 60 and 90 RPM respectively, with workload and type of exercise having no effect on the internal work component. The study by Hesser *et al.* was carried out at 60 RPM and so the internal work component would be expected to be around 20.0 watts. Although our value for internal work during eccentric exercise is somewhat lower than 20 watts at 8.8, the value obtained for concentric exercise is in closer agreement at 15.7 watts. Considering the physiological process involved, one would expect there to be a difference between the two types of exercise. The larger the external work, the greater the tension required to overcome or resist that force and thus the more muscle fibers activated. Naturally, the increased fibre recruitment would mean larger frictional and viscous forces, which would mean a higher internal work component for concentric exercise. As already pointed out, cinematography cannot quantify this component of internal work and so any estimate of internal work using this technique will omit that component. Thus, if anything, the estimates of Wells *et al* are low and the reason why they found no difference between the two types of exercise is likely due to the limitations of the technique. Regardless, our results of internal work are in closer agreement with recent cinematographical analysis.

4.3.1.5. Heart Rate Data

Another discrepancy between the results of phase I and phase II appears in the heart rate data. Figure 4-4 shows that heart rate is higher for concentric than for eccentric exercise at any level of oxygen consumption. This is in complete disagreement with the phase I results and previous studies. It was thought that individual variation in fitness, as indicated by VO_2max (table 4-1), might have confounded these results. To test this hypothesis oxygen consumption was expressed as a percentage of VO_2max, an accepted routine to pool exercise data from subjects of differing physical fitness, and re-plotted against heart rate. Again it was found that heart rate was higher for concentric than for eccentric exercise at any level of percentage of maximal oxygen uptake. From this data it is difficult to say whether the observed discrepancy was or was not due to differing fitness levels of the six subjects as only one of the six subjects (subject D) completed a full series of both eccentric and concentric exercise. It is hardly possible to compare heart rate data from subject C during eccentric exercise to data during concentric exercise for subject A, even if the data is standardised for fitness level. To overcome this problem and to test this hypothesis, only data for subject D was plotted (figure 4-5). This graph conformed to previous studies and phase I, confirming the problem associated with pooling data for subjects of varied physical fitness.

4.3.2. Eccentric and Concentric Exercise - Internal Work

The results pertaining to internal work support the concept of expending extra energy to overcome frictional and viscous resistance in the muscles, to accelerate and decelerate limb segments and to maintain posture. In terms of the total work performed by a subject while pedaling, failing to take into account the internal work component of exercise will result in an overestimation of eccentric work and an underestimation of the concentric work. Contrary to a very recent cinematographic study on internal work (Wells, Morrisey and Hughson, 1986), this study did not find internal work to be of an equal magnitude for eccentric and concentric exercise. In fact, internal work during eccentric exercise was found to be almost one-half that for concentric exercise during zero load pedaling. These results would appear consistent with the observed physiological differences noted to occur between the two types of exercise in that during eccentric exercise it has been shown that fewer muscle fibers are activated and so therefore there would be less viscous and frictional forces to be overcome. Cinematography as a technique to estimate internal work is limited in that it quantitates only the mechanical work required to raise and lower limb segments and change their velocities. It cannot quantify energy expenditure due to increased respiratory and cardiac work, increased postural efforts or energy required to overcome frictional and viscous resistances in muscles and joints. Unfortunately, whole-body calorimetry cannot be used to assess internal work at various work rates above zero load as the energy required to overcome these forces must ultimately be derived from aerobic metabolism and thus would show up as metabolic heat production. Thus, on comparing ***We*** to ***W***, one would expect no difference between the two i.e. ***We*** = ***W***. In fact, after fifty minutes of exercise, ***We*** was found not to equal ***W*** (figure 4-6). Assuming our estimates of ***M***, ***SHE*** and ***IHE*** are correct and recognizing the fact that this difference cannot equal internal work, ΔW must equal body heat storage, ***S***. These results confirm the sensitivity of the calorimeter in assessing heat balance . With direct calorimetry it is possible to detect rates of heat storage which cannot be detected by thermometry at the conventional body sites.

4.3.2.1. Internal Work or Heat Storage

When figure 4-4 was generated to compare the imposed external mechanical workrate *We* with the workrate term *W* in the heat balance equation (eq. 1, page 3), care was taken to provide evidence that heat storage was zero, or negligible (section 4.2.0.3). This evidence was based on minimal changes in mean skin temperature, as evidenced by the constancy of sensible heat exchange, and on minimal changes in esophageal or tympanic membrane temperature. The regression lines in 4-4 yielded, when extrapolated to zero external workrate, results that compared favourably with those obtained from the oxygen consumption-workrate relationship (figure 4-3), particularly with the estimate of the physiological minimum load (section 4.2.0.5). Any further inference from the increasing deviation from the line of identity in both directions must be handled with extreme caution. The first and foremost possibility must be that there is, even after 50 minutes or more of continuous exercise, a small but persistent heat storage. This study did not include the duration of the exercise period as an independent variable. Thus, the possibility that a new caloric equilibrium would have been established after 10 or 20 minutes more cannot be verified. The observed heat storage is small; an average of 33 watts for all experiments. A heat storage rate of 33 watts converts in a 70 kg subject to a rise in average body temperature of 0.008°C/min. This may well go undetected by observing the eardrum and mean skin temperature, especially if the storage takes place in peripheral body regions such as the exercising muscle. Relatively large heat storages i.e. greater than 100 watts, were observed only in three subjects on four separate occasions at high concentric and eccentric workrates. This suggests that the storage is related to the applied work, and not to the metabolic heat production. A second, but more remote possibility is a systematic error made in calculating one or more components of the heat balance equation. After all, even with a calorimeter the only unmitigated term is sensible heat exchange. Metabolic heat production is the result of manipulating oxygen consumption, and insensible heat exchange is the result of multiplying water vapor loss by the heat of vaporisation. The fact that the deviations in figure 4-1 on the concentric side, with much higher oxygen uptakes and consequently insensible heat exchange, are more than twice as large as on the eccentric side, with lower oxygen uptakes and insensible heat exchange, adds fuel to these doubts. This aspect is, however, beyond the scope of this study; the conversion factors for metabolic heat production and insensible heat exchange must be taken as they are currently accepted. The term *Wi* can, however, be approached by reasoning. Work, performed inside the body, in this study particularly inside the leg muscles, must promptly degenerate into heat, and therefore dealt with by heat dissipating mechanisms such as sensible and insensible heat exchange. *Wi* can be considered to be analogous to the mechanical work performed by the heart muscle or by the respiratory muscles. Nobody would ever dream of trying to solve for the work of the heart with the heat balance equation. Oddly enough, if we assume ΔW to be *Wi* and add it, with the appropriate sign, to *We*, there is striking agreement in the magnitude of the internal work component of exercise reported here and by that of a recent paper (Wells, Morrisey and Hughson, 1986). At -180 watts and +180 watts exercise, Wells *et al*(1986) estimate the actual work performed by the subject to be -118 and 242 watts. This study would estimate -108 and 288 watts.

However tempting it may be, this agreement must be considered coincidental. The picture might have been completely different if the exercise period would have lasted 70 minutes instead of 50 minutes.

4.3.2.2. Effect of RPM and brake force on Internal Work

Wells et al. (1986) found that increasing pedaling frequency increased internal work. From our results we cannot comment directly on how internal work changes with increasing RPM but our results found no such effect of RPM on oxygen uptakes at varying applied workrates with analysis of covariance, and thus suggests that if internal work is changing it isn't significant enough to change the relationship between applied work and oxygen consumption at different RPM. The RPM effect noted by Wells et al. (1986) was greatest when the RPM was increased above 90. Little difference was found between 30 and 60 RPM. Again it is possible that the range of RPM evaluated here was not large enough to elicit an RPM effect. The possibility of such a finding is considered likely, however, as it was found by all subjects that postural efforts were considerably greater at the higher pedaling speeds. Further research is needed to clarify this particular point.

4.3.3. The Perception of Effort

When comparing concentric and eccentric exercise at the same workrate, concentric work was perceived as being more stressful than eccentric exercise. These results are consistent with subjective comments by the subjects. Similar findings have been reported by a number of authors (Henriksson, Knuttgen and Bonde Petersen, 1972) and with different types of exercise (Pandolf, Kamon and Noble, 1978). However, when comparing metabolic and heart rate data, concentric exercise was perceived as being less stressful than eccentric exercise. It is generally thought that the perception of exertion consists of a number of signals originating in a variety of locations in the body, both centrally and locally (Lollgen, Ulmer and Nieding, 1977). These undetermined inputs dominate the perception of exertion to the extent that different levels of metabolism, heart rate and workrate are perceived to be equally stressful. Although not evaluated in this study, it is likely that the tension developed in the muscle in response to exercise is a major input to perceived exertion. This would be consistent with our findings that eccentric exercise was perceived to be more stressful than concentric exercise at similar levels of metabolism and heart rate. The tension developed in muscle fibers is greater during eccentric exercise than concentric exercise and thus would explain why eccentric exercise is being perceived as more stressful even when oxygen consumption is considerably less in the former than the latter. Further research is necessary to assess this possibility.

Chapter 5

Conclusions

1. With regards to the total work performed by a subject while pedaling, failure to take into account the internal work component of exercise will result in an overestimation of eccentric exercise and an underestimation of concentric exercise.

2. For eccentric exercise, steady state levels of oxygen consumption are reached within ten minutes of the start of exercise, which represents a time frame similar to that for concentric exercise.

3. Ratings of perceived exertion support the hypothesis that no single local or central factor can account for the perception of effort.

4. It is not possible to quantitate internal work thermodynamically as the energy required to overcome these forces must ultimately be derived from aerobic metabolism and thus would show up as metabolic heat production.

5. With direct calorimetry it is possible to detect rates of heat storage which cannot be detected by thermometry at the conventional body sites.

6. No advantage was found in using the modified bicycle ergometer over the original ergometer, the observed physiological responses on both ergometers comparing favourably with each other and previous studies.

Appendix A

Consent Form

MEMORIAL UNIVERSITY OF NEWFOUNDLAND
St. John's, Newfoundland, Canada A1B 3V6

Faculty of Medicine
Health Sciences Centre

Telex: 016-4101
Tel. (709) 737-6300

CONSENT FORM

A CALORIMETRIC ANALYSIS OF HUMAN ECCENTRIC EXERCISE

The major objective of this investigation is to establish a reliable estimate of sensible and insensible heat exchange during eccentric exercise using direct calorimetry. The entire study will consist of twelve separate experiments/subject, excluding a training period. The training period will involve three 20 minute bouts of eccentric exercise of the same nature as the exercise to be carried out in the study and using the same apparatus (modified monarch bicycle ergometer). You will have to complete these training runs at least one week before the start of the study. In addition you will have to observe a number of conditions prior to each experiment:no strenuous exercise for 24 hours; get a normal nights sleep; and eat a moderate breakfast. You will also be asked to avoid alcohol and xanthine derivatives for at least 24 hours prior to each experiment. The exercise will be carried out under two different temperatures and at three different work loads for both concentric and eccentric exercise. These work loads are light to moderate and must be sustained for estimated periods of 40 to 50 minutes. At the start of each experiment you will enter the calorimeter and begin exercise immediately. Exercise will be carried out on a modified monarch bicycle ergometer and will be maintained at 60 RPM's for 30 minutes or until steady state is reached. Oxygen consumption, sensible and insensible heat exchange, esophageal temperature and heart rate will be monitered continuously. The experiment will be terminated once steady states of the monitered variables have been reached and under no conditions will it exceed 60 minutes.

For this study it is necessary that you undergo a procedure for determining your maximal oxygen uptake (.indicator of aerobic power-, expressing the ability of the cardiorespiratory system to transport oxygen to active tissues and of these tissues to use it). Again a bicycle ergometer will be used but it will not be modified. Gas samples(expired) will be collected while you exercise at different work loads. The work load will start off at 2.5 kp(measure of force) and increase by .5 kp every two minutes until exhaustion. The leg work will be maintained at 60 RPM's.

Also it is necessary that you be able to swallow an esophageal catheter(diam. 1.5mm) without too much difficulty. This is necessary to give us a reading of your esophageal temperature during each experiment.

Apart from the sweating and strain associated with exercise, no real discomforts are involved in the study. Exercising at 20°C is quite comfortable while 30°C is considered warm yet not unbearable. Work loads will not exceed 60% VO_2max and are not hard to maintain for periods of one hour or more. The only risks involved deal with the eccentric exercise itself. To simulate eccentric exercise a 3 H.P. motor drives the fly wheels of two monarch bicycle ergometers which are connected to each other by a car differential. The break force is applied to one wheel, which causes the other wheel to spin twice as fast. The subject is required to keep this wheel turning at 60 RPM. Should the subjects feet slip off the pedals, the pedals will speed up. To avoid any injury a mechanical handbreak will be hooked up and made available to the subject so that he can stop the pedals immediately. Also a person will be situated by the motor at all times where a manual stop switch exists. A three-way intercom system will be set up to link the experimentor, brakeman and subject. The pre-study training will also serve to decrease the chances of such complications.

Participation in the study is entirely voluntary and in no way will compliance or non-compliance affect your standing or reputation. In addition, you are assured that all results pertaining to this study will be kept confidential. It is hopeful that the results will be published upon completion of the study but anonymity of the subjects will be maintained when writing the manuscript.

If you wish to participate in this study you must allow yourself to be examined by a qualified physician to determine your suitability for the study.

The purpose, nature and risks of the procedures have been fully explained to me.

I understand that my participation in the study is entirely voluntary and that I may withdraw from it at any time.

I hereby consent to participate in this study.

SUBJECT'S SIGNATURE

DATE

INVESTIGATOR'S SIGNATURE

DATE

Appendix B

Ethics Form

y 81

MEMORIAL UNIVERSITY OF NEWFOUNDLAND - FACULTY OF MEDICINE

Human Investigation Committee - Application Form

This form is intended as a convenience to speed up the processing of applications to the Committee; if all the relevant information is readily available, it should be possible to reach a decision on the proposal at the first meeting at which it is considered. The form was designed to cover as large a variety of proposals as possible: not all questions will apply to all projects; however, please consider each question carefully before writing it off as "Not applicable."

As the form will be photocopied, please type your answers or print them legibly with a black felt pen. If the space provided is not adequate and it is necessary to add further information, please submit this in single spaced typing, indicating clearly to which question the addition refers.

Applications which are not submitted on a form may still be considered by the Committee but risk delay in processing if pertinent questions are not clearly answered. Where investigators feel that their proposal involves a matter of manifest triviality only, they should consult the Chairman or the Secretary of the Committee to ascertain whether a short statement on the proposed investigation would be acceptable.

1. Name(s) of investigator(s): R.T. Farrell, Dr. J.W. Snellen and Dr. K.S. Chang

2. Name of supervisor, in case of student applicant(s): Dr. J.W. Snellen

3. Title of investigation: A calorimetric analysis of human eccentric exercise

4. List of hospitals/community settings involved:	patients/ residents	records	facilities
Health Sciences Centre - Calorimetry Lab			✓

(Check type of involvement)

5. State, briefly, objectives of the investigation: The major objective of this investigation is to establish a reliable estimate of sensible heat exchange(SHE) and insensible heat exchange(IHE) during eccentric exercise using direct calorimetry.

6. Which of the following are to be employed in the investigation:

(a) Samples to be taken from subjects: State type of sample, frequency and amount. Would samples be taken especially for this investigation or as part of normal patient care?

No samples of any nature will be taken from the subjects.

(b) Questionnaires: To whom will they be administered? How will confidentiality be maintained? Attach copy of questionnaire to be used.

No questionnaire.

(c) Clinical trials: Will this be experimental therapy / /, cross over comparison / /, double blind trial /-/, placebo / /, other (specify) Physiological study State drugs, dosage and route of administration.

No drugs used.

7. Scientific background: (If necessary, attach another sheet of paper.) If this investigation has been done previously with human subjects, why repeat it? If it has not been done with humans before, has the problem been worked out as fully as possible with animals, both to perfect analytical and technical aspects and to assess possible toxic effects? Many contemporary models of thermoregulation propose that average skin temperature and body core temperature are the thermal inputs which control heat dissipation during exercise. The available evidence suggests that for eccentric exercise(lengthening of stimulated muscle fibers) this view may be an oversimplification.

In direct contrast to concentric exercise, where work is being done by the stimulated muscle, during eccentric exercise work is done on the stimulated muscle. In exercise of the latter type, for example running downhill, mechanical energy is absorbed and converted to heat. Higher mean skin temperatures and lower internal temperatures are observed during eccentric exercise, compared to concentric exercise of the same intensity(4,5). Also the metabolic heat production of similar exercise intensities has been demonstrated to be much less when performed with(con'd)

8. Number of subjects: 6 Will pregnant subjects be excluded? YES ~~NO~~ (delete one). State how subjects will be selected. Healthy students will be asked to volunteer. Potential subjects will be screened to determine their suitability for the study. It is necessary that they be able to introduce an esophageal catheter (diameter 1.5mm) without to much difficulty. Due to the nature of the eccentric exercise each subject will also have to be trained. The training will entail 3 separate 20 minute bouts of eccentric exercise to have been completed (con'd)

9. Number of controls: 0 State how they will be selected. No control necessary. Each subject will complete bouts of both concentric and eccentric exercise at equivalent work loads (60, 90 and 120 watts) for comparative purposes. Exercise will be carried out on a modified monarch bicycle ergometer.

10. Give a brief description of the design of the study. The entire study will consist of twelve separate experiments/subject, excluding the three training runs. Pre-test protocol will require each subject to observe a number of conditions prior to each experiment: no strenuous exercise for 24 hours; get a normal nights sleep; and to eat a moderate breakfast. Subjects will also be asked to avoid alcohol and xanthine derivatives for at least 24 hours prior to each experiment. The exercise will be carried out under two different temperatures and at three different work loads. These work loads are light to moderate and must be sustained for estimated periods of 40 to 50 minutes. The subject will enter the calorimeter (after baselines have been established) and immediately begin exercise. The type of exercise, work load and temperature will be randomly assigned for each subject(con'd)

Work (watts)	Break force (kg)	Temperature (C) 20	Temperature (C) 30
60	1.0	+ve / -ve	+ve / -ve
90	1.5	+ve / -ve	+ve / -ve
120	2.0	+ve / -ve	+ve / -ve

+ve : concentric exercise
-ve : eccentric exercise

11. Describe the procedures and any tests or substances to be administered to patients (special diets, drugs, isotopic tracers, etc.)

This study involves healthy young individuals , not patients. No special drugs or diets will be administered.

12. What risks and discomforts are involved in the study? Apart from the sweating and strain associated with exercise no real discomforts are involved in the study. Exercising at 20°C is quite comfortable while 30°C is considered warm yet not unbearable. Work loads will not exceed 60% VO_2 Max and are not hard to maintain for periods of one hour and more. The only risks involved deal with the eccentric exercise itself. To simulate eccentric exercise a 3 H.P. motor drives the fly wheels of two monarch bicycle ergometers which are connected to each other by a car differential. The break force is applied to one wheel, which causes the (con'd)

13. What benefits can be anticipated from the study?

Direct calorimetry , being a more sensitive technique for measuring human energy balance, will ultimately yield more accurate information on the input-output relationships of the thermoregulatory control mechanisms.

14. Are there any immediate benefits arising out of the study for the subjects? (Specify)

There are no immediate benefits arising out of this study for the subjects.

15. Is there any invasion of privacy? NO ___ If yes, what steps will be taken to preserve confidentiality?

16. Explain the procedure for obtaining the subject's consent, where appropriate. Where applicable, attach copy of (i) consent form, and (ii) explanation of the investigation which will be given to the subject/guardian.

Consent form attached

17. Will subjects include minors /_/, mentally incompetent persons /_/, legally incompetent persons /_/? If so, what steps will be taken to protect their rights?

N/A

18. What will be the mechanism for debriefing or feedback to subjects?

Subjects will be given a verbal explanation of the results obtained. No information concerning any aspect of the study will be held back from the subjects.

19. What is the probable date of completion of the study? June 1984

20. Will volunteers receive reimbursement for expenses /_/, time lost from work /_/, or payment for participation in the study /_/? Please specify.

Nil

21. Will any tangible benefit, financial or otherwise, be derived from the investigation by the investigator or the institution?

Nil

22. Will data become the exclusive property of the pharmaceutical company or other outside agency? N/A

23. It is the responsibility of the investigators to ensure that permission is obtained from clinicians, departments, institutions or communities whose patients/residents will be involved in the study. Have the appropriate contacts been made? Yes

24. Are you agreeable to this form being passed on to any hospitals listed in # 4, if requested by them? N/A

Date of submission: FEB.29/84 Signature of principal investigator:

Signature of supervisor in case of student applicant:

Human Investigation Committee - Application Form

Investigation - A calorimetric analysis of human eccentric exercise

Question 7 con't

eccentric muscle "contractions" than with concentric contractions (1,2,3). These observations present an interesting situation for the study of human thermoregulation. During eccentric exercise when work done on the muscles is converted to heat, control mechanisms as of yet not clearly understood regulate the dissipation of this excess heat from the skin through radiation, convection and evaporation. Although the pattern of thermal exchange during concentric exercise has been well documented, the profile on eccentric exercise is still incomplete. The physiology of eccentric muscular work has been carried out before but not using direct calorimetry. Direct calorimetry, being a more sensitive technique for measuring human energy balance, will ultimately yield more accurate information on the input-output relationships of the thermoregulatory control mechanisms.

REFERENCES

1. Abbott,B.C., B. Bigland, and J.M. Ritchie. The physiological cost of negative work. J. Physiol., London 117:380-390, 1952.

2. Asmussen,E: Positive and negative muscular work. Acta Physiol. Scand. 28: 364-382, 1952.

3. Gregor,R.J. and D.L. Costill. A comparison of the energy expenditure during positive and negative grade running. J. Sports Med.,13: 248-252,1973.

4. Nadel E.R., U. Bergh and B. Saltin. Body temperatures during negative work exercise. J. Appl. Physiol. 33(5): 553-558,1972.

5. Nielsen, B. Thermoregulation in rest and exercise. Acta Physiol. Scand. Suppl. 323: 1-74,1969.

Question 8 con't

not less than one week prior to the start of the study. Maximum oxygen consumption will also have to be determined for each subject under the supervision of a licenced physician.

Question 10 con't

prior to the start of the study. Exercise will be maintained at 60 RPM's for 30 minutes or until a steady state is reached. Oxygen consumption, SHE, IHE, esophageal temperature and heart rate will be monitered continuously. The experiment will be terminated once steady states of the monitered variables have been reached and under no conditions will it exceed 60 minutes.

Human Investigation Committee- Application Form

Investigation - A calorimetric analysis of human eccentric exercise

Question 12 con't

other wheel to spin twice as fast. The subject is required to keep this wheel turning at 60 RPM. Should the subjects feet slip off the pedals, the pedals will speed up. To avoid any injury a mechanical handbreak will be hooked up and made available to the subject so that he can stop the pedals immediately. Also, a person will be situated by the motor at all times where a manual stop switch exists. A three-way intercom system will be set up to link the experimentor, brakeman and subject. The pre-study training will also serve to decrease the chances of such complications.

MEMORIAL UNIVERSITY OF NEWFOUNDLAND
St. John's, Newfoundland, Canada A1B 3V6

Office of the Dean of Medicine
The Health Sciences Centre

Telex: 016-4101
Tel.: (709) 737-6602

March 14, 1984

To: Mr. R. Farrell, Dr. J. Snellen & Dr. K. Chang

From: Dean of Medicine

Re: Application to Human Investigation Committee

The Human Investigation Committee of the Faculty of Medicine has reviewed your proposal entitled "A calorimetric analysis of human eccentric exercise".

Full approval has been granted from point of view of ethics as defined in the terms of reference of this Faculty Committee.

Yours sincerely

A.... Cox, M.D., F.R.C.P.(C)

cc: Dr. C. Triggle
Secretary, HIC
Dr. K. Gogan

References

Aastrand, P.O. (1960). Aerobic Work Capacity in Men and Women with Special Reference to Age. *Acta Physiol. Scand.*, *49 - Suppl.169*, 92p.

Abbott, B.C. and B. Bigland. (1953). The Effects of Force and Speed Changes on the Rate of Oxygen Consumption during Negative Work. *J. Physiol.*, *120*, 319-325.

Abbott,B.C., B. Bigland and J.M. Ritchie. (1952). The Physiological Cost of Negative Work. *J. Physiol.*, *117*, 380-390.

Asmussen,E. (1952). Positive and Negative Muscular Work. *Acta Physiol. Scand.*, *28*, 364-382.

Asmussen, E. (1965). Muscular Exercise. In *Handbook of Physiology: Respiration, Vol. II.* American Physiological Society.

Bigland-Ritchie, B., H. Graichen and J. Woods. (1973). A Variable-speed Motorized Bicycle Ergometer for Positive and Negative Work Exercise. *J. Appl. Physiol.*, *35*, 739-740.

Bigland-Ritchie, B. and J.J. Woods. (1976). Integrated Electromyogram and Oxygen Uptake During Positive and Negative Work. *J. Physiol.*, *260*, 267-277.

Bligh, J. and K.G. Johnson. (1973). Glossary of Terms for Thermal Physiology. *J. Appl. Physiol.*, *35*, 941-961.

Borg, G. (1962). In *Physical Performance and Perceived Exertion.* Lund:Gleerup.

Borg, G. (1970). Perceived Exertion as an Indicator of Somatic Stress. *Scand. J. Rehab. Med.*, *2*, 92-98.

Borg, G. and B.I. Noble. (1974). Perceived Exertion. In *Exercise and Sport Science Reviews.* Academic Press, New York.

Carpenter, T.M. (1939). . In *Tables, Factors, and Formulas for Computing Respiratory Exchange and Biological Transformation of Energy.* Carnegie Institute, Washington.

Chauveau, A. (1896). Le Loi de L'Equivalence dans les Transformations de la Force Chez les Animaux . *C.R. Acad. Sci., Paris,* *122*, 118-120.

Cooper, K.E. and J.R.Kenyon. (1957). A Comparison of Temperature Measured in the Rectum, Esophagus and on the Surface of the Aorta during Hypothermia in Man. *Brit. J. Surg.,* *44*, 616-619.

Cooper, K.E., W.I.Cranston and E.S.Snell. (1964). Temperature in the External Auditory Meatus as an Index of Central Temperature Changes. *J. Appl. Physiol.,* *19*, 1032-1035.

Croisant, P.T. and R.A. Boileau. (1984). Effect of Pedal Rate, Brake Load and Power on Metabolic Responses to Bicycle Ergometer Work. *Ergonomics,* *27* *NO.6*, 691-700.

Daly, D.J. and P.R.Cavanagh. (1976). Asymmetry in Bicycle Ergometer Pedalling. *Med. Sci. Sports,* *8*, 204-208.

Felig, P. and J. Wahren. (1973). Amino Acid Metabolism in Exercising Man. *J. Clin. Invest.,* *50*, 2703-2714.

Gaesser, G.A. and G.A.Brooks. (1975). Muscular Efficiency during Steady-Rate Exercise: Effects of Speed and Work Rate. *J. Appl. Physiol.,* *38*, 1132-1139.

Henriksson, J., H.G. Knuttgen and F. Bonde-Petersen. (1972). Perceived Exertion During Exercise with Concentric and Eccentric Muscle Contractions. *Ergonomics,* *15* *NO.5*, 537-544.

Hesser, C.M., D. Linnarsson and H. Bjurstedt. (1977). Cardiorespiratory and Metabolic Responses to Positive, Negative ~~and~~ Minimum-load Dynamic leg Exercise. *Resp. Physiol.*, *30*, 51-67.

Katz,B. (1939). The Relation Between Force and Speed in Muscular Contraction. *J. Physiol.*, *96*, 45-64.

Knuttgen,H.G., F.Bonde Petersen and K.Klausen. (1971). Oxygen Uptake and Heart Rate Responses to Exercise Performed with Concentric and Eccentric Muscle Contractions. *Med. Sci Sports*, *3*, 1-5.

Knuttgen,H.G., E.R.Nadel K.B.Pandolf and J.F.Patton. (1982). Effects of Training with Eccentric Muscle Contractions on Exercise Performance, Energy Expenditure, and Body Temperature. *Int. J. Sports Med.*, *3*, 13-17.

Komi, P.V. (1973). Relationship between Muscle Tension, EMG and Velocity of Contraction under Concentric and Eccentric Work. In *New Developments in Electromyography and Clinical Neurophysiology*. Karger,Basel.

Linnarsson, D. (1974). Dynamics of Pulmonary Gas Exchange and Heart Rate Changes at Start and End of Exercise. *Acta. Physiol. Scand.*, *92* - *Suppl.415*, 68p.

Lollgen,H., H.V. Ulmer and G.V. Nieding. (1977). Heart Rate and Perceptual Response to exercise with Different Pedalling Speed in Normal Subjects and Patients. *Eur. J. Appl. Physiol.*, *37*, 297-304.

Margaria,R. (1968). Positive and Negative Work Performances and their Efficiencies in Human Locomotion. *Int. Z. angew. Physiol. einsehl Arbeitsphysiol.*, *25*, 339-351.

McGilvery, R.W. (1973). The Use of Fuels for Muscular Work. In *Metabolic Adaptation to Prolonged Physical Exercise.*, Birkhauser Verlag Basel.

Mitchell, D., N.B. Strydom, C.H.van Graan and W.H. van der Walt. (1971). Human Surface Area: Comparison of the Du Bois Formula with Direct Photometric Measurement. *Pflugers Arch, 325*, 188-190.

Nielsen, M. (1938). Die Regulation der Körpertemperatur bei Muskelarbeit. *Skand. Arch. Physiol., 79*, 193-230.

Nielsen, B., S.L. Nielsen and F. Bonde Petersen. (1972). Thermoregulation During Positive and Negative Work at Different Environmental Temperatures. *Acta Physiol. Scand., 85*, 249-257.

Pandolf, K.B., E. Kamon and B.J. Noble. (1978). Perceived Exertion and Physiological Responses During Negative and Positive Work in Climbing a Laddermill. *J. Sports Med., 18*, 227-236.

Pimental,N.A., Y. Shapiro and K.B. Pandolf. (1982). Comparison of Uphill and Downhill Walking and Concentric and Eccentre Cycling. *Ergonomics, 25 NO.5*, 373-380.

Saltin,B. and L.Hermansen. (1966). Esophageal, Rectal and Muscle Temperature during Exercise. *J. Appl. Physiol., 21*, 1757-1762.

Shephard, R.J. (1982). . In *Physiology and Biochemistry of Exercise*. Praeger.

Snellen,J.W. (1966). Mean Body Temperature and the Control of Thermal Sweating. *Acta Physiol. Pharmacol. Neerl., 14*, 99-174.

Snellen,J.W. and K.S. Chang. (1981). Calorimeter Ergometer for Concentric and Eccentric Work. *Med. Biol. Eng. Comput., 19*, 356-358.

Snellen,J.W., K.S. Chang and W. Smith. (1983). Technical Description and Performance Characteristics of a Human Whole-Body Calorimeter. *Med. Biol. Eng. Comput.*, *21*, 9-20.

Thomson, D.A. (1971). Cardiac Output During Positive and Negative Work. *Scand. J. Clin. Lab. Invest.*, *27*, 193-200.

von Döblen, W. (1954). A Simple Bicycle Ergometer. *J. Appl. Physiol.*, *7*, 222-224.

Washburn, R.A. and H.J. Montoye. (1984). The Validity of Predicting VO2max in Males Age 10-39. *J. Sports Med.*, *24*, 41-48.

Wells, R., M. Morrissey and R. Hughson. (1986). Internal Work and Physiological Responses During Concentric and Eccentric Cycle Ergometry. *Eur. J. Appl. Physiol.*, *63*, 611-617.

Whipp,B.J. and K.Wasserman. (1969). Efficiency of Muscular Work. *J.Appl.Physiol.*, *26*, 644-648.

Williams,C.G., G.A.G. Bredell, C.H. Wyndham, N.B. Strydom, J.F. Morrison, J. Peter, P.W. Fleming and J.S. Ward. (1962). Circulatory and Metabolic Reaction to Work in Heat. *J. Appl. Physiol.*, *17*, 625-638.

Winter,D.A. (1979). A New Definition of Mechanical Work done in Human Movement. *J.Appl.Physiol.*, *46*, 79-83.