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EVALUATION OF STATIC WORK CAPABILITIES IN A HOT ENVIRONMENT

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THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

EVALUATION OF STATIC WORK CAPABILITIES IN A HOT ENVIRONMENT

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

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degree of

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by

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1980

EVALUATION OF STATIC WORK CAPABILITIES

IN A HOT ENVIRONMENT

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ABSTRACT

The purpose of this study was to investigate the effects of hot environments on various measures of static work capability. Using a static hand-grip contraction, the maximum strength and continuous hold endurance of five female subjects in good physical condition were tested under different heat stress conditions.

Body core temperature was employed as an independent variable. Muscle strength and endurance were measured at various levels of core temperature and an attempt made to determine the dependence of strength and endurance on the heat strain level. Because of the variation in body core temperature between individuals and to facilitate the use of existing predictive biophysical models, the core temperature increment above the resting level was selected as the major factor of interest. Five temperature increments were selected: Ø.Ø, Ø.3, Ø.6, Ø.9 and 1.2 °C above the resting level for each subject.

The primary objective was to determine the relationships between maximum strength and core temperature and between continuous hold endurance and core temperature. In order to evaluate strength and endurance in the above manner, it was necessary to generate and maintain an elevated body core temperature at a fixed level for the duration of the measurements. An additional requirement, therefore, was to develop a feasible procedure for "controlling" an individual's core temperature using some combination of environmental heat and metabolic work load.

The results indicated that there was only a slight decrease in maximum strength from the Ø.Ø to the 1.2 °C levels (approximately 8%). However, the differences in continuous hold endurance were more dramatic. At the 1.2 °C core temperature increment, there was almost a 6Ø% decrease in the length of time an individual could exert 1/3 of his maximum strength compared with the Ø.Ø °C control level. Significant differences also existed at the other core temperature levels.

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CHAPTER I

INTRODUCTION

Despite advances in modern technology, numerous jobs still exist which require moderate amounts of physical strength. In fact, strength is necessary for most types of manual labor, such as manual material handling. A large number of these jobs are performed in hot environments. For example, firefighters have the difficult tasks of moving and holding hoses and carrying heavy equipment while exposed to extremely hot conditions. Workers in steel mills, foundries and warehouses are required to exert large forces under conditions of high heat stress.

In these situations, each worker must be capable of exerting the forces required for the particular task. If the worker does not have sufficient strength, there is risk of injury, overexertion and danger for other workers. A higher strength means that a lower percentage of the individual's maximum is needed for lifting, moving or exerting the same force. Less strength means that the task requires a greater percentage of the available capacity which is more taxing and can have harmful long-term effects.

Maintaining strength throughout the task and throughout the entire work day is also very important. The term for this maintenance of strength is endurance. Again, the key principle is that the lower the percentage of a worker's maximum capability that is required, the easier it is to perform the task. Thus, both strength and endurance are essential in performing any manual work task and must be available regardless of the work environment. If they are not available, the task must be modified to reduce the work load or the work/rest schedule must be altered.

In evaluating the demands of a work task, it is often convenient to treat physical work as being composed of two components, a static component and a dynamic component. Static work consists of exerting a constant force without any movement, while dynamic work implies force exertion with movement. Most work tasks involve both components and there is seldom a clear-cut distinction between the two. However, the physical requirements and the physiological responses for the two types of work differ in several respects. Some of the more important differences will be discussed in Chapter II.

One approach to evaluating an individual's working ability is to consider the static and dynamic components separately. Indirect measures may be used which are based on the physiological responses to the particular activity, such as changes in heart rate, blood pressure, oxygen consumption and body temperature. More direct measures may pertain to the particular type of work involved. For static work, two appropriate measures are maximum strength and continuous hold endurance. For dynamic work, appropriate measures might include speed of movement and physical work capacity.

It is essential to realize that these measures are dependent on various environmental conditions including temperature, humidity, noise and vibration. Effective evaluation of an individual's ability to perform a task requires a knowledge of the changes that occur with changes in the environment.

An interesting area for investigation and the subject of this dissertation is the change in an individual's static work capability when exposed to a hot environment. The ultimate goal of such an investigation would be to evaluate maximum strength and continuous hold endurance as a function of environmental temperature and metabolic work load. However, different individuals exhibit a wide variation in the magnitude of their responses to a particular work environment.

Evaluation and explanation of changes in strength and endurance are further complicated by the fact that the environment does not directly create the changes. Rather, various physiological mechanisms, which come into action as a result of an environmental stressor, are ultimately responsible for whatever changes occur. In addition, the relationships between the environment, work load and duration of exercise, and such physiological responses as body core temperature, blood flow and muscle temperature are extremely complex.

Thus, evaluating changes in static work capability as a function of the heat stress level and the metabolic work load is difficult and even inappropriate, since the physiological responses vary widely among individuals. A better approach would be to relate changes in strength and endurance to an indicator of heat strain more closely associated with the physiological mechanisms. In this way, a more accurate appraisal of the changes in strength and endurance may be achieved, possibly resulting in a better understanding of the underlying mechanisms. This latter approach was used, with body core temperature serving as the heat strain indicator.

Problem Statement

To properly outline the scope of this investigation, it is necessary to discuss some of the decisions made in defining the research problem. Partially acclimatized subjects in good physical condition were used, as they are representative of individuals employed in heat stress occupations. The muscle group selected for the study consisted of those muscles involved in hand-grip contractions. This was done to allow comparison with previous research results. For the same reason, the force required for the endurance tests was 1/3 of each subject's maximum voluntary strength. This level of force also placed an increased demand on the cardiovascular system.

Body core temperature was employed as an independent variable. Muscle strength and endurance were measured at various levels of core temperature and an attempt made to determine the dependence of strength and endurance on the heat strain level. Because of the variation in body core temperature between individuals and to facilitate the use of existing predictive biophysical models, the core temperature increment above the resting level was selected as the major factor of interest.

The primary objective was to determine the relationships between maximum strength and core temperature and between continuous hold endurance and core temperature. In order to evaluate strength and endurance in the above manner, it was necessary to generate and maintain an elevated body core temperature at a fixed level for the duration of the measurements. An additional requirement, therefore, was to develop a feasible procedure for "controlling" an individual's core temperature using some combination of environmental heat and metabolic work load.

Thus, the specific question addressed by this investigation may be stated as follows:

> When using the forearm muscles in a static hand-grip exercise, what changes in maximum strength and continuous hold endurance occur for an individual exposed to an environment which increases body core temperature by a predetermined amount?

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

Prior to discussing the actual research in more detail, it would be beneficial to review several topics:

(1) Physiological Effects of Static vs. Dynamic Work

(2) Thermoregulatory System of the Human Body

(3) Effects of a Hot Environment - Heat Stress vs. Heat Strain

(4) Models of Combined Effects of Metabolic and Environmental Conditions on Body Temperature

(5) Assessment of Static Work Capability - Strength and Endurance

(6) Effects of Heat Stress on Work Capabilities

Static vs. Dynamic Work

The primary distinction between static and dynamic work was presented in the introduction. The different physiological responses to the two types of work have been studied by several researchers with a good overview given by Lind and McNicol (1967a). In general, active muscles require a greater quantity of blood than do resting muscles. To accomplish this, blood vessels to the muscles dilate, cardiac output and pulmonary ventilation increase, and blood flow to other parts of the body is decreased by vasoconstriction. At high work loads and in hot environments, blood flow to the skin also increases for the purpose of thermoregulation. These changes in the cardiovascular system depend on the severity of the muscular activity and the volume of muscle involved.

Whether the muscular contractions are static with tension exerted continuously or dynamic with alternating periods of contraction and relaxation, the metabolic events that occur in the muscle are the same. However, the cardiovascular responses to sustained contractions are not at all similar to those found during rhythmic exercise. The basis for the differences was described over a hundred years ago by Gaskell (1877). During a contraction, the blood vessels to the muscle dilate, but the increased flow of blood through the dilated vessels is opposed by the mechanical compression of the contracting muscle fibers. With static contractions, the mechanical compression is sustained and presents a continuous impediment to the flow of blood. In dynamic exercise, the mechanical interference is intermittent and blood flow during the relaxation periods is high. In fact, the alternate contraction and relaxation acts as a pump to assist the flow of blood.

The primary cardiovascular responses which are affected by muscular activity are heart rate, cardiac output, blood pressure and blood flow in the limbs. Again, the magnitude of the changes in these parameters depends on the type, intensity and duration of the activity.

For static muscular contractions below 15% of the maximum strength of a muscle group, there are small increases in heart rate, cardiac output, blood pressure and blood flow until steady state is reached. These contractions are usually not fatiguing. At tensions above 15% of maximum, all of the responses continue to increase for the duration of the contraction. Increases in heart rate and cardiac output are modest, while the increase in blood pressure is large. This rise in blood pressure attempts to increase the blood flow against the restriction caused by mechanical compression. However, the blood flow is never adequate for the metabolic requirements of the muscle. The higher the percentage of maximum tension exerted, the greater the restriction of blood flow. No steady state is achieved and fatigue is inevitable.

During dynamic exercise, the blood flow alternates between a restricted flow during the periods of contraction and a high flow during the periods of relaxation. The heart rate and cardiac output increase greatly but the blood pressure shows little or no change.

Recovery of these parameters also depends on the type, intensity and duration of the activity. For brief static contractions to fatigue, heart rate and blood pressure return to resting levels quickly, while blood flow usually requires 10 to 15 minutes (Lind and McNicol, 1967a). Recovery of muscle function (the ability to repeat the activity) is only 75% complete after 40 minutes and complete recovery requires several hours (Lind, 1959). Schutz (1972) performed an extensive study of the effects of varying work loads and work/rest periods on continuous hold endurance. In terms of the recovery process following static exercise, he noted that complete recovery was approached asymptotically as rest time increased and that 30 to 60 minutes was required for "nearly complete" recovery (73 to 78 % of initial continuous hold endurance).

With dynamic activity, recovery depends on the remaining oxygen demands of the muscle which were not satisfied during the activity itself. For short periods of activity (5 to 10 minutes), blood flows return to resting levels in 2 to 3 minutes (Barcroft, 1963).

The effects of combined static and dynamic work have also been examined by various researchers (Lind and McNicol, 1967c; Legars et al., 1976). Lind and McNicol investigated the cardiovascular responses to sustained hand-grip contractions at 20, 30 and 50% of maximum strength while the subjects engaged in treadmill walking at three levels of energy expenditure. In general, the blood pressure and heart rate responses to the hand-grip contractions were superimposed on the cardiovascular responses to treadmill walking. Also, forearm muscle function was not diminished by the treadmill walking and there was evidence that blood flow in active muscles of the forearm even increased during the dynamic exercise.

The results of Legars et al. indicated that the cardiac and energy costs of a combined task were higher than the sum of the individual costs for the static and dynamic components.

Thermoregulatory System

One property of the human body is homeothermy - the ability to maintain a warm-blooded state. The internal body temperature of humans and other mammals is maintained within a narrow range on either side of 37 ^{o}C. It has been hypothesized that 37 ^{o}C is an optimum temperature for many metabolic reactions (Burton and Edholm, 1955). Homeothermy has several advantages such as the ability to survive in a wide range of environments while maintaining normal alertness and effectiveness. However, it is accomplished at an appreciable cost and only with the aid of a complex regulatory system.

This system must provide regulation for two different situations. It must adjust the body physiology to meet environmental thermal demands and also rebalance biothermal heat-exchange mechanisms to dissipate metabolic heat loads during exercise. Often, these two situations occur simultaneously, requiring even larger heat transfers and complicating the regulatory process.

In order to maintain thermal equilibrium, heat production plus heat gain must equal heat loss. This may be represented by the following equation:

$$M - E \pm Cd \pm Cv \pm R = 0$$

where:

M = Metabolic Heat Production

E = Evaporative Heat Loss

Cd = Conductive Heat Exchange

Cv = Convective Heat Exchange

R = Radiative Heat Exchange

If steady state does not exist, there is an overall heat gain or loss which may be represented by a slight modification of the equation:

$$M - E \pm Cd \pm Cv \pm R = S$$

where:

S = storage of body heat (positive if body heat is rising, negative if body heat is falling)

The flow of heat by conduction, convection and radiation depends on the temperature of the body surface with respect to the surroundings. When the air temperature or the temperature of the surrounding objects exceeds the skin temperature, there is a positive transfer of heat to the body.

Besides air temperature and the temperature of surrounding objects, two other environmental factors which affect thermal balance are humidity (or vapor pressure) and air movement. High humidity, especially at higher temperatures, reduces the rate of evaporation and thus, the heat loss from the body. Higher air velocities force more air over the body surface and interact with air temperature and humidity to determine cooling or heating by evaporation and convection.

The two individual factors which affect the equation are metabolic rate and clothing. The rate of metabolic heat production is directly related to the work load and the amount of oxygen consumed during the work. Clothing acts as a barrier between the body and the environment and affects the transfer of heat in both directions and in all modes. The effects are usually assessed in terms of the insulation properties and porosity of the material.

Insulation is measured in clo units. A clo unit is the thermal insulation which will maintain a resting person indefinitely comfortable in an environment of 21 ^{o}C, with relative humidity less than 50% and air movement of 6 meters/minute (Burton and Edholm, 1955). The amount of insulation depends on the air trapped in the fabric and the ability of moisture to pass through the fabric. Porosity influences the amount of evaporation and is expressed in terms of air permeability.

All of the heat exchange factors in the above equations can be represented by heat transfer equations.

Although the equations are usually generalizations, they can be used as rough estimates of the heat exchange processes. These heat transfer functions have been included in different models which predict the state of thermal balance in terms of various indicators such as core temperature and heart rate. Additional information is provided in a later section.

Although considerable heat gains and losses may take place within the human body and between the body and the environment, the thermoregulatory system attempts to maintain a constant deep body or "core" temperature. It does this by transferring heat from the core to the shell where it is lost to the environment. The temperature of the core may change during this process, but if properly controlled, it does not rise above critical limits.

The principal thermoregulatory mechanisms are the ability to produce heat internally or lose heat at the surface and the ability to change the conductivity of the shell. For a hot environment, the primary mechanisms are vasodilation and sweating.

Vasodilation of the peripheral blood vessels causes the blood flow to the skin to increase. This increases the conductivity of the shell and increases the skin temperature, allowing a more rapid heat loss by convection, radiation and evaporation. It also results in a reduced blood supply to the muscles.

Sweating dissipates body heat by evaporation. If the environmental temperature is greater than the skin temperature, sweating is the only means by which the body can maintain its heat balance.

Hot Environment

Various approaches have been employed to evaluate the factors of a hot environment which affect human performance, safety and health. The concept of an environmental stressor resulting in physiological strain is very appropriate in dealing with the effects of heat on humans. For several years, physiologists have sought to describe the environment in terms of the important factors and develop a heat stress index which could accurately predict heat strain. The ultimate test of the validity of an environmental heat stress index is the ability to provide an accurate prediction of how people will respond to the environmental conditions being measured.

In order to understand what is meant by a heat stress index, it is important to understand the terms "heat stress" and "heat strain". According to Henschel (1963), heat stress is the total load on the individual from both environmental and metabolic sources. Heat strain is the sum of the biochemical, physiological and psychological adjustments made by the individual in response to the stress. The most common parameters used to measure heat strain are body temperature, heart rate and sweat rate. Other physiological indices of heat strain are blood volume, total body water, kidney and liver function, electrolyte concentration in the body fluids, hormone production, blood pressure, work capacity and behavior. In general, body temperature, heart rate and sweat rate all increase when an individual is exposed to a heat stress environment.

Heat Stress Indices

Environmental factors concerned with the production of thermal stress in humans have been examined since the earliest times by Hippocrates. Investigators have conducted numerous studies relating human responses to various environmental heat levels using several different indices. Each index usually includes some combination of air temperature, humidity, air velocity, radiation and metabolic work load. It may range from the simple Dry-Bulb Temperature to the more sophisticated Belding-Hatch Heat Stress Index. A review of the development of some of the indices is provided by Brown and Dunn (1975).

An excellent discussion of the search for a universal heat stress index is given by Belding (1970) who lists fourteen systems for rating heat stress and heat strain. Many of these systems had obvious limitations which prevented them from ever gaining widespread usage. Others became popular for a period of time and then lost their popularity because shortcomings were discovered or because an apparently better index was developed. Several of these indices are in use today, but none has achieved a position of universal acceptability because each index appears to have shortcomings in certain environments. A discussion of some of the more prominent indices follows.

The Dry-Bulb Temperature (DB) is most widely used by the layman in describing the temperature of the environment. It can be measured by a common mercury thermometer or by an electronic thermistor circuit with a digital readout. It is acceptable as a heat stress measurement only if the air is quite dry and there is minimal radiation and air movement.

The Wet-Bulb/Dry-Bulb Index (WD) is given by the formula:

$$WD = 0.85\ WB + 0.15\ DB$$

where WB is the unaspirated wet-bulb temperature. With minimal radiation and air movement, the wet/dry index is a good predictor of human stress.

Houghten and Yaglou (1923) established the Effective Temperature Index (ET) as the first physiological index of heat stress using the parameters of dry-bulb temperature, wet-bulb temperature and air movement. An environment at a given effective temperature provides the same thermal sensation as an environment with the same dry-bulb temperature and a relative humidity of 100 percent. For example, the combination of a dry-bulb temperature of 27 °C and a relative humidity of 40% feels as warm as still, saturated air at 25 °C and thus corresponds to 25 °C on the ET scale.

According to Belding (1970), the original ET scale overemphasizes the effect of humidity in cool conditions and underemphasizes its effect in warm conditions.

The ET index was later modified by Bedford (1946) to include the effects of radiation. This index is known as the Corrected Effective Temperature Index (CET) and is calculated by substituting the globe temperature for the dry-bulb temperature on the ET nomograph.

Yaglou (1950) considered Bedford's correction for radiant heat to be inadequate and developed an index which he called the Equivalent Effective Temperature Corrected for Radiation (ETCR). He introduced an additional correction by substituting a pseudo wet-bulb reading for the psychrometric wet-bulb along with the substitution of globe temperature for dry-bulb temperature. The resulting index values given by ET, CET and ETCR are unreliable at higher environmental temperatures (Brown and Dunn, 1976). This fact led to the exploration of the various physical determinants involved in the production of thermal stress.

McArdle et al. (1947) suggested the Predicted Four Hour Sweat Rate (P4SR). In a series of experiments, they found that sweat loss was the physiological measurement that correlated best with the severity of the work environment. They developed a scale based on the amount of sweat produced in four hours by acclimatized young men performing a prescribed amount of work. The index accounts for globe or dry-bulb temperature, wet-bulb temperature and air speed, with adjustments for energy expenditure and the amount of clothing worn. Leithead and Lind (1964) expressed the opinion that P4SR is the most accurate indicator of heat stress, but that it would be applicable only where sweating occurs continuously.

The Heat Stress Index (HSI) was developed by Belding and Hatch (1955) and was later modified by Hatch (1963). The HSI is based on heat exchange equations and includes the metabolic work load and evaporation rates in addition to the previously mentioned environmental variables. The underlying concept is that in order to maintain body temperature within the safe range, the body's heat loss must equal or exceed its heat gain. The Heat Stress Index is defined as follows:

$$HSI = \frac{M + C + R}{Emax} \times 100$$

where:

M = Heat load from metabolism

C = Heat gain or loss from convection

R = Heat gain or loss from radiation

Emax = Evaporative capacity of the environment (maximum amount of heat that an individual can lose through evaporation)

In 1956-1957 the Wet Bulb-Globe Temperature Index (WBGT) was formulated by Yaglou and Minard (1957). The index was derived from Effective Temperature scales and is defined as follows:

Indoors: $WBGT = 0.7\ NWB + 0.3\ GT$

Outdoors: $WBGT = 0.7\ NWB + 0.2\ GT + 0.1\ DB$

where:

NWB = natural wet-bulb temperature

GT = globe temperature

DB = dry-bulb temperature

WBGT is inexpensive to determine, yields a single value for interpretation and is usable over a wide range of indoor and outdoor conditions. Instrumentation has been developed to provide instantaneous readout of the WBGT value (Kuehn, 1968).

The American Conference of Governmental Industrial Hygienists (ACGIH) proposed threshold limit values (TLV's) for heat stress utilizing the WBGT index (ACGIH, 1972). The TLV's were based on the assumption that an acclimatized, fully clothed worker whose deep body temperature is maintained at 38 ^{o}C or less is not subjected to heat stress. The limits were modified depending on the level of physical activity.

The WBGT was also used in the NIOSH criteria document on hot environments in 1972 (NIOSH, 1972). This criterion assumed a continuous heavy muscular work output. The U.S. Department of Labor modified the WBGT index to incorporate air velocity as well as physical activity (DOL, 1974). Dukes-Dobos and Henschel (1973) used graphical methods to modify the index in terms of physical activity.

The Wet Globe Temperature (WGT) was developed by Botsford (1971). It consists of a dial thermometer with a heat sensor enclosed in a 6.35 cm diameter copper sphere covered with a wet black cloth. It was designed to take into account all the forms of heat exchange which affect man's response to hot environments: evaporation, conduction, convection and radiation.

Jensen and Heins (1976) compared five prominent heat stress indices: Corrected Effective Temperature, Effective Temperature Corrected for Radiation, Wet Globe Temperature, Wet Bulb-Globe Temperature and the Belding-Hatch Heat Stress Index. They concluded that the Wet Bulb-Globe Temperature provided the best evaluation of environmental heat stress in the majority of industrial environments. WBGT correlated highly with various heat strain indices and was relatively easy to compute. Their conclusions supported previous recommendations by Mutchler et al. (1975).

Recently, Pulket et al. (1980) made a comparison of heat stress indices in hot-humid environments. In addition to the above indices, their examination included the Relative Strain Index (RS) of Lee and Henschel (1963) and two indices developed by Pulket (1975). Correlation coefficients between eleven stress indices and four strain indices indicated that most empirical heat stress indices correlated best with mean skin temperature. However, the rational indices derived from the thermal balance equation correlated best with heart rate and sweat loss. Because of the ease of use, WGT and CET were recommended for preliminary industrial surveys in hot-humid environments.

Predictive Models

Various approaches have been used in an attempt to model the thermoregulatory system of the human body. The models may be divided into two categories. In one category are those models which predict the internal temperatures of specific regions of the body using heat transfer equations. In these models, characteristics of the environment are used to establish boundary conditions for the solution of the equations. The other type of model uses significant environmental and individual factors to predict physiological responses such as core temperature or heart rate. Both types include the metabolic heat generation of the body.

Wissler (1963) developed a model for temperature profiles of body segments which included the following factors: (1) local generation of heat by metabolic reactions, (2) conduction of heat due to thermal gradients, (3) convection of heat by circulating blood, (4) the geometry of the body, (5) the existence of an insulating layer of fat and skin, (6) countercurrent heat exchange between adjacent large arteries and veins, (7) heat loss through the respiratory tract, (8) sweating, (9) shivering, (10) the storage of heat and (11) conditions of the environment, including temperature, wind speed and relative humidity. He modeled the human body using six cylindrical elements representing the trunk, head, two arms and two legs.

Assuming uniform heat generation within each cylinder and neglecting longitudinal conduction of heat, Wissler developed a set of differential equations representing the various heat flows in each segment. Boundary conditions were established by assuming that the local rate of heat conduction to the surface through the tissue was equal to the rate of heat transfer from the surface to the environment. All of the environmental factors were condensed to the product of a heat transfer coefficient and the difference between the surface temperature and an effective environmental temperature.

The model can be used to estimate temperatures at various distances from the center of each element for both steady state and transient conditions. It also provides a good estimate of transient state rectal temperatures for various work loads and environments. The major difficulties in using the model are in selecting appropriate values for the heat transfer coefficients, blood flows and rates of metabolic heat generation. Also, a large number of iterative computations are required to solve the equations once the parameters have been chosen.

A model developed by Crosbie, Hardy and Fessenden (1963) uses a slightly different approach to avoid some of the difficulties of Wissler's model. An analog computer is used to solve the many nonlinear differential equations and to provide continuous temperature readings over time. Rather than predicting temperatures at any radius from the center of a segment, they only consider three layers: the core, the muscle layer and the skin layer.

The model includes metabolic heat generation, heat transfer by radiation and convection and heat loss by vaporization. Predicted variables include rectal temperature, skin temperature, metabolic rate, vasomotor rate and evaporative heat loss. As with Wissler's model, many of the parameters are arbitrarily selected.

The second category of models attempts to predict physiological responses based on measurable variables and does not rely on the proper selection of heat transfer coefficients. Vogt et al. (1973) derived a mathematical model from empirical data which predicts the heart rate response of men exposed to heat. The inputs to the model include rectal and skin temperatures. In practical applications, however, these inputs are often more difficult to measure than heart rate itself. Also, the model was derived using data from unacclimatized subjects and does not include climatic measurements or clothing properties.

Givoni and Goldman (1972, 1973) developed two biophysical models which predict the time pattern of rectal temperature and heart rate responses of heat acclimatized men exposed to various combinations of work, environmental conditions and clothing properties. In each model, three separate formulas are used, one for rest in the heat, another for the rising stage during work and a third for the recovery stage.

The following factors are included in the model:

(1) air temperature

(2) environmental vapor pressure

(3) ambient air velocity

(4) metabolic energy expenditure (determined from subject weight, speed and grade of walking or running and load carried)

(5) thermal resistance of clothing

(6) permeability properties of clothing

(7) different modes of heat transfer (evaporation, conduction, convection and radiation)

The input variables for each model are easily determined and calculation of the predicted values is straightforward. Givoni and Goldman also included nomograms to aid in computing the various components of the prediction equations. The predictions of the models were compared with data collected from several studies at different work loads and environmental conditions. The correlation between the predicted and measured rectal temperatures at the end of work was high

(Ø.83 to Ø.97). However, significant individual variation existed in the rectal temperature response.

Dayal (1974, 1976) modified the models of Givoni and Goldman by including the radiant heat load and the aerobic capacity of the subject. He performed additional experimentation to validate the modified models and again found close agreement between the predictions and the experimental data. Correlation coefficients between measured and predicted values were Ø.89 for rectal temperature and Ø.97 for heart rate. More accurate predictions could be obtained with individual adjustment of the parameters of the model for each subject.

Static Work Capability

There are two commonly used measurements to evaluate an individual's static work capability, maximum strength and muscular endurance. As set forth by Simonson (1971), tests of maximum strength involve static work with an unlimited counterforce, such as tests with a spring dynamometer. On the other hand, tests of muscular endurance involve static work with a limited counterforce, such as holding a weight. Both of these types of muscular performance have been investigated and both measurements have their advantages and limitations.

Strength Measurement

As with many physiological parameters, accurate and objective measurement of strength is difficult. There are many classifications of strength such as isometric, isotonic, dynamic and explosive. There are also several different techniques and devices which have been used to measure strength. One definition of strength currently in use is that proposed by Kroemer (1970). "Strength is the maximal force muscles can exert isometrically in a single voluntary effort." The term usually used for this force exertion is maximum voluntary contraction (MVC). Isometric contraction means that the length of the muscle does not change when the force is being exerted. This implies that there is no movement of the body segments involved in the contraction. Voluntary strength must be used since there is no safe method of determining absolute muscle strength.

An individual's voluntary strength depends on a number of factors, including: (a) individual characteristics such as health, prior training, sex and age, (b) body position, (c) motivation, and (d) the level of fatigue at the time of the exertion.

The amount of external force which can be applied is a function of the length of the muscle and the prevailing mechanical advantage. These, in turn, depend on the joint angles for the muscle group being measured. For any strength measurement to be meaningful, it is important that the joint angles and the point of application of the force be accurately specified and controlled.

Previous studies have shown that human strength measurements are dependent on the level of motivation and the particular instructions given to the subject (Caldwell et al., 1974). When subjects can be selected for their high degree of motivation, variation of repeated tests of static strength is small. However, when experiments involve large groups of subjects that cannot be selected with such care, the problems of motivation become evident.

Ikai and Steinhaus (1961) found that many of their subjects produced maximum effort only after a preceding stimulus such as a shout. The maximum tension produced was 7 to 12 percent higher than without the preceding stimulus. Furthermore, hypnosis has also been shown to increase maximum strength of many subjects. Barber (1966) made a critical review of the literature on the effects of hypnosis. He concluded that "motivational suggestions or suggestions of increased strength and endurance are generally as effective in augmenting performance when given to 'awake' subjects as when given to subjects who have received a 'hypnotic induction' and who appear to be in 'trance'."

Thus, it appears that hypnosis or other stimuli improve the maximum contraction, particularly in poorly motivated, untrained subjects, by removing some form of inhibition. Highly motivated subjects, on the other hand, can produce their maximum effort without such stimuli. In general, experiments involving highly motivated subjects yield results with much less individual variation than those experiments involving less motivated subjects.

Coincident with motivation is the decision whether or not to inform the subjects of their performance. Knowledge of the score may significantly increase their maximum strength (Berger, 1967; Johnson and Nelson, 1967). To minimize the variation due to these effects when testing large groups of subjects, Chaffin (1975) recommends the following procedure:

(1) Instructions to the person during testing should be objective in tone and not include emotional appeals.

(2) The person should be told to increase exertion to a maximum in about one to four seconds and hold it there for a four second count while a measurement is made.

(3) The person should be informed of his or her general performance in positive terms but not be given specific values to compare with norms or other participants.

(4) In general, specific monetary incentives, fear, noise, spectators or any other factors which could emotionally influence the person's concentration and cooperation during the testing period should be minimized.

Even though the muscular tension during strength testing is maintained for a relatively short time period, muscle fatigue can occur which reduces the maximum tension. Adequate rest periods between repeated exertions are necessary to minimize fatigue. Various studies have shown that two-minute rest periods appear to be adequate if about fifteen measurements are taken in a test session. A minimum of thirty seconds is required if only a few measurements are made. In addition, Chaffin recommends that careful verbal monitoring be used to determine if additional rest is needed.

The experience of those conducting the tests and the efficiency and accuracy of their equipment can also affect the measurements. These factors may account for at least some of the discrepancies that appear in the literature either between studies or between results of different muscle groups in the same study.

Taking into account the above difficulties, the measurement of maximum strength is still a reliable indicator of a person's ability to perform static work. Most of the studies which examine the distribution of repeat standard deviations of large numbers of subjects exerting maximum voluntary contractions of different muscle groups show fairly good agreement. For example, Rohmert (1961) and Muller (1961) showed that in 95 percent of their measurements, the standard deviation was within plus or minus 8.5 percent of the mean. In investigating the reproducibility of maximum strength measurements, Tornvall (1963) measured coefficients of variation (standard deviation/mean) ranging from 3.2 percent for elbow flexion to 11.4 percent for backward flexion of the trunk. From this it can be concluded that a complex contraction is more difficult to measure accurately than a simple contraction.

Start and Graham (1964) found a correlation coefficient of 0.94 for test - retest reliability of the strength of forearm flexion. Martens and Sharkey (1966) found that the coefficient of variation of the same muscle groups in exerting power was 11.1 percent. Bruce et al. (1968) reported a coefficient of variation for maximum voluntary hand grip contraction of 4.5 percent in subjects not chosen for their high motivation. Elbel (1949) examined over 500 subjects on six separate occasions. He found a coefficient of reliablilty of the maximum strength of leg muscles to be between 0.93 and 0.96.

Various approaches have been used in an attempt to improve the reliability of strength measurements. Chaffin (1975) recommends that the voluntary force be maintained over a period of four to six seconds. This provides adequate time to assume a steady state exertion and still minimize the effects of fatigue. Caldwell et al. (1974) make the following recommendations:

(1) Static strength should be assessed during a steady exertion sustained for four seconds.

(2) The transient periods of about one second each before and after the exertion should be disregarded.

(3) The strength score is the mean value recorded in the first three seconds of the steady exertion.

In any case, it is recommended that the effort be maintained for a period of at least three seconds. Even though the contraction is required for only a few seconds, the exerted force is not constant but fluctuates in an irregular and unpredictable manner. These fluctuations complicate the measurement task.

Strength Measuring Procedure

Any strength measuring procedure must include (a) a device for measuring the force or torque developed by the particular muscle group, (b) a means of attaching the force measuring device to the person, (c) a device for positioning and restraining the person in the proper location for the test, and (d) some type of data acquisition system. One of the key factors in strength measurement is the type of instrumentation used since this determines, either explicitly or implicitly, the actual criterion for the measured strength value.

Most instruments used to measure muscle strength can be categorized as either "indicating" or "recording" instruments. Initially, strength measurements were made using either a spring scale or cable tensiometer (Clarke, 1954,1966). Both of these instruments are of the indicating type and usually employ pointers. They are no longer recommended since they are subject to significant measurement error (Chaffin, 1975). The reading of the fluctuating pointer had to be made quickly by the experimenter who usually recorded the peak value observed rather than the more stable three-second average.

In recent years, accurate and sensitive force transducers consisting of resistance strain gages with appropriate electrical bridge circuitry and signal amplification have been successfully used. The slight deflection of a piece of metal when a force is applied changes the resistance of the strain gage attached to it. This difference in resistance can be detected and amplified to provide a voltage output which is directly proportional to the force applied. The electrical output of the strain gage can be used as input to a chart recorder or can be converted to provide a digital readout. It also conveniently lends itself to computer processing.

The force measuring device must be attached to the person in such a way that it does not influence the individual's exertion by causing localized discomfort where it couples to the body. For strength measurements involving the limbs, a 2.5 to 5.0-cm wide strap or padded contact surface should be provided. If pushing, pulling or squeezing forces are exerted by the hands, the handles should be sufficiently padded to minimize contact discomfort.

The body position of the person must be controlled to obtain the proper measurement and minimize the effects of body mass and size. Various joint angles should be measured with a protractor or goniometer, and the positioning of the force transducer should be made using known body landmarks. Restraint systems may also be used to restrict the movement of other parts of the body.

Finally, a data acquisition system is needed. This may range from a person reading the pointer of a spring scale to a sophisticated system utilizing electronic circuitry to time-average the force exertion. Whereas the use of spring scales and cable tensiometers results in a peak value for the strength measurement, strain gage transducers allow more freedom in establishing the strength criterion. Not only can the peak value be determined, but several time-averaging techniques can also be used.

One method is to merely calculate the average over the middle three seconds of the measurement period. This may be done graphically from the chart recording. A more precise analysis can be achieved by sampling the data using an analog-to-digital converter and mathematically computing the mean, standard deviation and other values. After this conversion, the raw data consists of a sequence of values stored as a function of time. Various types of time series analyses can then be applied to the converted data.

Several time-averaging techniques were investigated by Owings et al. (1975). Their approach was to find the "maximum moving point average" during the period of the exertion. The procedure was as follows:

(1) Perform analog-to-digital conversion of the five seconds of data at the rate of 20 points per second.

(2) Divide the entire time period into intervals of n points in length.

(3) Calculate the average for the 1st through the nth point.

(4) Calculate the average for the 2nd through the n+1 th point.

(5) Continue until the average is found for the final n points.

(6) Select the maximum of these averages for the strength score.

This procedure yields the maximum of all possible sets of contiguous intervals of length n. After examining intervals of length 1, 5, 10, 20, 40, 60 and 100 points, Owings et al. selected 20 points as the interval length yielding the smallest test-retest differences. Thus, the strength score they selected is the maximum one-second moving point average found after analyzing five seconds of data. This provides a long enough period of time to eliminate effects due to explosive strength and a short enough period to eliminate the decreases in strength due to fatigue and loss of motivation.

Endurance Measurement

If force is exerted by a muscle or muscle group for any significant time period, the muscle becomes fatigued. The causes of fatigue are numerous and not completely understood. In fact, defining fatigue in terms of some measurable characteristic is very difficult. One approach involves the evaluation of muscular endurance, a second measure of static work capability.

There are various ways of measuring endurance depending on the amount of force required for the test and the method of generating the force. Some of the methods are:

(1) continuous hold endurance at a fixed percentage of MVC

(2) continuous hold endurance at fixed load

(3) continuous force exertion at maximum strength

(4) series of maximal strength exertions

In almost all cases, the test involves limited counterforce, such as holding a weight. Because of this, endurance measurements are more representative of most work tasks than are strength measurements.

One of the most common measurements is continuous hold endurance. Continuous hold endurance is the amount of time an individual can sustain a fixed static contraction without significant tremor. Because a person can exert a maximum force for only a short time period (less than five seconds), the contractile force required in a continuous hold endurance test is usually submaximal.

In most cases, the required force is based on the maximum strength and taken as a fixed percentage of the MVC. Consequently, the force used for different individuals is not equal, but should represent an equivalent physiological load. Some researchers measure continuous hold endurance using a fixed load rather than a fixed percentage of MVC. This provides an indication of "absolute" endurance rather than "relative" endurance and may be more applicable when evaluating the ability to sustain the fixed loads encountered in a work environment.

Start and Graham (1964) performed a study to compare the absolute endurance with the relative endurance of the elbow flexors using thirty male subjects. For the fixed load tests, they used a force equal to five eighths of the "average" maximum strength of all thirty subjects. For the relative endurance tests, they used a force equal to five eighths of each individual's maximum strength. Their findings were that there was a correlation between maximum strength and absolute endurance of Ø.749, significant at the 1 percent level, while the correlation between maximum strength and relative endurance was -Ø.356, which was not significant at the 1 percent level. This differs from the findings of Monod and Sherrer (1957), Monod et al. (1956), Rohmert (1965), Caldwell (1964) and Rohmert (1968), all of whom found a clear relationship between the maximum strength of individuals and their endurance times at submaximum tensions.

By fixing the required force (whether absolutely or relatively), one source of voluntary cooperation is eliminated. However, maximum endurance times are still dependent on subject motivation. With highly motivated subjects (Clarke, Hellon and Lind, 1958; Lind, 1959), coefficients of variation for endurance times were low, ranging from 3.6 to 3.8 percent. However, with large groups of subjects, the repeatability of endurance times is less consistent than the repeatability of maximum strength measurements.

In their study, Start and Graham (1964) found the correlation coefficient for endurance to be 0.83 compared to a value of 0.94 for maximum strength. Bruce et al. (1968) found the coefficient of variation for endurance to be 20 percent for the first two days of testing, decreasing to 7 percent after two weeks of training. This compares to a value of 4.5 percent for maximum strength for the same subjects over the same period. Martens and Sharkey (1966) found the coefficient of variation for endurance at three eighths maximum strength to be 18.1 percent compared to 11.1 percent for maximum power. Elbel (1949) found a coefficient of reliability for endurance of 0.68 compared to a value of

0.93 to 0.96 for maximum strength.

Measurement of muscular endurance involves an exertion to fatigue as opposed to the five second maximum effort required for strength measurement. Additional motivation is required to maintain the tension through discomfort and sometimes even pain. It is the author's belief that this fact is responsible for the lower reliability of endurance measurements. In addition, differences in muscle temperature have been shown to affect muscular endurance but not maximum strength (Lind and McNicol, 1967c).

Schutz (1972) used continuous hold endurance with fixed loads as a measure of local muscle fatigue in examining various work-rest periods and recovery times. He justified its use by showing its relevance to fatigue and its ease of quantification. His laboratory experience demonstrated the correlation between continuous hold endurance and other attributes of performance such as tremor, coordination and discomfort.

Another approach to measuring endurance is to perform a continuous hold at maximum strength. As time progresses, the maximum force exerted declines and an isometric fatigue curve is generated. The shape of the curve is exponential starting at maximum force and approaching an asymptote after approximately two minutes. This type of endurance measurement provides information on the cumulative effects of exerting maximum force for an extended period of time.

Clarke and Gentry (1971) used this type of measurement in investigating differences between hand grip and elbow flexion fatigue. Correlations between hand grip and elbow flexion were generally low. They found the shape of the curves to be similar for the two different muscle groups, even though the curve parameters were quite different. However, their curves were different from those obtained by Royce (1958), Clarke (1962) and Clarke and Stelmach (1966), in which hand-grip contractions were used. The differences occurred primarily in the first minute of exercise.

Finally, endurance can be measured by means of a series of repeated maximum voluntary contractions. As stated earlier, even though a maximum strength measurement lasts only five seconds, an adequate time must be allowed between measurements or fatigue of the muscle group will occur. If a series of maximum force exertions is made without adequate recovery time, the change in strength which occurs will form a measure of fatigue and endurance. As the time between measurements is reduced, the task becomes a measure of isotonic endurance. This is often referred to as rhythmic isometric exercise.

Endurance Measuring Procedure

The measurement of endurance employs much of the same equipment and procedures used for strength measurement. The equipment must include (a) a device for generating the force or torque required of the particular muscle group, (b) a means of attaching the device to the person, (c) a device for positioning and restraining the person in the proper location for the test, and (d) some type of data acquisition system. These were all discussed in a previous section.

For continuous hold endurance using a fixed percentage of MVC or a fixed load, a weight may be held in a fixed position to generate the required force. Another alternative is to use a load cell and provide feedback to the subject. The subject is then required to exert the proper amount of force for the test by observing the output from the transducer.

Two major items are needed as part of the data acquisition system. Some type of apparatus is needed to determine when the required force is no longer being exerted along with the criterion for terminating the measurement. Also, some means of measuring the endurance time is required.

In his research, Schutz (1972) experimented with various methods of making continuous hold measurements and devised a method which would minimize the variability in the measurements. His experiment consisted of supporting a weight by the wrist with the elbow fixed at a 90 degree angle. The subject was required to keep his forearm in contact with a wire positioned perpendicular to the forearm just above the wrist. The test was terminated when the subject's forearm fell below the wire and remained off the wire for a count of five. The endurance time was recorded as of the time the subject's arm initially fell. This technique provided a distinct termination point and thus a smaller variation in endurance times. Throughout his study, Schutz used highly motivated subjects. His procedure would probably be more effective than the feedback technique even with less motivated subjects.

Measurement of endurance by means of a continuous maximum strength measurement or a series of maximum strength measurements requires the same equipment as that used for strength measurement plus recording equipment and a scheme for sampling the continuous data. With the aid of a mini-computer, the sampling can be performed automatically.

Work Capabilities vs. Heat Stress

Whenever an individual is engaged in physical work in the heat, the physiological responses and the ability to perform that work are directly affected by the hot temperature. Previous research has been conducted to evaluate these effects and to establish standards which will protect the worker's health and safety. For the most part, this research has been performed for two general work classifications - dynamic work tasks and sedentary work tasks.

Investigators in the area of dynamic work capabilities have examined the effects of heat stress on various physiological parameters for moderate to heavy metabolic loads. Some of the parameters which have been investigated include body core temperature, skin temperature, heart rate, and sweat loss. The goal of a majority of studies has been to develop a heat stress index which can be related to changes in the physiological indices. Limits of exposure can then be set which keep these changes under control. Research in this area has been performed by Lind (1963) and others with several different heat stress indices being used. WBGT has been selected by the National Institute of Occupational Safety and Health in its recommended standards (NIOSH, 1976). The point which must be emphasized is that these standards have been recommended for predominantly dynamic work tasks requiring a moderate to heavy energy expenditure.

In recent years, a second area of interest has evolved dealing with the effects of heat stress on performance in sedentary jobs (Ramsey et al., 1975). Although work tasks involving a light metabolic work load may not adversely affect an individual's health, it has been shown that a person's motor abilities and mental skills are affected by exposure to hot environments over periods of time. This can result in an impaired ability to make fine manipulations and skilled judgments which would affect both the safety of the worker and others (Ramsey and Ayoub, 1975). Combined upper limits of exposure time and temperature have been recommended by NIOSH for unimpaired mental performance.

Again the heat stress index used has been the WBGT.

Until the present time, static work capabilities under various heat stress conditions have not been extensively studied. Gould and Dye (1932) stated that, "The most favorable temperature for muscular activity is about one degree above the normal body temperature." Hill (1956), in summarizing the effects of temperature on muscular activity, pointed out that the speed of muscular contraction can be quickened approximately 20 percent by elevating the body temperature 2 ^{o}C. However, a greater speed of contraction does not imply greater endurance.

Various researchers have investigated the relationship between strength and body core temperature, but the results have been inconclusive. Robbins (1942) stated that strength, as measured by a hand dynamometer, decreased following a hot shower. These statements are general in nature and do not mention any relationship between strength or endurance and body core temperature.

Bechtol (1954) noted a variation in grip strength of as much as 30 percent during the day. He found gripping power to be low in the early morning and to reach a maximum between 4:00 and 8:00 in the evening. Wright (1959) also investigated the variation in grip strength with time of day. As seen in Figure 1, he found a close relationship between grip strength and oral body temperature measured throughout the day. Although the closeness of the

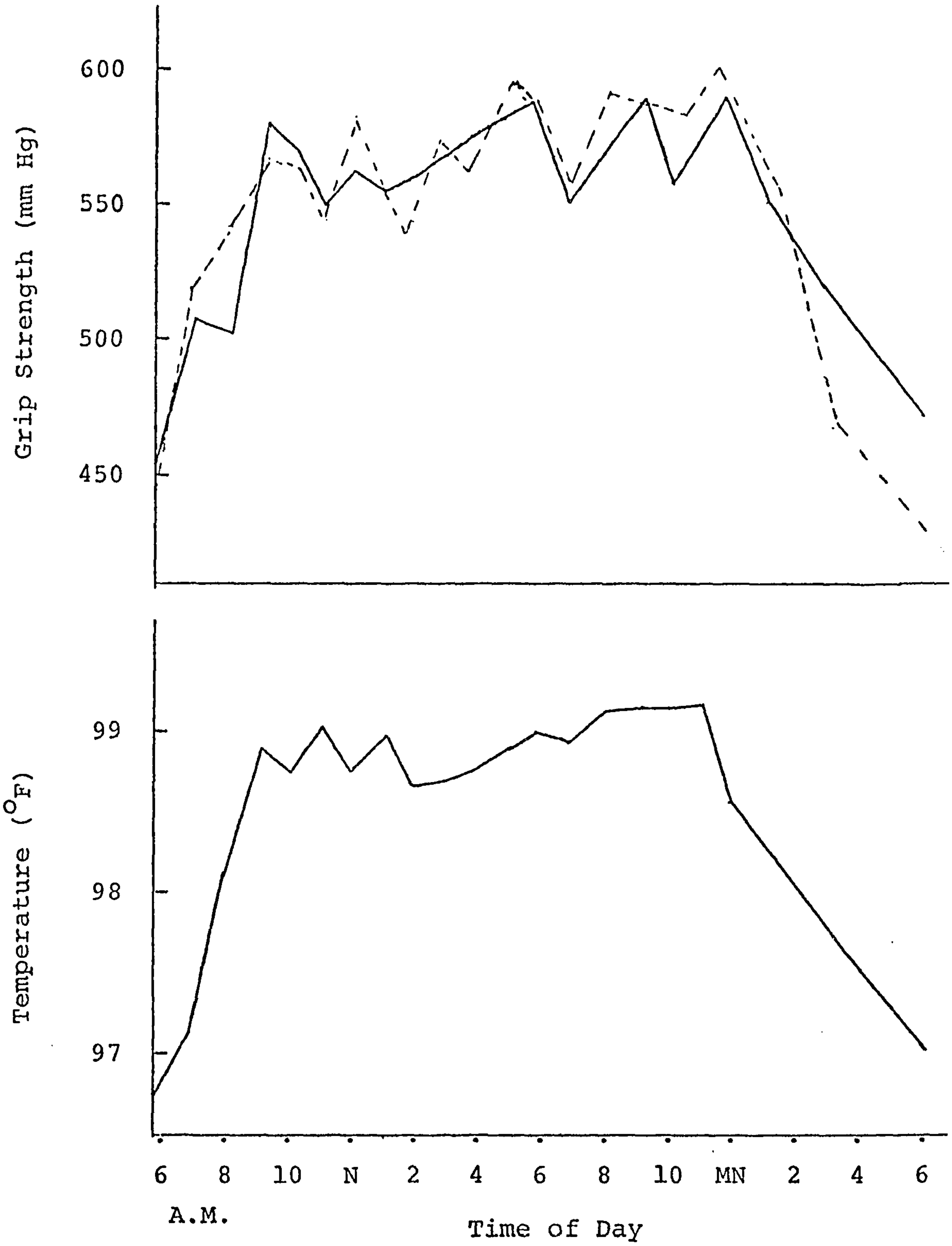

Figure 1. Diurnal variation of grip strength and body temperature. (Wright, 1959)

relationship does not establish cause and effect, it encourages further research in this area.

On the other hand, Dickson et al. (1972) reported no change in grip strength during the course of a working day (9:00 a.m. to 4:00 p.m.). Tornvall (1963) was also unable to show a systematic variability in strength that was related to time of day when measuring the strength of the elbow flexors and knee extensors. Thus, there does not appear to be a well established relationship between core temperature and strength. Even less is known about the relationships involving muscular endurance.

Several researchers have examined changes in the strength and endurance of certain muscle groups as a function of the muscle temperature. For the most part, changes in the muscle temperature have been produced by immersing the limb in a hot water bath. Nukada (1955) showed that when a limb was immersed for a short period in water ranging from 20 to 40 ^{o}C, the maximum endurance steadily decreased from the lower to the higher water temperatures. For weights of 7, 10, and 15 kg, the maximum endurance occurred at a water temperature of 20 ^{o}C and the shortest endurance at 40 ^{o}C. This effect was attributed to the shift of blood from the muscles to the skin.

Grose (1958) found that immersion of the forearm in hot water (48 ^{o}C) for 8 minutes did not significantly affect initial strength, although there was a small gain in grip strength in 8 of 12 subjects. He did find a 34 percent increase in how rapidly subjects fatigued as measured by a spring-loaded ergograph.

The most extensive studies in this area were performed and published by A. R. Lind and his associates during 1956 to 1959. Lind and Samueloff (1957) made grip strength and endurance measurements while the forearm was immersed in a water bath at 18 or 34 °C. The grip strength measurements were taken before immersion in the water bath. The endurance measurements consisted of a series of five successive contractions to fatigue using 1/3 of the maximum strength. Fixed rest intervals of 20 or 40 minutes were allowed between contractions. The first measurement was made after the arm was immersed for 30 minutes. They found that the contractions were always longer in water at 18 °C.

In an expanded study by Clarke, Hellon, and Lind (1958), the bath temperature was varied over a greater range, from 2 to 42 °C. They employed the same procedure using bath temperatures of 2, 10, 14, 18, 26, 34 and 42 °C and a rest interval of 20 minutes. The temperature of the brachio-radialis muscle, blood flow in the forearm, and action potentials were also monitored in an attempt to explain the changes in muscular performance with temperature. Four male subjects were used, two with thick forearms (9.0 and 9.3 cm in diameter) and two with thin forearms (8.3 and 8.4 cm).

The differences in endurance times for the first of the five successive contractions are shown in Figure 2 and follow the same pattern for all four subjects. Again, the first contraction was made after 30 minutes immersion in the water bath. There is an average decrease of over 60% in going from a water bath temperature of 18 °C (about 320 seconds) to a temperature of 42 °C (about 120 seconds). The peak duration is also dependent on forearm thickness, occurring at 18 °C for the two subjects with the thinner forearms and 14 °C for the two subjects with the thicker forearms. The data for the five contractions is shown in Figure 3 and again shows the dependence on water bath temperature.

As can be seen in Figure 4, the muscle temperatures, measured halfway between the skin and the center of the forearm, are dependent on both the water temperature and the sustained contraction. Figure 5 shows the relationship between the average contraction duration and the muscle temperature. For the different subjects, the muscle temperatures for the peak durations ranged from 25 to 29 °C. This is 6 to 10 °C lower than that found in the normal, resting, clothed forearm. Above and below this range the durations decreased.

At a muscle temperature of 39 °C, the endurance time had fallen off by 65 percent, while at a muscle temperature of 20 °C, the endurance had fallen off by about 80 percent. The authors concluded that as muscle temperature increases

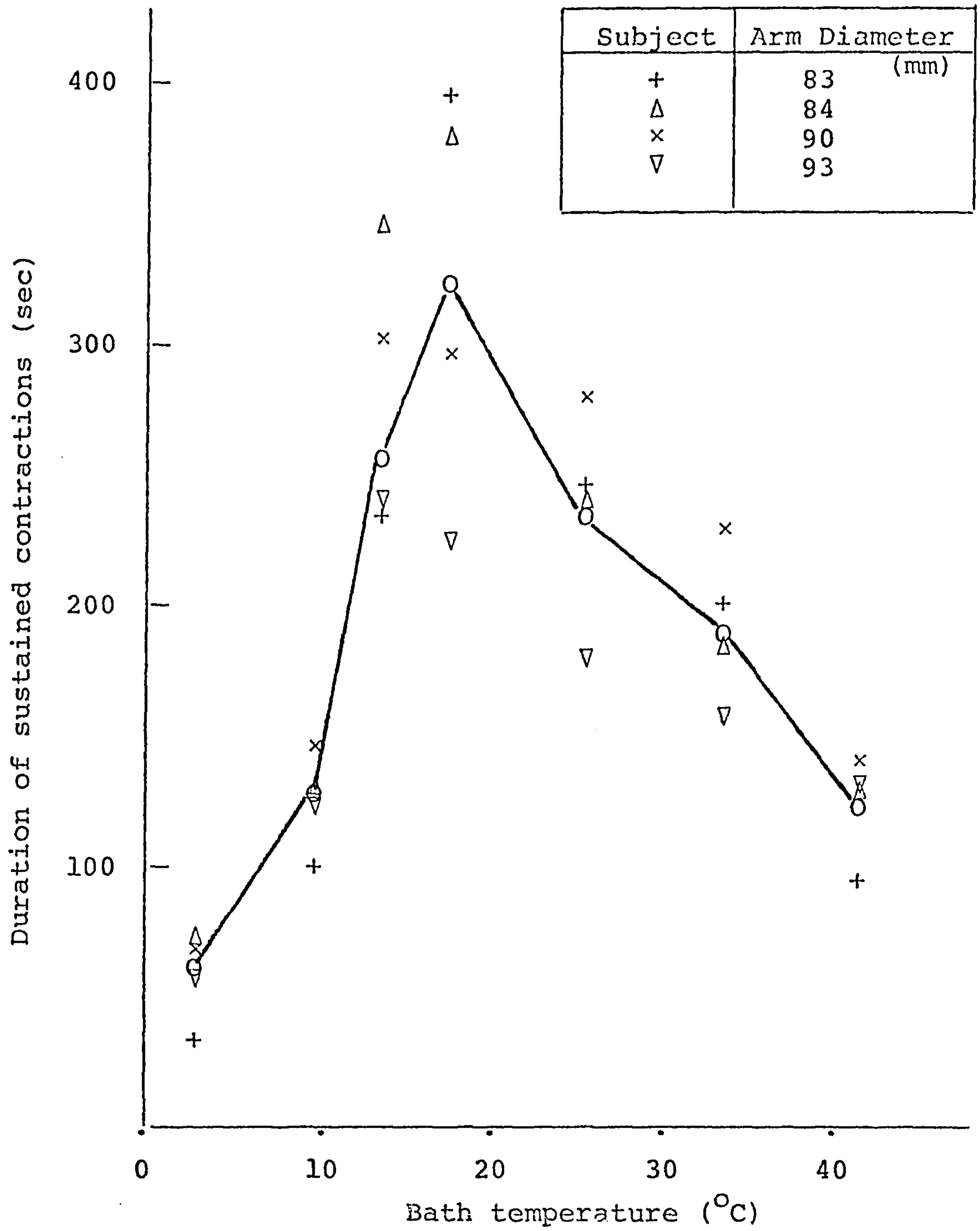

Figure 2. Individual (symbols) and mean (O-O) durations of the first of five successive sustained contractions in water at seven temperatures. The diameter of the forearm of each subject, taken 6 cm above the midposition of the forearm, is shown inset. (Clarke, Hellon, and Lind, 1958)

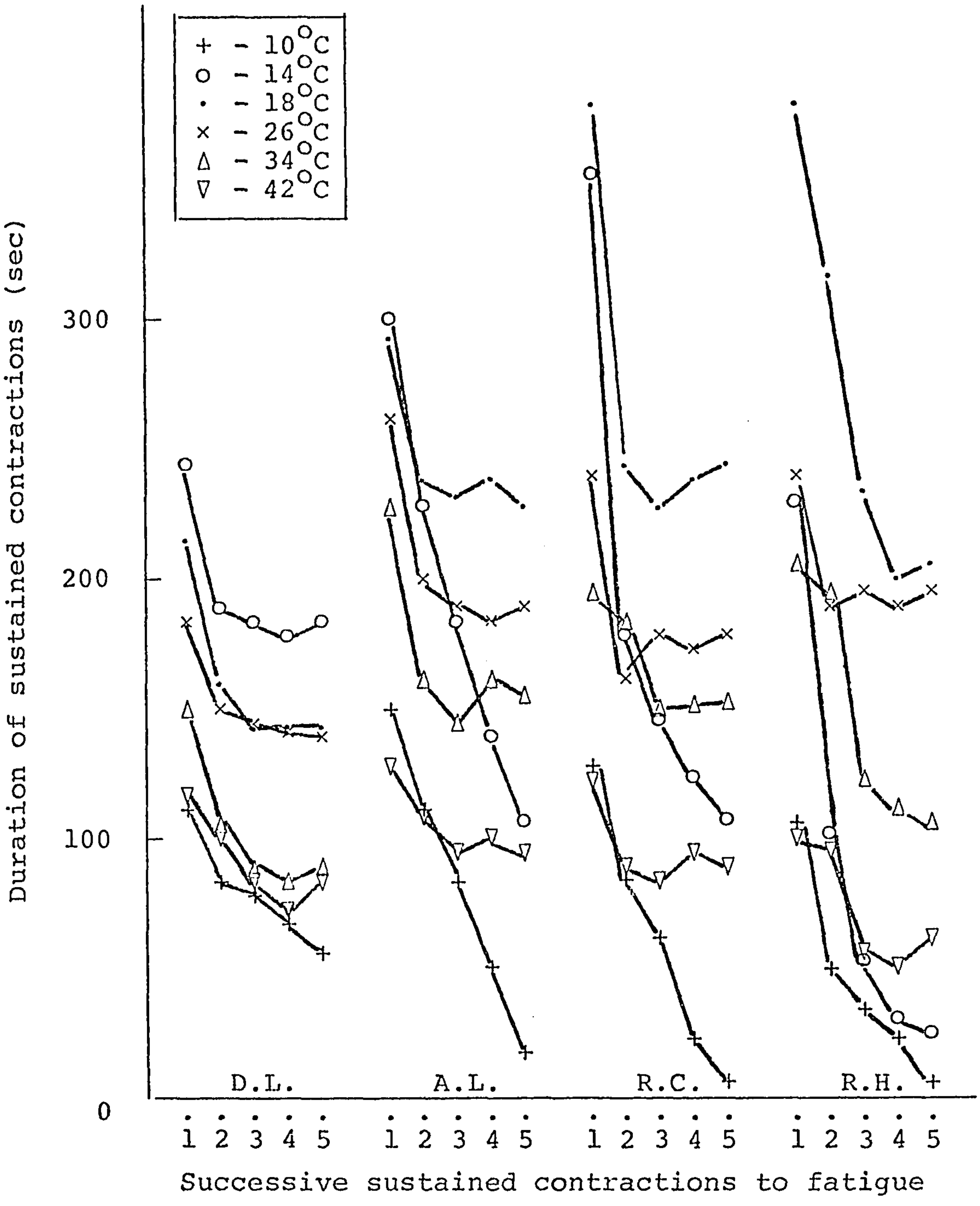

Figure 3. The duration, for each subject, of the five successive sustained contractions in water at 10, 14, 18, 26, 34 and 42°C. Results at 2°C are not shown, since only one contraction was completed at this temperature. (Clarke, Hellon and Lind, 1958)

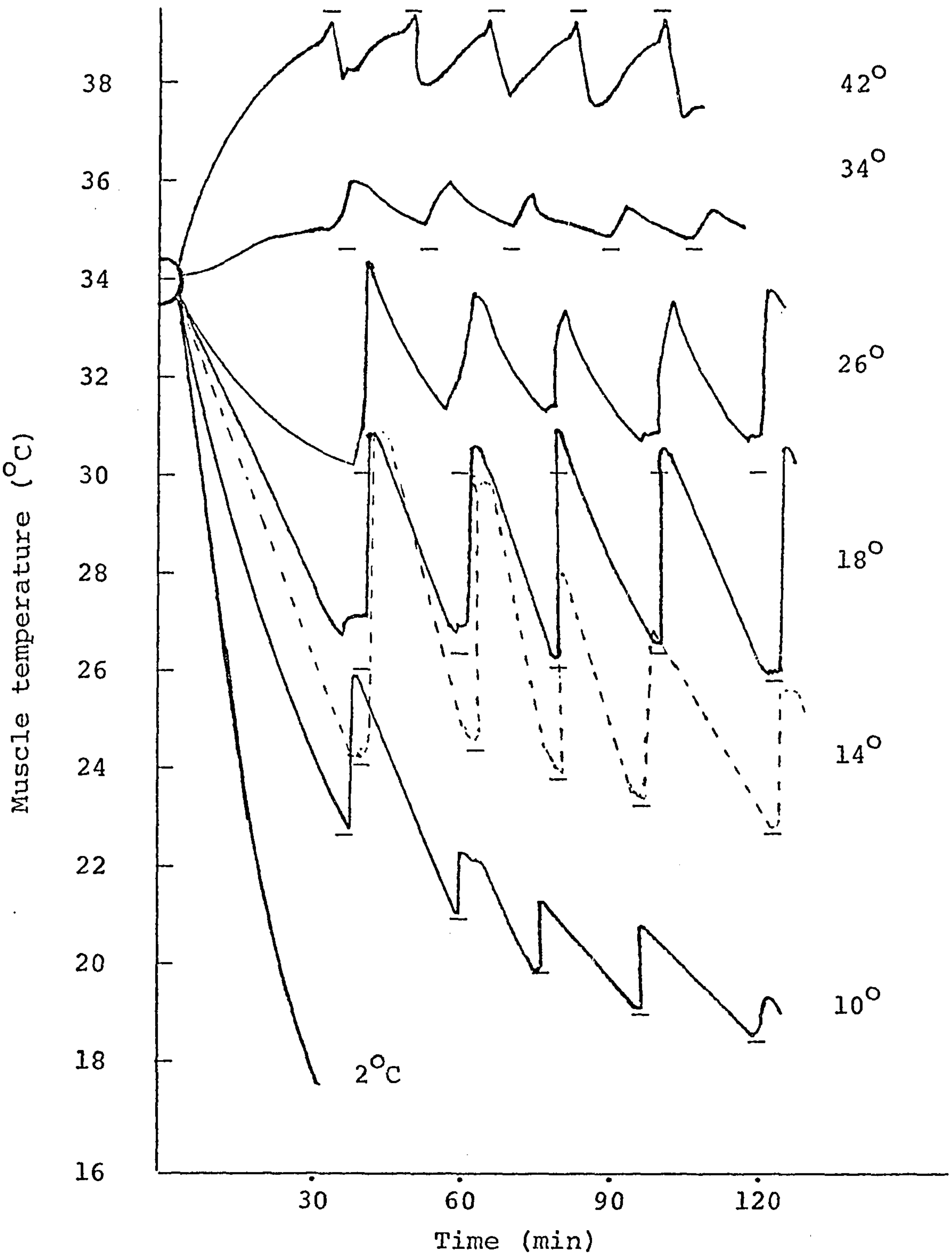

Figure 4. Mean muscle temperatures vs. time for the seven water temperatures. The contractions are represented by the dashes. (Clarke, Hellon, and Lind, 1958)

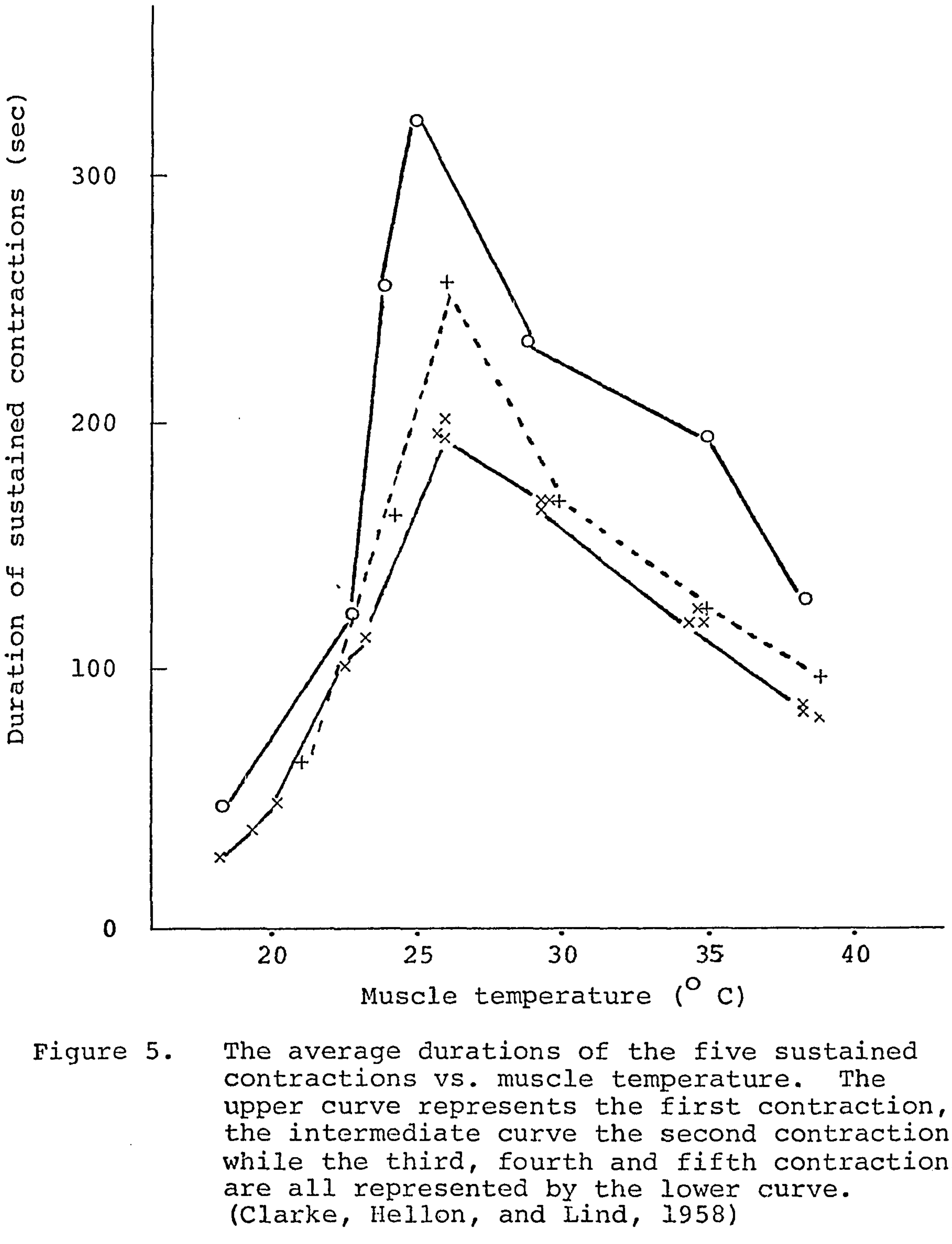

Figure 5. The average durations of the five sustained contractions vs. muscle temperature. The upper curve represents the first contraction, the intermediate curve the second contraction, while the third, fourth and fifth contractions are all represented by the lower curve. (Clarke, Hellon, and Lind, 1958)

above 27 °C, the rate of metabolism increases and results in a more rapid accumulation of metabolites. At muscle temperatures below 27 °C, a proportion of the more superficial muscle fibers do not contract as a result of interference with neuromuscular transmission due to cooling.

Maximum strength measurements were also made before and after immersion of the forearm for 30 minutes in the various water bath temperatures. The results are shown in Figure 6. At muscle temperatures between 27 °C and 39 °C the maximum strength was constant. Below 27 °C the maximum strength decreased as the muscle temperature decreased.

Using the same procedure and subjects, Lind (1959) again extended the experiment by examining the effects of varying the length of the rest period. He used intervals of 3, 7, 20 and 40 minutes and water temperatures of 18 and 34 °C. The intent of this experiment was to determine the relationship of muscle temperature and rest interval to the process of recovery. The results indicated that the contraction duration and the muscle temperature were greatly affected by both the water temperature and the rest interval.

From the above studies, it is apparent that increases in muscle temperature, although they have minimal effect on strength, do have a significant effect on muscular endurance. Lind and his colleagues attributed this result to a more rapid accumulation of metabolites. Again, the temperature increase was generated by immersing the forearm in

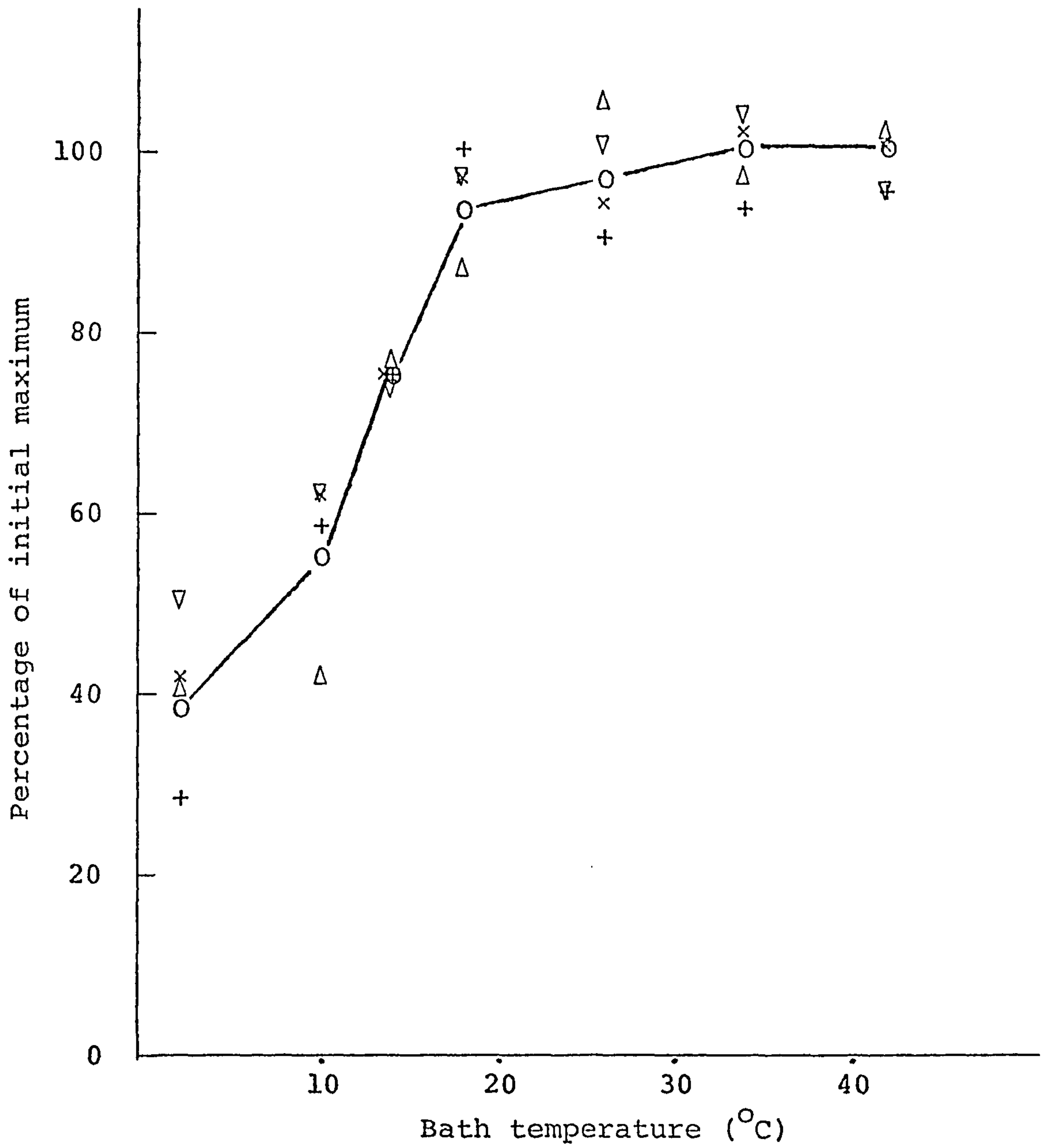

Figure 6. Individual (symbols as in Figure 2) and average (O-O) maximal tensions, expressed as a percentage of initial maximum tension, recorded after the forearm had been immersed at each of the seven temperatures for 30 minutes. (Clarke, Hellon and Lind, 1958)

a hot water bath. The investigators stated that "Precautions were taken to avoid general body heating or cooling. Oral temperatures taken every 10 minutes throughout each experiment did not vary greatly (not greater than 0.4 ^{o}C)." (Clarke, Hellon and Lind, 1958).

Carlile (1958) has pointed out that muscle temperature is known to vary independently of rectal temperature. Thus, the applicability of Lind's results to situations involving overall changes in core temperature has not been determined. In contrast to the technique of immersing a limb in a hot water bath, this study investigated changes in strength and muscular endurance as a function of an overall hot environment which increases body temperature.

CHAPTER III

EXPERIMENTAL METHODOLOGY

This chapter outlines the experiment and statistical design used in investigating the relationships between strength, endurance, environmental temperature and core temperature. The general approach was to establish predetermined levels of core temperature and to make measurements of strength and endurance at these levels. The following sections discuss the experimental variables, equipment, experimental procedure and experimental design.

Independent Variables

The independent variables consisted of body core temperature and subject.

Core Temperature

The primary independent variable was deep body or "core" temperature. Core temperature usually refers to the temperature of the deep central areas of the body including the heart, lungs, abdominal organs and brain. It may be measured at various sites such as the rectum, mouth, esophagus or tympanic membrane. Although the temperatures at these sites differ in magnitude and rate of change, each may be considered a measure of core temperature.

Rectal temperature responds more slowly than the other measures, but is a representative indicator of deep body temperature, providing the measurement is made under steady-state conditions, 30 to 40 minutes after a change in heat transfer rates. In this study, 30 minutes was allowed for the core temperature to stabilize before any measurements were made. An additional criteria for steady state (Lind, 1963) limited the fluctuation in core temperature to $\pm$ 0.03 °C in a 15 minute period.

Rather than use five absolute levels of core temperature, it was decided that the levels used would be specific increments above each subject's resting level. This was done to provide the same relative level of heat stress for all subjects, since resting core temperatures varied greatly between subjects, while the temperature of each subject showed little variation from day to day. The increments selected were 0.0, 0.3, 0.6, 0.9 and 1.2 °C above the resting level. This ensured that the highest level of body temperature would be kept below a safety limit of 39 °C. The resting value for each subject was determined during a five-day period of preliminary testing and checked each day to detect any significant deviation.

The established increments represent a range from the "normal" core temperature to a temperature which indicates considerable heat strain but which is still within critical safety limits. Although core temperature is dependent on metabolic and environmental conditions, it was considered an independent variable for the purposes of this study. The five levels of core temperature were generated as outlined in the experimental procedure and held fixed throughout the course of each trial.

Subjects

Five female subjects were selected from a pool of potential subjects based on the following physiological and performance criteria:

(1) health and physical condition

(2) physiological response to heat stress

(3) performance of strength and endurance measurements

(4) availability to follow the experimental schedule

All subjects were in good health and physical condition and were predominantly mesomorphic according to the somatotyping scheme of Croney (1971). Written informed consent was obtained along with medical certification of physical health.

Each subject was questioned about her ability and willingness to be exposed to various hot environments (up to 40 ^{0}C WBGT) for moderate periods of time (up to two hours), and to allow the experimenter to monitor core temperature, skin temperatures and heart rate. Each subject's physiological responses to the hot environment, as measured by core temperature and heart rate, were examined during a series of preliminary testing sessions.

All subjects followed the general pattern of change described in previous studies and modeled by Dayal (1974). This consisted of (1) a time lag between the onset of exercise and a noticeable increase in core temperature and (2) a temperature increase which follows a negative exponential function. In addition, the variation in core temperature with time was sufficiently predictable that it could be "controlled" by the environmental and metabolic conditions for the duration of each experimental trial. None of the subjects displayed any of the anomalies which had been observed in some subjects in a previous study (Kositzky and Eubanks, 1978), such as an unpredictable time lag or a linear increase in core temperature with time.

Each subject was also tested to determine her ability to produce consistent strength and endurance values. This ability was the major criterion used in the final selection of subjects. To improve the reproducibility of the measurements, each subject was trained in the use of the measuring equipment during an initial acclimatization period.

All subjects were paid for their time and effort, and the importance of being properly motivated was stressed continuously throughout the experiment.

Various anthropometric measurements of the subjects were made using the following procedures. Grip span was measured with a functional hand anthropometer. The midpoint of the fleshy area between the index finger and the thumb was marked and placed against the midpoint of one side of the anthropometer. Another mark was placed on the midpoint of the middle phalanx of the middle finger. When this mark was aligned with the midpoint of the other side of the anthropometer, the grip span was recorded as the distance between the marked parts of the hand.

Hand length was measured as the distance from the tip of the middle finger to the most distal wrist crease. Forearm length represented the distance from the wrist to the elbow.

Forearm diameter was measured by using a large pair of calipers to measure the thickest part of the forearm (just below the elbow) with the arm resting on a table surface and the thumb pointing upward.

Data for the five subjects is provided in Table 1. The subjects ranged in age from 19 to 24 years. The average height was 160 cm and the average weight was 54 kg. The amount of regular exercise for each subject fell into two categories, 12 to 15 hours per week and 3 to 5 hours per week. A wide range of variation was observed in the anthropometric measurements. This was particularly noticeable with respect to grip span which ranged from 4.4 to 4.9 cm.

Table 1

SUBJECT DATA

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Age (years)	21	21	19	24	19
Height (cm)	162.6	170.2	165.1	172.7	157.5
Weight (kg)	58.1	56.7	55.8	54.4	47.6
Exercise (hrs/wk)	15	15	12	5	3
Grip Span (cm)	4.6	4.9	4.5	4.8	4.4
Hand Length (cm)	16.0	18.0	17.3	17.1	17.4
Forearm Length (cm)	21.7	23.5	22.5	24.0	23.5
Forearm Diameter (cm)	7.3	7.4	7.0	7.1	7.3

Dependent Variables

Strength and Endurance

The primary dependent variables were static muscular strength and static muscular endurance. Each strength measurement consisted of a five-second maximum voluntary handgrip contraction with the force values sampled at the rate of twenty points per second. The strength score for the exertion was determined following the procedure of Owings et al. (1975) described in Chapter II.

Using the same muscle group, the duration of a sustained submaximal (1/3 MVC) contraction held to exhaustion was used as the measure of static muscular endurance. The value for this continuous hold endurance was determined using the procedure of Schutz (1972). Detailed description of these variables was given in Chapter II and the procedures for making the measurements are described in the section titled Experimental Procedure.

Finally, a series of 40 strength measurements was made at 30-second intervals. Each measurement consisted of a five-second MVC. This combined strength-endurance measure was selected to evaluate the cumulative effects of repeated force exertion for different heat stress levels. It provided an indication of the degree of fatigue involved and the adequacy of recovery time for repeated static exertions.

Other Variables

Physiological variables which were measured include heart rate and various skin temperatures. The heart rate of each subject was monitored on a continuous basis using a standard bipolar EKG.

Skin temperatures were monitored at the calf, thigh, chest, inner surface of the non-working forearm and at three sites on the working arm: outer upper arm, outer forearm and inner forearm. Mean skin temperature was computed using the formulas of Ramanathan (1964).

Control Variables

Environmental variables were continuously monitored and adjusted in order to control the core temperature of the subject. They included dry-bulb, natural wet-bulb, aspirated wet-bulb and globe temperatures along with relative humidity.

The clothing worn by the subjects consisted of a bikini or halter top, cotton shorts, sockettes and running shoes. For each subject, the same articles of clothing were worn for all trials. In addition, each subject was tested at the same time each day for all of her trials. This minimized the day-to-day differences in core temperature and initial grip strength.

The subjects were provided with an unlimited supply of water and encouraged to drink frequently. The temperature of the water was the same as the environmental temperature to minimize any cooling of the body core.

Equipment

The equipment for this study can be divided into three categories: (a) equipment for the physical measurements of strength and endurance, (b) equipment for the physiological measurements of core temperature, skin temperature and heart rate, and (c) equipment for establishing and monitoring the environment and work load.

Physical Measurements

The equipment for the strength and endurance measurements included a strain gage force transducer and associated recording equipment. The maximum strength of any muscle group is dependent on several factors including muscle length, the positions of various joints, the involvement of other muscles and overall body posture. Thus, a special apparatus was constructed to maintain precise control over the posture of the subject, various joint angles and the actual muscles engaged in the hand-grip contraction. The apparatus consisted of a mounting platform, a straight-backed chair with an adjustable arm rest and an adjustable support cage for the gripping handles and force transducer (Figure 7). The gripping handles had a radius of curvature of 1.2 cm with 3-mm thick padding to minimize the discomfort to the subject from contact pressure. Straps were provided on the arm rest to minimize movement of the forearm.

In addition, a unique means of supporting the gripping handles was used to eliminate any contribution to the force exertion from other muscles. The handles and the strain gage force transducer were mounted within a separate triangular frame (Figure 8). One handle was fixed to the frame. The other handle slid on low friction brass bushings. The entire frame was able to slide freely in the fore and aft direction within the larger support cage. Because of the large range of movement of the triangular frame,

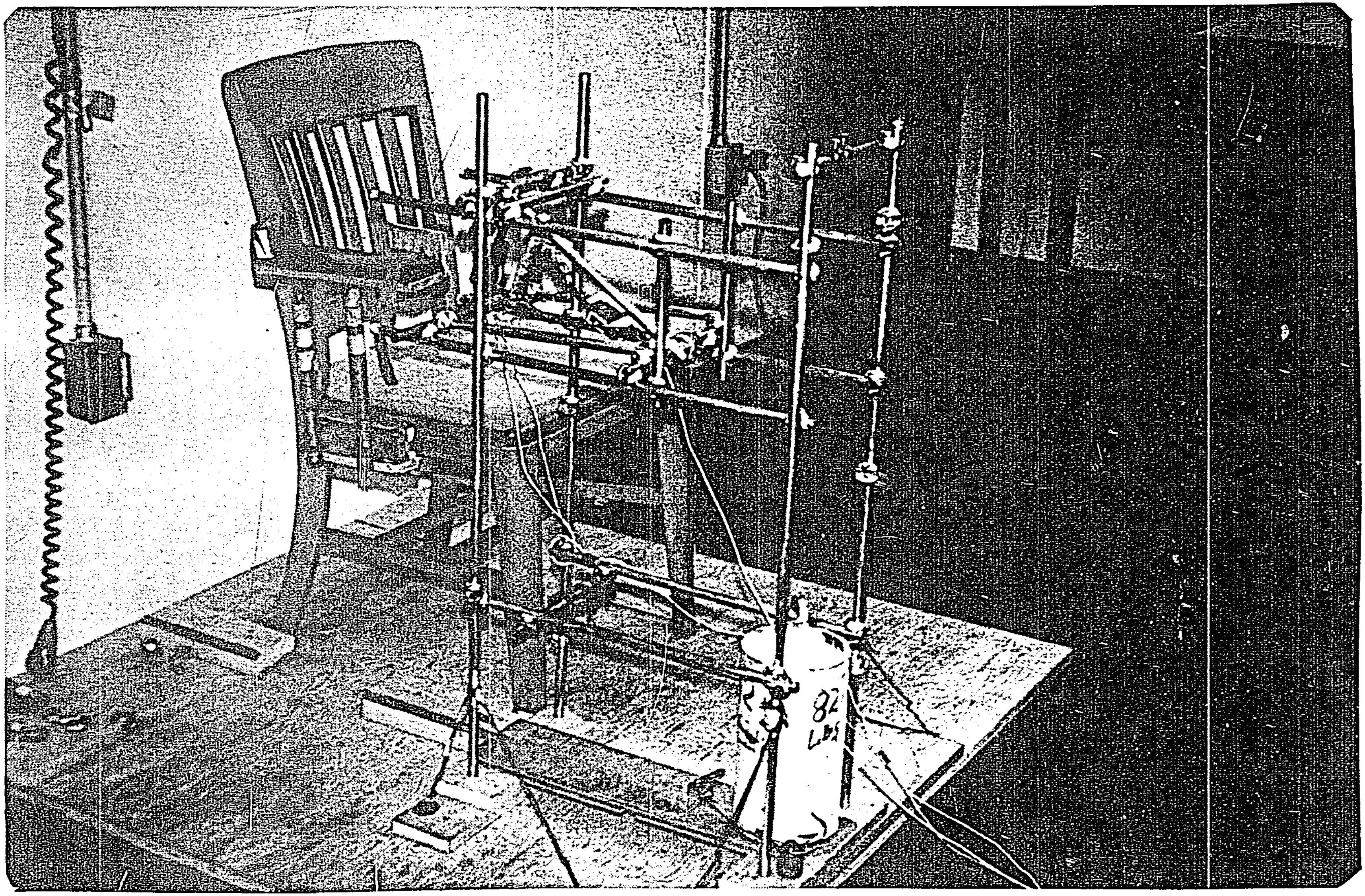

Figure 7. View of Strength and Endurance Measurement Apparatus

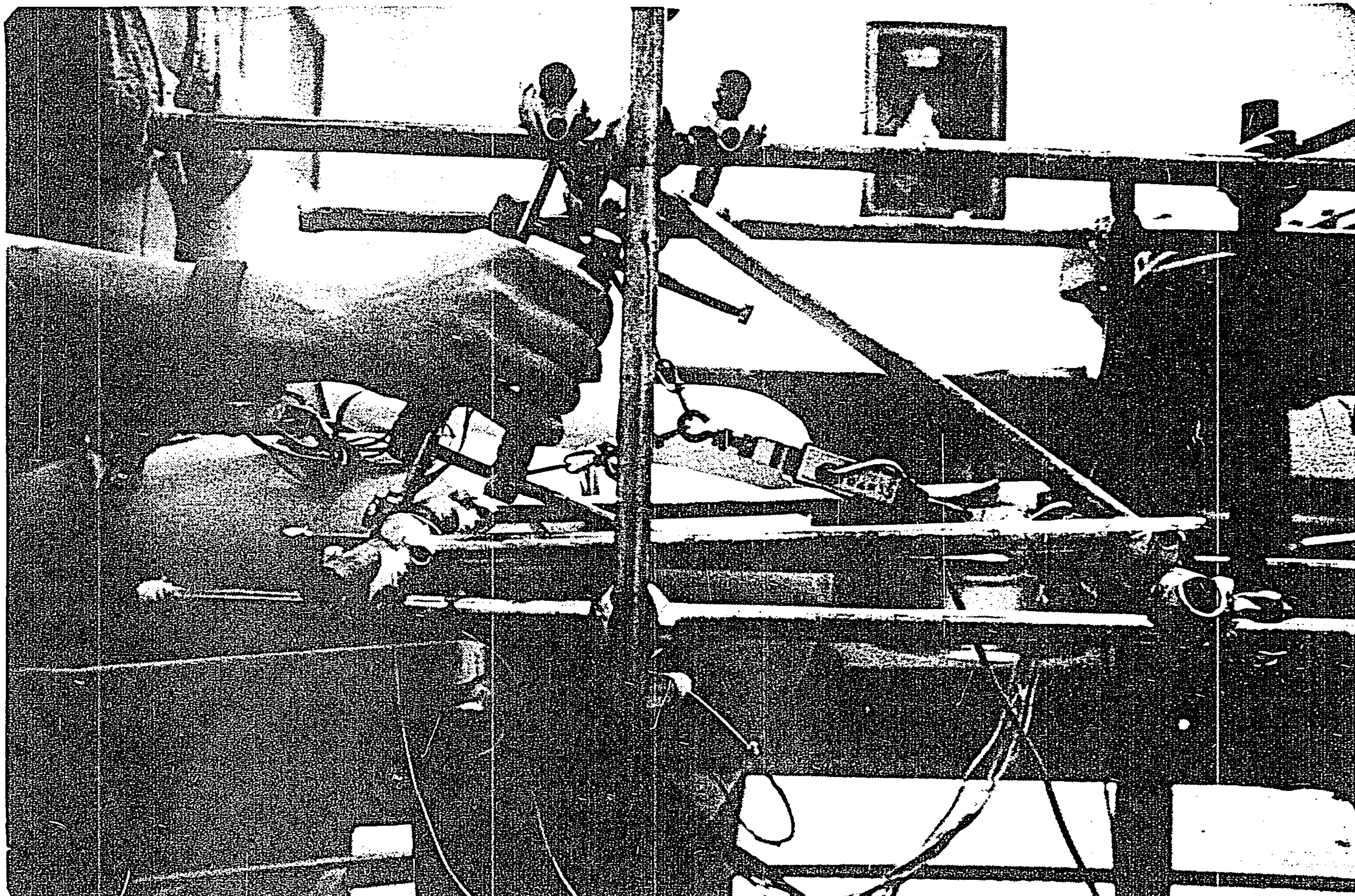

Figure 8. View of Sliding Framework and Gripping Handles

contraction of any muscles other than those directly involved in the gripping activity added nothing to the measured force exertion. This was even more important during the endurance tests as it eliminated the possible use of alternate muscle groups to prolong the contraction time. Both the triangular frame and the support cage were made of 1/2-inch steel rod assembled with clamps.

Further control of joint angles and body posture involved adjustment of arm rest height, distance from chair to cage, height of cage and distance between the gripping handles. For each subject, special fixtures were built to assure that these distances were maintained for all trials.

A list of the equipment used is as follows:

(1) Hand-Grip Framework and Support Cage

(2) Model SM-250 Load Cell - Interface, Inc.

(3) Model 7172 Strain Gage Coupler - Narco Bio-Systems, Inc.

(4) Model 7070 Channel Amplifier - Narco Bio-Systems, Inc.

(5) Brush Model 220 Strip Chart Recorder - Gould, Instruments Division

(6) Fluke Model 8000A Digital Multimeter

(7) Weights for Calibration of Load Cell

(8) Tone Generator for Subject Feedback

Physiological Measurements

Monitoring equipment for the physiological measurements included the following:

(1) YSI Model 401 Rectal Thermistor Probe - Yellow Springs Instruments, Inc.

(2) YSI Model 409 Skin Thermistor Probes - Yellow Springs Instruments, Inc.

(4) Thermistor Interface Circuitry

(5) Dispos-a-trodes EKG Electrodes - The Burdick Corporation

(6) Model 7171 Hi-Gain Coupler - Narco Bio-Systems, Inc.

(7) Model 7302 Biotachometer - Narco Bio-Systems, Inc.

Environmental Monitoring and Control

All trials were conducted in a controlled environment room with the aid of the following equipment:

(1) Model CER 1216 Sherer-Dual Environmental Chamber - 12' x 16'

(2) Model 707 TW Humidifiers - Herrmidifier Co., Inc.

(3) Model 3930 Dehumidifiers - Sears, Roebuck and Co.

(4) Dry-Bulb Thermometer

(5) Aspirated Wet-Bulb Thermometer

(6) Natural Wet-Bulb Thermometer - 125 ml flask, 2.5 cm wetted wick

(7) Globe Thermometer - 15.2 cm diameter

copper sphere painted flat black

(8) Model 594 Hygro-Thermograph Humidity Sensor - Bendix Corporation, Friez Instrument Division

(9) Model 1650 Air Velocity Meter - TSI Incorporated

(10) Model 14-44-A Treadmill - Quinton Instruments

Data Collection System

A DECLAB 11/03 minicomputer system with a PDP11/03 microprocessor and an analog-to-digital converter was used for all data collection. This includes the strength and endurance measurements, the timing of endurance periods and the monitoring of the physiological variables. A multiplexer system and distribution panel was used to interface the transducer outputs with the computer. In addition, the computer was used to control the entire sequence of each experimental trial.

An integrated collection of software programs was developed to:

(1) sample the strain gage output

(2) perform the time-averaging technique of Owings

(3) perform the endurance test as outlined by Schutz

(4) collect core and skin temperature data

(5) provide timing of the testing and rest periods

The accuracy and reliability of the hardware and software were verified prior to the start of the experiment. Additional checks were performed throughout the experiment.

Experimental Procedure

Adjustment of Apparatus

After the initial selection procedure, each subject returned to the laboratory for preliminary measurements to assure proper adjustment of the gripping apparatus. The first step involved adjustment of the height of the arm rest such that both right and left shoulders were level. This provided an angle of abduction of the upper arm of approximately 15 degrees. The angle of the forearm with respect to the upper arm was 135 degrees.

Next, the height of the support cage was adjusted to provide a neutral wrist angle, defined such that the extensor digitorum tendon maintained a straight line through the wrist joint. To aid in setting this angle, three points were marked: (1) the point at which the extensor digitorum tendon of the middle finger meets with the middle phalangeal joint, (2) the point at which the tendon intersects with the mediocarpal joint, and (3) the point at which the extensor digitorum muscle joins with the radius at the elbow joint. These points were determined by palpation as the subject, seated with palm and forearm on a table surface, tapped the table with the tip of the middle finger.

Third, the distance from the chair to the grip handles was adjusted to match the subject's forearm length.

Finally, a critical adjustment was made of the spacing between the grip handles to match the grip span of each subject. The procedure for determining the spacing was the same as that used for the grip span measurement described previously. With moderate gripping force applied to the handles, the spacing was set such that the midpoint between the index and thumb was at the center of the fixed handle and the midpoint of the middle phalanx of the middle finger was at the midpoint of the sliding handle. Once established, this spacing was held constant for each subject using fixed length hardware items.

Physiological Monitoring

Before each trial, the various sensors were attached to the subject and tested for proper operation. Disposable EKG electrodes were attached to the sternum and to the left and right sides of the chest. The rectal thermistor probe was inserted to a depth of 10 cm beyond the anal sphincter. Finally, the skin temperature thermistors were attached to the previously mentioned sites using porous surgical tape.

The subject then entered the chamber and connected the leads from the sensors to their proper inputs. Baseline data was recorded while the subject rested in the chair. The existence of a marking dot between the thumb and forefinger was verified and darkened to ensure proper alignment with the gripping handles, and the test sequence was started. Heart rate data was monitored continuously throughout the trial. The core and skin temperatures were sampled every minute.

Testing Sequence

When each subject arrived at the laboratory, she was questioned about her conformance to the experimental requirements. These included:

(1) no food or drink other than water for the previous two hours

(2) minimum of eight hours of sleep the previous night

(3) no unusual exercise activity

(4) same clothing as worn for the previous trials

If it was determined that the requirements were satisfied, the various sensors were attached and baseline data was recorded. Next, three preliminary MVC measurements were taken with three minutes rest between each measurement. Each MVC consisted of a five-second maximum squeeze of the gripping handles. The subjects were instructed not to jerk on the handles, but rather to exert their maximum force steadily and to hold it constant for the entire five seconds. To aid in the timing of the force measurement, a tone generator was used to prepare the subject and to indicate the required length of the exertion. Four short tones were used as a countdown followed by a long tone of five seconds duration. During the rest periods, the subject's arm was unstrapped from the restraint and she was encouraged to move her hand and fingers to aid recovery.

Next, the subject walked on the treadmill for a time period determined by the desired core temperature change.

Upon removal from the treadmill and following a brief rest period, three additional MVC's were taken. Again, finger movement was encouraged between the MVC's.

After the MVC's, the endurance test was begun. For this measurement, weights totaling 1/3 of the average preliminary MVC for the particular trial were attached to the sliding grip handle. A momentary-contact push-button switch attached to the fixed handle indicated when sufficient force was exerted at the proper grip spacing. This switch was connected to the tone generator and to a timing circuit within the computer.

Again the subjects were instructed not to jerk the handles but to exert a steady squeeze to hold the weights up. For the duration of the test, the subject was required to exert force with all her fingers and was not to remove any finger from the gripping handles. If the subject released the force, the tone would sound indicating that more force must be applied. Three seconds were allowed for the subject to exert sufficient force and regain control of the weights. If the subject could not exert sufficient force, the test was stopped and the endurance time recorded as the time from the beginning of the test until the subject dropped the weight. Following the endurance test, the subject was allowed six minutes rest (approximately 65% recovery), during which time she was again encouraged to move her fingers.

Finally, the series of MVC measurements was made for a twenty-minute period. The measurements occurred once every 30 seconds, thus yielding 40 scores. During the rest periods, the subject was allowed to relax her fingers but was instructed not to remove her hand from the handles and to minimize finger movement. At the conclusion of the trial, the subject was permitted to cool down before leaving the chamber.

Ten trials were conducted with each subject during a two week period in late April, 1980. Only one trial per subject was conducted on any given day. A maximum of one day of rest was allowed between trials. The first five trials were employed as a training and partial acclimatization period for the subjects. The exact test sequence used during the first week is shown in Figure 9. Except on the first day, all subjects walked at a speed of 1.3 m/sec on a level treadmill while exposed to an environment of 34.5 ^{o}C WBGT with 40% relative humidity. The duration of the exercise was 51 minutes for all trials during the first week.

The testing sequence for the second week is shown in Figure 10. A slightly different sequence was used in order to control each subject's core temperature. After the preliminary MVC's, the subject began walking on the treadmill. However, the speed and elevation of the treadmill were changed to provide the correct rate of rise in core temperature. Speeds ranged from 0.5 to 1.3 m/sec while elevations ranged from 0 to 10%. The duration of the exercise was 30 to 40 minutes depending on the desired core temperature change. This was followed by a resting period to allow the core temperature, heart rate and blood flows to stabilize. For the remainder of the trial, the temperature and humidity levels in the chamber were adjusted to hold the subject's core temperature at the desired level.

```
         Time into
        Trial (min)                           Activity

Start     0                         MVC 1 \
          3                         MVC 2 - Preliminary
          6                         MVC 3 /
          9                 Begin   Treadmill Walking
          |                                 |
          |                                Work
          |                                 |
         60                 End     Treadmill Walking
          |                                 |
          |                                Rest
          |                                 |
         69                         MVC 1 \
         72                         MVC 2 - Strength Test
         75                         MVC 3 /
         78                 Begin   Endurance Test
          |                                 |
          |                                 |
          -                 End     Endurance Test
          |   6                             |
          |  min                           Rest
          |                                 |
          -                                 -
          |                                 |
          |  20                     Series of MVC's
          |  min                    One every 30 sec
          |                                 |
End       -                                 -
```

Figure 9. Sequence of Testing Activities - Week 1

```
        Time into
        Trial (min)                          Activity

Start      0                         MVC 1 \
           3                         MVC 2 - Preliminary
           6                         MVC 3 /
           9                Begin    Treadmill Walking
           |                                |
           |                               Work
           |                                |
         30-40              End      Treadmill Walking
           |                                |
           |                               Rest
           |                                |
          60                         MVC 1 \
          63                         MVC 2 - Strength Test
          66                         MVC 3 /
          69                Begin    Endurance Test
           |                                |
           |                                |
           -                End      Endurance Test
           |    6                           |
           |   min                         Rest
           |                                |
           -                                -
           |                                |
           |   20                    Series of MVC's
           |   min                   One every 30 sec
           |                                |
End        -                                -
```

Figure 10. Sequence of Testing Activities - Week 2

Core Temperature Control

The predictive models of Givoni and Goldman (1972) and Dayal (1974) were used to determine the environmental and metabolic conditions needed to produce the desired core temperature increments for each subject. Because of the large number of factors included in the models, it was first necessary to fix some of the factors at specific values. With the exception of air temperature, vapor pressure and metabolic load, the factors of the models were fixed at levels which would permit the desired change in core temperature. Air temperature and vapor pressure were varied to provide control within the allowable range. To accelerate the core temperature rise, the metabolic load was initially increased to produce the desired rate of change.

As a preliminary step in the procedure, an iterative computer program was used to find the levels of the variables that would yield the desired equilibrium rectal temperatures. The basic program was a variation of a program given by Dayal (1974) to predict equilibrium core temperature based on the specified inputs to the model. Allowable values of the variables were as follows:

(1) air temperature - 25 to 40 °C

(2) radiant heat load - 0
(globe temperature = dry-bulb temperature)

(3) relative humidity - 40 to 50 %

(4) ambient air velocity - < 1 m/sec

(5) metabolic work load
  (a) treadmill speeds - 0.5, 0.9 and 1.3 m/sec
  (b) treadmill elevations - 0, 2.5, 5 and 10 %

(6) aerobic capacity - above average

(7) clothing - cotton shorts, halter top, running

shoes and sockettes (long hair pulled back)

The program of Dayal was placed within a series of loops to determine the appropriate levels of air temperature and relative humidity which would produce the required core temperature increment with a zero work load. After these values were determined, the nomograms of Givoni and Goldman (1972) were used to select the combination of treadmill speed and treadmill elevation which would give the desired rate of increase.

For the control trials with a 0.0 ^{o}C increment, the chamber temperature was set at 25 ^{o}C. The subject walked for 21 minutes at a speed of 0.9 m/sec and an elevation of 0%, and then rested for 30 minutes before the testing. This was done so that blood flow would be increased as it was in the non-control runs. During the rest period, core temperature returned to its initial resting value and stabilized.

For all other trials, the initial chamber temperature was set at 35 ^{o}C and the subject began walking at a speed of 1.3 m/sec. A 0 % elevation provided a sufficient work load for the 0.3 ^{o}C increment. For the 0.6 ^{o}C run, the treadmill was initially elevated to 5 %, and for the 0.9 and 1.2 ^{o}C runs, it was elevated to 10 %. As the core temperature approached the desired value, the treadmill was lowered in stages (10 %, 5 %, 2.5 %, 0 %). Treadmill speed was then reduced to 0.9, 0.5 and finally 0.0 m/sec. Simultaneously, the air temperature and relative humidity were adjusted to the levels required to maintain the core temperature. Upper limits on air temperature and relative humidity were set at 40 ^{o}C and 50 %, respectively. The subject's heart rate was continuously monitored, and if it exceeded 150 beats per minute, treadmill elevation and/or speed were reduced accordingly.

Although the predictive models provided good estimates of the equilibrium temperatures, there were large variations in the individual time pattern of the responses. Thus, it was desirable to have some initial information on the particular response pattern of each subject. This data was collected during the first five testing sessions. Even with this information, continuous monitoring of rectal temperature was necessary to make the proper changes in work load and environment. During each trial, the experimenter or his assistant noted the trend in the changing core temperature by observing the previous five or six readings. Based on this information and various time lag information for the particular subject, decisions were made concerning the timing and the magnitude of the changes in the work load and environmental conditions.

If the core temperature had stabilized at the correct value within the 30 minute rest period following exercise, the strength and endurance testing was begun. Control of core temperature continued throughout the testing period by means of slight changes in the environmental conditions.

Experimental Design

The statistical model for the experiment was a Latin square design with core temperature increment as the main factor and subject and testing order as the blocking factors. An outline of the design is given in Table 2.

Table 2

OUTLINE OF EXPERIMENTAL DESIGN

FACTOR	LABEL	LEVELS	EFFECT
Core Temperature	T	0.0,0.3,0.6,0.9,1.2	Fixed
Subject	S	1,2,3,4,5	Random
Order	O	1,2,3,4,5	Random

The model for this design is as follows:

$$Yijk = u + Ti + Sj + Ok + e(ijk)$$

where:

Yijk = dependent variable observed for the ith temperature and the jth subject (k represents the order in which the ith temperature was used for the jth subject.)

u = mean effect for entire experiment

Ti = effect due to core temperature; i=1,2,3,4,5

Sj = effect due to subjects; j=1,2,3,4,5

Ok = effect due to order of testing; k=1,2,3,4,5 e(ijk) = random error

Table 3 shows the order of testing for each subject with the core temperature increments given in the body of the table.

Table 3

COUNTERBALANCING SCHEME FOR TRIAL ORDER

SUBJECT	TRIAL NUMBER 1	2	3	4	5
1	Ø.9	Ø.6	Ø.Ø	1.2	Ø.3
2	Ø.Ø	1.2	Ø.3	Ø.9	Ø.6
3	Ø.6	Ø.Ø	1.2	Ø.3	Ø.9
4	1.2	Ø.3	Ø.9	Ø.6	Ø.Ø
5	Ø.3	Ø.9	Ø.6	Ø.Ø	1.2

Note: Entries in table show core temperature increment for a given subject and trial number.

Separate analyses were performed for the strength tests, the endurance tests and the series of MVC's. In addition, regression and correlation analyses were used to quantify the significant changes.

CHAPTER IV

RESULTS

The results are presented in five sections:

(1) Baseline Data

(2) Core Temperature Control

(3) Strength Measurements

(4) Endurance Measurements

(5) Physiological Measurements

An overall summary of the important results is provided at the end of the chapter.

Baseline Data

Baseline data for the two weeks of experimentation is given in Table 4. Each entry in the table represents a five-day average of resting core temperature, resting heart rate or preliminary grip strength. As can be seen, there was a large variation between the five subjects in terms of core temperature (37.00 to 37.77 ^{o}C), heart rate (56 to 99 beats per minute) and grip strength (18.9 to 28.1 kg). However, the change in these values from week 1 to week 2 was minimal. The maximum difference in average core temperature was 0.08 °C for subject 5 with an average absolute difference across all subjects of 0.04 °C. Similar results can be observed with resting heart rate. The largest difference was 7 beats per minute for subject 1 with an average absolute difference of 4 beats per minute.

Changes in grip strength from week 1 to week 2 ranged from a 1.1 kg (5.8%) decrease in strength for subject 4 to a 1.6 kg (7.8%) increase for subject 1. Two subjects exhibited a decrease in strength while the remaining three exhibited an increase. Overall, there was a 0.4 kg (1.8%) increase in strength from week 1 to week 2.

Table 4

SUBJECT RESTING DATA

	Core Temp. (°C)		Heart Rate (bpm)		Prelim. MVC (kg)	
	Week 1	Week 2	Week 1	Week 2	Week 1	Week 2
Subject						
1	37.35	37.36	62	55	20.5	22.1
2	37.05	37.01	56	57	28.1	27.6
3	37.50	37.51	76	70	24.1	24.5
4	37.00	37.05	74	70	19.1	18.0
5	37.77	37.69	99	95	18.9	20.0

Note: Entries in table represent averages of preliminary data for each five-day period - Week 1 vs. Week 2

Core Temperature Control

Table 5 shows the absolute levels of core temperature for each trial. The target levels were based on the average resting core temperature for each subject during week 1.

Table 5

TARGET vs. ACTUAL CORE TEMPERATURES (^{o}C)

		Core Temperature Increment (^{o}C)				
		0.0	0.3	0.6	0.9	1.2
Subject						
1	T	37.35	37.65	37.95	38.25	38.55
	A	37.10	37.68	37.90	38.22	38.62
	E	-0.25	0.03	-0.05	-0.03	0.07
2	T	37.05	37.35	37.65	37.95	38.25
	A	36.89	37.22	37.56	38.04	38.76
	E	-0.16	-0.13	-0.09	0.09	0.51
3	T	37.50	37.80	38.10	38.40	38.70
	A	37.38	37.68	38.17	38.38	38.70
	E	-0.12	-0.12	0.07	-0.02	0.00
4	T	37.00	37.30	37.60	37.90	38.20
	A	37.00	37.40	37.58	37.85	38.00
	E	0.00	0.10	-0.02	-0.05	-0.20
5	T	37.77	38.07	38.37	38.67	38.97
	A	37.78	38.06	38.18	38.69	38.94
	E	0.01	-0.01	-0.19	0.02	-0.03
Avg. Error		-0.10	-0.03	-0.06	0.00	0.07

T - target core temperature for trial
A - actual core temperature during endurance test
E - error between actual and target (A - T)

The correlation between the target temperatures and the actual temperatures was Ø.96. Of the 25 trials, 12 were conducted with an error between the target and actual values of Ø.Ø5 °C or less. On the other hand, five trials had an error exceeding Ø.15 °C. This is significant in relation to the core temperature increment of Ø.3 °C. The average of the absolute errors for all 25 runs was Ø.Ø9 °C.

The largest "error" occurred for the Ø.Ø °C control level. This level was conducted at a dry-bulb temperature of 25 °C, which is the temperature for thermal balance. The core temperatures of three of the subjects dropped significantly (Ø.12 to Ø.25 °C) during this run. This meant that the actual spread between the control run and the Ø.3 °C run was closer to Ø.4 °C. Based on the averages for the actual temperatures during the endurance test, the temperature increments relative to the control run were as follows:

Ø.37 Ø.64 1.ØØ 1.37

Although the control of core temperature worked reasonably well, several runs were conducted which had a large error. This offset the averages as outlined above. For each trial, a ratio was formed by dividing the error by the desired core temperature increment. Analysis of the data was performed both including and excluding those trials which had an error greater than 1Ø%. By excluding those points where the core temperature was in error by more than

10%, 11 points were removed from the analysis. Those trials which remained are shown in Table 6.

Table 6

TRIALS WITH LESS THAN 10% ERROR

	TRIAL NUMBER				
	1	2	3	4	5
SUBJECT					
1	0.9	0.6	xxx	1.2	0.3
2	xxx	xxx	xxx	0.9	xxx
3	xxx	xxx	1.2	xxx	0.9
4	xxx	xxx	0.9	0.6	0.0
5	0.3	0.9	xxx	0.0	1.2

Note: Entries in table show core temperature increment for a given subject and trial number.

The following general observations were made during the course of the investigation with respect to the difficulties encountered. In attempting to control an individual subject's core temperature, it was evident that three major factors had to be considered:

(1) Various time lags existed between changes in the external conditions and observed changes in core temperature.

(2) Core temperature usually continued to drift upward after reduction of the work load.

(3) Certain types of activity (e.g. a sustained static contraction) caused a significant drop in core temperature which was not accounted for by any model.

The major problems were due to the large variability in the above responses for the different subjects. Although good estimates of the various time lags for each subject were obtained during the preliminary testing week, compensating for the wide variation was very difficult. Also, three different response patterns were observed when the subjects were removed from the treadmill:

(1) The core temperature dropped immediately.

(2) The core temperature climbed for a short time (5 minutes) but then remained steady.

(3) The core temperature climbed for a long time (10 minutes) and dropped slowly.

These patterns appeared to depend primarily on the individual subject, regardless of the temperature increment, and were an additional source of difficulty.

Strength Measurements

The preliminary MVC measurements for each trial during the second week are shown in Table 7. Each value represents the maximum 20 point moving average for a five-second exertion. The three tests for each subject at each temperature level are given, along with their average and the overall average for each level.

Table 7

PRELIMINARY MVC MEASUREMENTS - GRIP FORCE (kg)

	Core Temperature Increment (^{o}C) 0.0	0.3	0.6	0.9	1.2
Subject					
	(3) 19.7	(5) 21.6	(2) 21.3	(1) 22.3	(4) 22.3
1	21.0	21.5	22.7	23.0	22.6
	23.9	22.3	23.2	21.5	22.3
Average	21.5	21.8	22.4	22.3	22.4
	(1) 27.2	(3) 27.3	(5) 29.1	(4) 26.3	(2) 28.5
2	27.1	26.5	26.6	25.2	28.1
	30.9	28.3	27.2	27.7	28.7
Average	28.4	27.4	27.6	26.4	28.4
	(2) 23.3	(4) 24.9	(1) 24.5	(5) 25.5	(3) 25.3
3	21.2	26.1	22.0	26.3	28.0
	23.2	27.2	19.7	23.7	26.9
Average	22.6	26.1	22.1	25.2	26.7
	(5) 18.0	(2) 17.1	(4) 16.6	(3) 16.7	(1) 17.3
4	20.0	18.5	17.7	15.8	18.0
	22.6	19.0	17.3	17.6	17.8
Average	20.2	18.2	17.2	16.7	17.7
	(4) 19.1	(1) 19.5	(3) 20.5	(2) 19.1	(5) 21.5
5	20.8	18.1	20.9	18.8	20.8
	20.4	19.8	20.6	19.3	21.7
Average	20.1	19.1	20.7	19.1	21.3
Temp. Avg.	22.6	22.5	22.0	21.9	23.3

Note: Numbers in parenthesis indicate trial sequence.

The results of an analysis of variance performed on the cell means are summarized in Table 8. There was a slight increase (1.3 kg) in the average strength of the subjects from the first run to the fifth run. However, this change was not statistically significant, and the correlation between the trial order and the preliminary grip strength was 0.12. A closer examination of the data reveals that only subject 3 had a substantial increase in strength. The remaining subjects showed random fluctuation about their average strengths. Plots of the averages across all trials are provided for the trial sequence in Figure 11.

Table 8

ANOVA TABLE - PRELIMINARY MVC MEASUREMENTS

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Temperature	4	6.32	1.58	0.92
Subject	4	284.84	71.21	41.43 **
Order	4	5.05	1.26	0.73
Error	12	20.62	1.72	
Total	24	316.83		

** $p < 0.0001$

Figure 12 shows the averages for each temperature level. The averages indicate random fluctuation with a

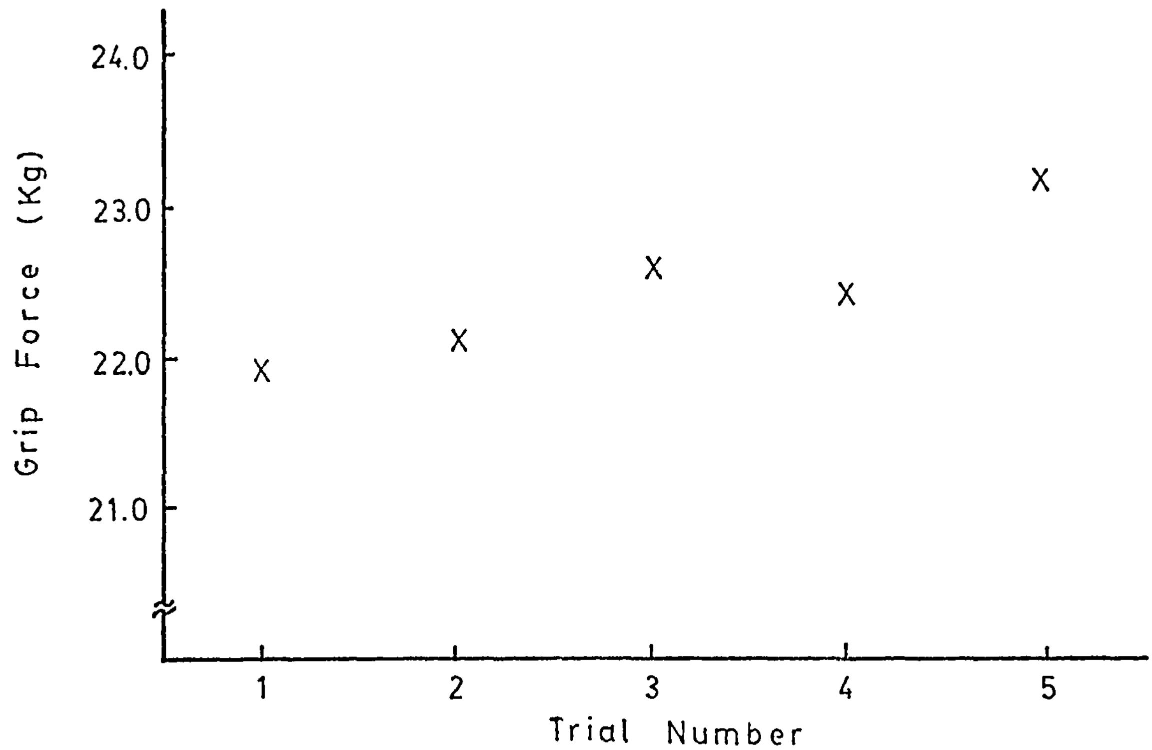

Figure 11. Preliminary MVC's vs. Trial Number

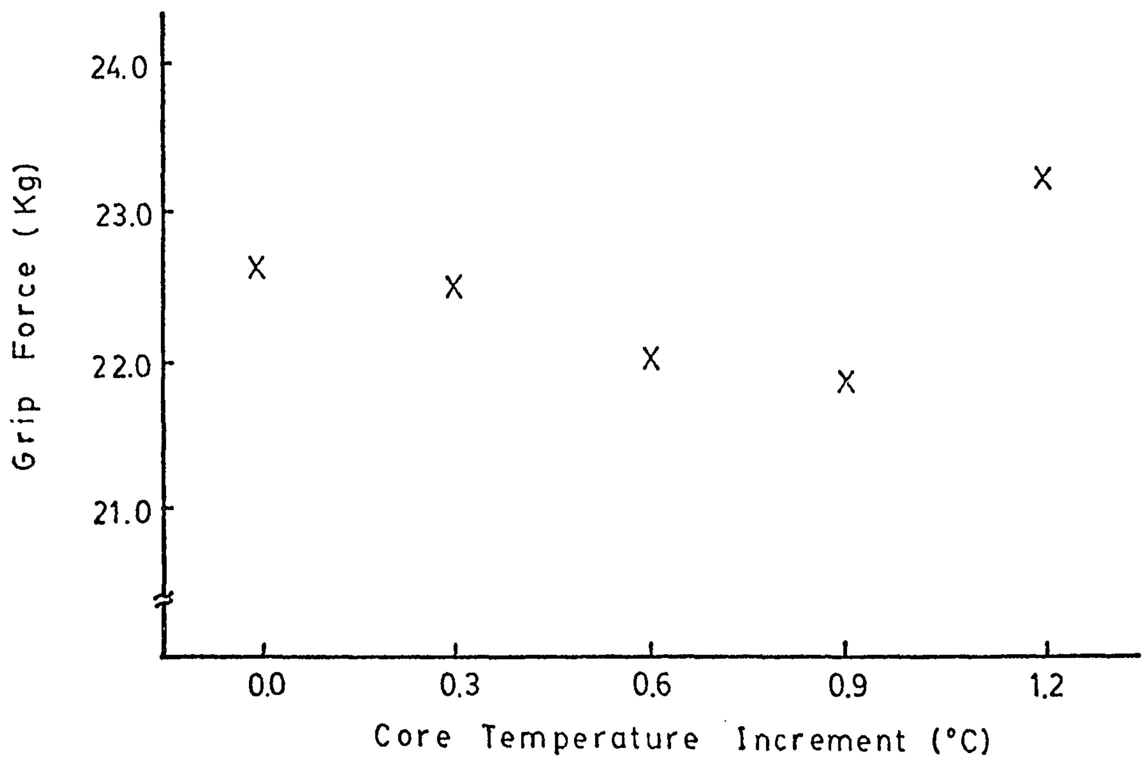

Figure 12. Preliminary MVC's vs. Core Temperature

slightly higher value (23.3 kg) for the 1.2 ^{o}C increment. The correlation between the actual core temperature increments and the preliminary grip strengths was Ø.Ø8 and the analysis of variance revealed no significant difference between the temperature levels at an alpha level of Ø.Ø5.

A highly significant difference existed between subjects. A Duncan multiple-range test revealed that all five subjects were significantly (alpha = Ø.Ø5) different with respect to preliminary grip strength.

Analysis of the reduced data set using only the trials given in Table 6 yielded similar results. There was no significant difference between trials or temperature levels at a Ø.Ø5 level of significance. The correlation of trial order and temperature level was -Ø.Ø8. However, the highly significant difference between subjects was still evident ($p < Ø.ØØ7$).

Corresponding data for the post-exercise MVC's is provided in Table 9. The effect of trial sequence is shown in Figure 13. Again there was a slight increase in the average strength (1.5 kg) from the first to the last run, but the change was not statistically significant. The correlation between the MVC's and the trial sequence was Ø.13.

Figure 14 shows the average for each temperature level. A slight downward trend can be observed but it is masked by the large variability between subjects.

Table 9

POST-EXERCISE MVC MEASUREMENTS - GRIP FORCE (kg)

	Core Temperature Increment (°C)				
	0.0	0.3	0.6	0.9	1.2
Subject					
	(3) 22.3	(5) 22.1	(2) 22.5	(1) 19.4	(4) 18.1
1	22.2	21.0	19.4	21.4	17.2
	21.3	22.5	21.5	20.5	20.3
Average	21.9	21.9	21.1	20.4	18.5
	(1) 29.2	(3) 26.9	(5) 25.5	(4) 25.6	(2) 27.6
2	29.0	27.6	27.5	26.4	29.5
	29.1	29.5	26.2	24.5	28.6
Average	29.1	28.0	26.4	25.5	28.6
	(2) 21.5	(4) 25.9	(1) 19.7	(5) 24.4	(3) 25.1
3	23.1	27.6	21.5	23.9	24.9
	23.5	23.9	xxxx	25.4	25.0
Average	22.7	25.8	20.6	24.6	25.0
	(5) 18.2	(2) 16.4	(4) 18.2	(3) 15.6	(1) 17.0
4	20.0	16.4	18.6	18.6	14.4
	20.9	16.8	18.3	20.0	16.0
Average	19.7	16.5	18.4	18.1	15.8
	(4) 19.3	(1) 18.8	(3) 19.3	(2) 16.6	(5) 19.1
5	21.1	18.3	19.7	17.4	18.9
	19.8	18.2	19.2	16.6	20.0
Average	20.1	18.4	19.4	16.9	19.3
Temp. Avg.	22.7	22.1	21.2	21.1	21.4

Note: Numbers in parenthesis indicate trial sequence.

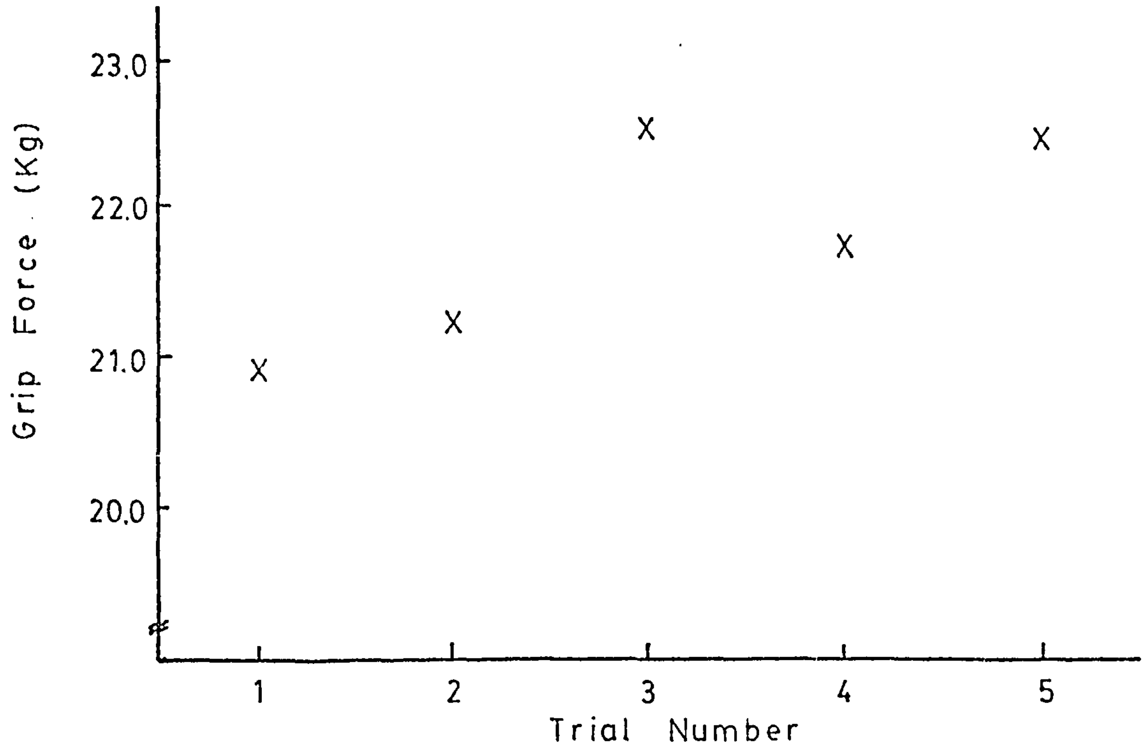

Figure 13. Post-Exercise MVC's vs. Trial Number

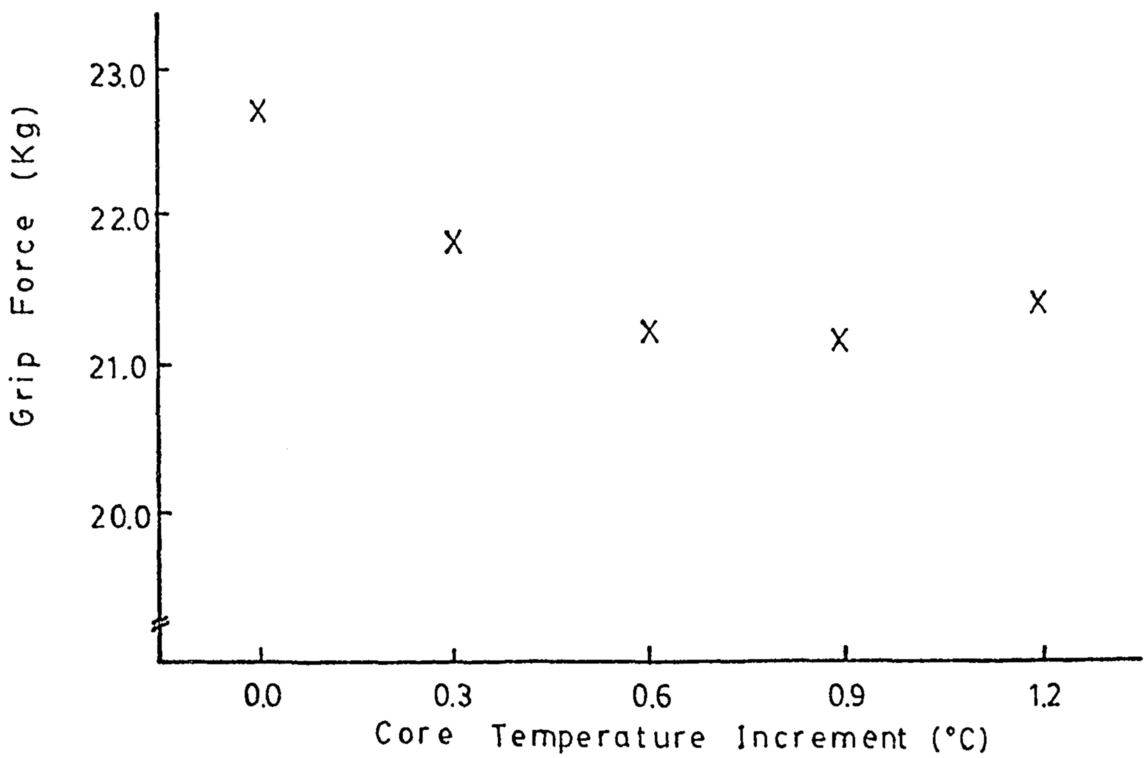

Figure 14. Post-Exercise MVC's vs. Core Temperature

The correlation between the actual temperature increments and the MVC's was -0.07. Analysis of variance again showed a significant difference only between subjects (Table 10).

Table 10

ANOVA TABLE - POST-EXERCISE MVC MEASUREMENTS

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Temperature	4	9.46	2.36	0.93
Subject	4	315.62	78.90	31.12 **
Order	4	10.19	2.55	1.00
Error	12	30.43	2.54	
Total	24	365.70		

** $p < 0.0001$

For the post-exercise MVC's, analysis of the reduced data set yielded slightly different results. The highly significant difference between subjects remained. Also, there was still no significant difference due to trial order. However, the temperature level was marginally significant at alpha = 0.05.

Due to the high correlation (0.95) between the preliminary and the post-exercise MVC's, an analysis of covariance was performed on the post-exercise grip strengths using preliminary grip strength as a concomitant variable. Although this analysis verified the strong relationship between the preliminary and post-exercise strengths ($F = 10.29$, $p < 0.0083$), it was not of any further value due to the large variation between subjects.

A better approach involved examining the decrements from the preliminary to the post-exercise grip strengths for each trial. This data is shown in Table 11. Each post-exercise MVC was subtracted from the average of the three preliminary MVC's for the same trial. This had the effect of removing an extremely large part of the variability in the data. By also removing the daily variation from the data, the pattern of results becomes clearer. A difference of 2.0 kg is observed when comparing the strength change at 0.0 ^{o}C with the decrement at 1.2 ^{o}C. This amounts to an 8% decrease in strength. The average change in strength for each temperature is plotted in Figure 15.

Analysis of variance (Table 12) detected the significant effect due to temperature level. A Duncan multiple-range test indicated that the grip strength changes at the 0.0 and 0.3 ^{o}C increments were significantly different (alpha = 0.1) from the change at the 1.2 ^{o}C increment. There was no significant difference due to subjects or trial sequence. This verifies the effectiveness of examining the difference between the preliminary and post-exercise MVC's in terms of reducing the large variation between subjects.

Table 11

(PRE-POST) MVC MEASUREMENTS - GRIP FORCE (kg)

	Core Temperature Increment (°C)									
		0.0		0.3		0.6		0.9		1.2
Subject										
	(3)	-0.8	(5)	-0.3	(2)	-0.1	(1)	2.9	(4)	4.3
1		-0.7		0.8		3.0		0.9		5.2
		0.2		-0.7		0.9		1.8		2.1
Average		-0.4		-0.1		1.3		1.9		3.9
	(1)	-0.8	(3)	0.5	(5)	2.1	(4)	0.8	(2)	0.8
2		-0.6		-0.2		0.1		0.0		-1.1
		-0.7		-2.1		1.4		1.9		-0.2
Average		-0.7		-0.6		1.2		0.9		-0.2
	(2)	1.1	(4)	0.2	(1)	2.4	(5)	0.8	(3)	1.6
3		-0.5		-1.5		0.6		1.3		1.8
		-0.9		2.2		xxxx		-0.2		1.7
Average		-0.1		0.3		1.5		0.6		1.7
	(5)	2.0	(2)	1.8	(4)	-1.0	(3)	1.1	(1)	0.7
4		0.2		1.8		-1.4		-1.9		3.3
		-0.7		1.4		-1.1		-3.3		1.7
Average		0.5		1.7		-1.2		-1.4		1.9
	(4)	0.8	(1)	0.3	(3)	1.4	(2)	2.5	(5)	2.2
5		-1.0		0.8		1.0		1.7		2.4
		0.3		0.9		1.5		2.5		1.3
Average		0.0		0.7		1.3		2.2		2.0
Temp. Avg.		-0.1		0.4		0.8		0.8		1.9

Note: Numbers in parenthesis indicate trial sequence.

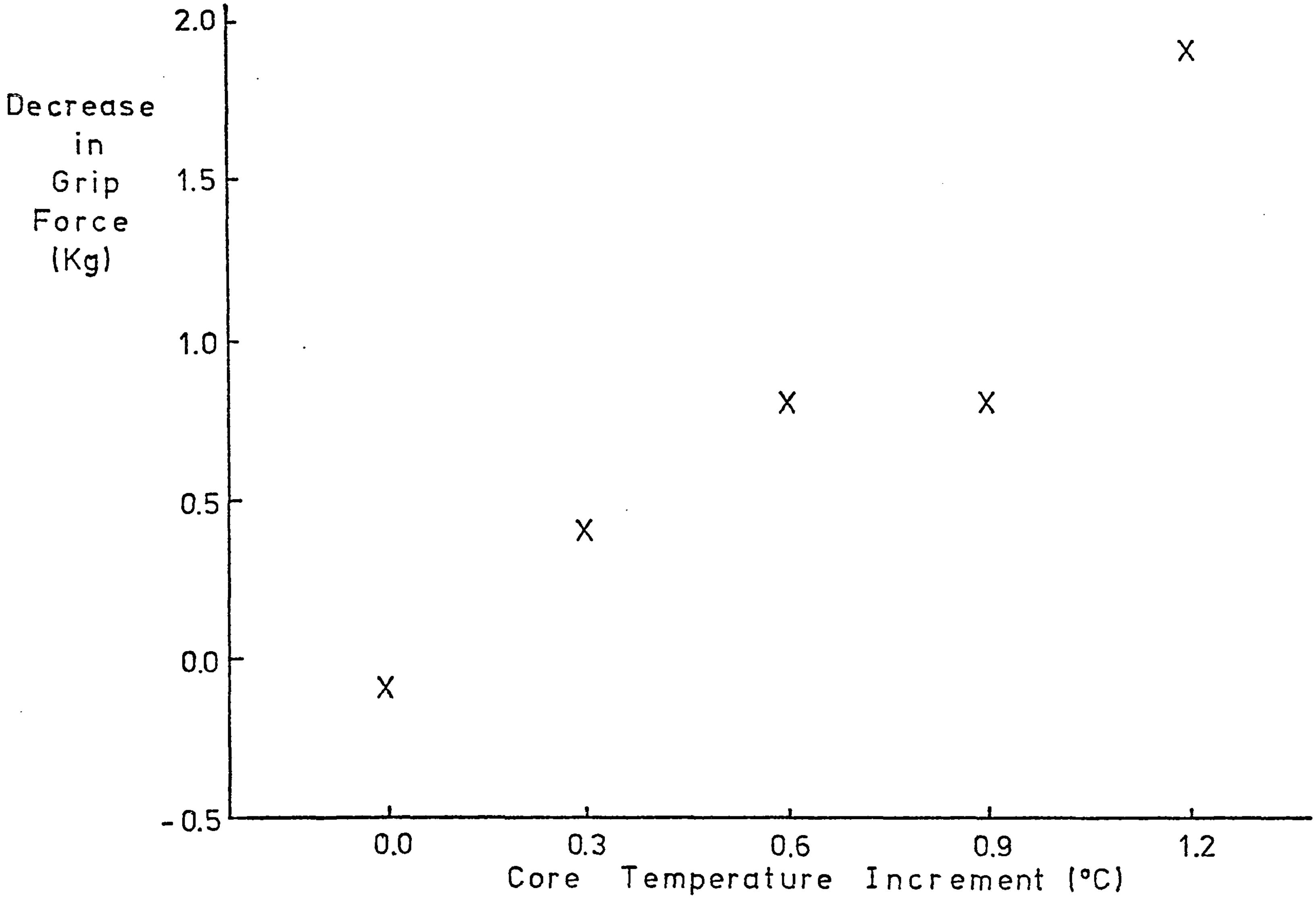

Figure 15. Decrease in Strength vs. Core Temperature Increment

Table 12

ANOVA TABLE - (PRE - POST) MVC MEASUREMENTS

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Temperature	4	10.76	2.69	1.97 *
Subject	4	5.65	1.41	1.03
Order	4	2.74	0.69	0.50
Error	12	16.90	1.41	
Total	24	36.30		

* $p < 0.16$

In performing the analysis on the data set containing only those points where the error in core temperature did not exceed 10%, similar results were obtained. There was no significant difference due to subjects or trial sequence. However, there was a significant difference between temperature levels (alpha = 0.07).

Endurance Measurements

Endurance times for each of the trials are presented in Table 13. Each value represents the length of time in seconds that the subject was able to exert a force equal to 1/3 of the average of the three preliminary MVC's for that trial. A wide variation can be seen in the times occurring at the different temperature levels. Figure 16 shows the

Table 13

ENDURANCE TIMES (seconds)

	Core Temperature Increment (^{o}C)									
		0.0		0.3		0.6		0.9		1.2
Subject										
1	(3)	814	(5)	425	(2)	525	(1)	267	(4)	276
2	(1)	819	(3)	263	(5)	784	(4)	320	(2)	230
3	(2)	277	(4)	204	(1)	325	(5)	264	(3)	162
4	(5)	2148	(2)	1085	(4)	1322	(3)	1046	(1)	1131
5	(4)	471	(1)	328	(3)	275	(2)	348	(5)	125
Average		906		461		646		449		385

Note: Numbers in parenthesis indicate trial sequence.

changes in endurance time as a function of temperature. Inspection of the graph showed a large change in endurance time for all of the hot temperature levels when compared with the control level. The relative endurance with respect to the 0.0 ^{o}C increment ranged from 51% for the 0.3 ^{o}C increment to 42% for the 1.2 ^{o}C increment.

The analysis of variance results (Table 14) confirmed the existence of a highly significant effect ($p < 0.01$) due to temperature. A multiple-range test revealed primarily that the 0.0 level yielded higher endurance times than any

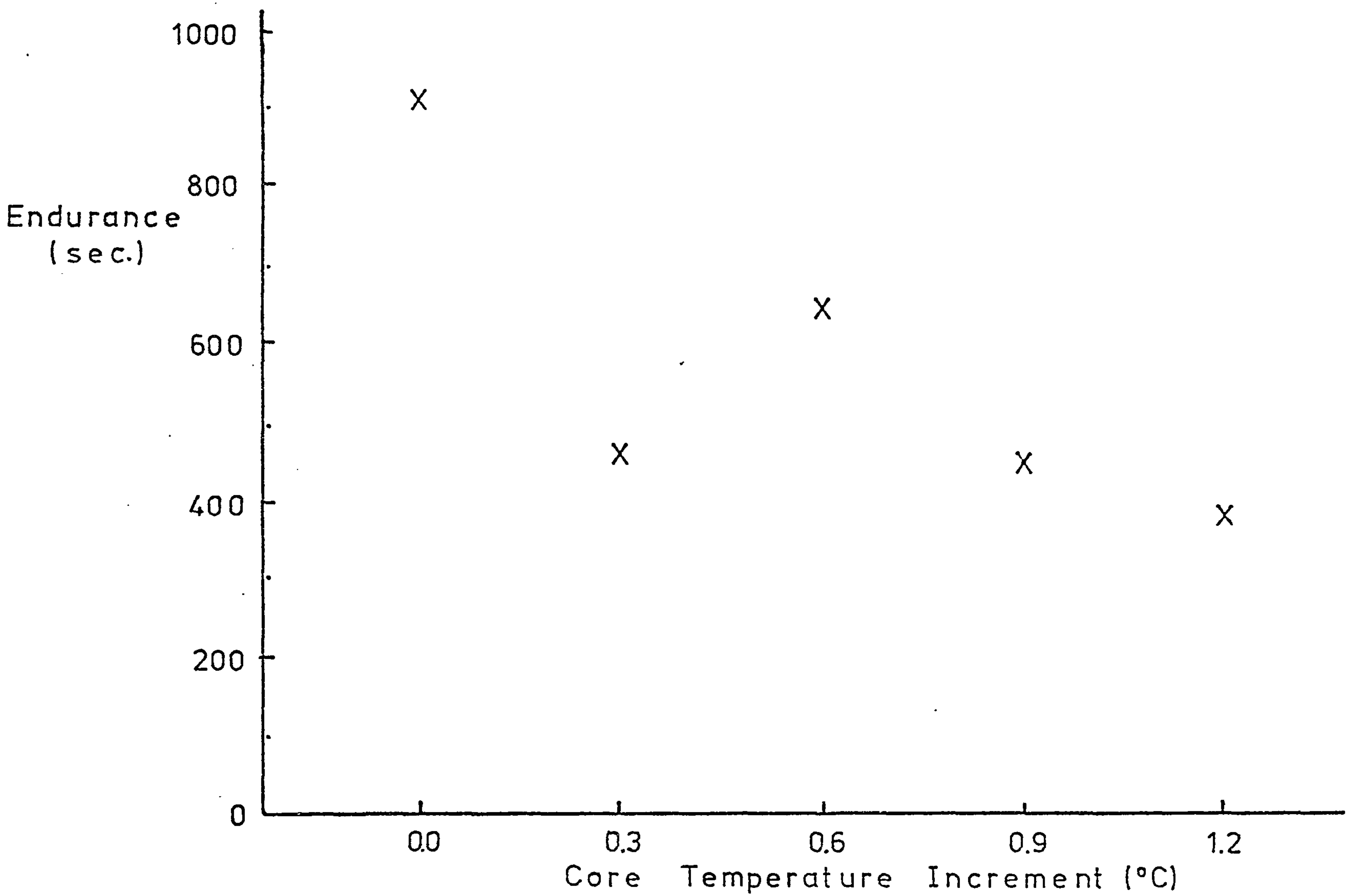

Figure 16. Endurance Times vs. Core Temperature Increment

Table 14

ANOVA TABLE - ENDURANCE TIMES

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Temperature	4	896935	224234	7.59 *
Subject	4	3973762	992441	33.61 **
Order	4	220308	55077	1.86
Error	12	354700	29558	
Total	24	316.54		

* p < 0.003
** p < 0.0001

of the other levels. There was also a significant difference between the 0.6 °C and the 1.2 °C increments.

It may be observed that subject 4 had extremely long endurance times. A Duncan multiple-range test revealed that the endurance times for subject 4 were significantly different (alpha = 0.05) from those of all the other subjects. However, there were no significant differences among the remaining subjects. It is also interesting to note that subject 4 was the weakest of the five subjects. This contributed to a moderately high correlation (-0.44) between preliminary grip strength and endurance.

Because of the unusual times achieved by subject 4, a separate analysis of variance for each of the dependent variables was performed excluding her data. The conclusions from the analyses were the same in all cases except for the endurance times. In this case, the difference between temperature levels was not as highly significant ($p < 0.03$). In addition, a Duncan multiple-range test indicated that the 0.0 and 0.6 °C increments were not significantly different.

Analysis of the reduced data set with core temperature errors less than 10% yielded the same results as the full analysis, although the level of significance was lower. This is to be expected due to the smaller number of data points. However, the differences between the temperature levels remained highly significant.

Table 15 gives an indication of the relative endurance times for each subject. Each entry in the table represents the ratio of the endurance time at that particular temperature divided by the endurance time for the given subject at 0.0 °C. For the five subjects, endurance at the 1.2 °C level ranged from 27% to 58% of the endurance at the 0.0 °C level.

An interesting phenomenon may be observed in examining either the absolute endurance times or the relative scores. In four of the five subjects, there was a decrease in endurance when comparing the 0.3 °C increment with the 0.0 °C increment. However, there was an increase in going from the 0.3 °C level to the 0.6 °C level. The reason for this change is not obvious.

Table 15

RELATIVE ENDURANCE TIMES - E/EØ

	Core Temperature Increment (°C)				
	Ø.Ø	Ø.3	Ø.6	Ø.9	1.2
Subject					
1	1.ØØ	Ø.52	Ø.64	Ø.33	Ø.34
2	1.ØØ	Ø.32	Ø.96	Ø.39	Ø.28
3	1.ØØ	Ø.74	1.17	Ø.95	Ø.58
4	1.ØØ	Ø.51	Ø.62	Ø.49	Ø.53
5	1.ØØ	Ø.7Ø	Ø.58	Ø.74	Ø.27
Average	1.ØØ	Ø.56	Ø.79	Ø.58	Ø.49

Note: E/EØ = (Endurance) / (Endurance at ΔT = Ø.Ø °C)

One explanation may be that the Ø.6 °C increment may increase muscle temperature to a level which is more favorable for sustained contractions. A better explanation may relate to the changes in blood distribution which occur during work in the heat. It is possible that the Ø.3 °C increment does not elicit as great an increase in blood flow as does the Ø.6 °C level. Although the increased blood flow may be primarily for the purpose of core temperature regulation, it will have a beneficial effect on muscle performance as well.

An alternative explanation involves the motivational levels of the subjects. It was observed that under levels of low heat stress (0.0, 0.3 °C), subject motivation did not appear as high as with the other levels (0.6, 0.9, 1.2 °C). Although this did not affect the endurance times for the 0.0 °C trials, it may have had an effect on the 0.3 °C trials.

Data from the 20 minute series of MVC's was inconclusive. A preliminary analysis was performed by comparing the average of the first five MVC's with the average of the last five for each temperature level. These averages are shown in Table 16.

Table 16

SERIES OF MVC'S - GRIP FORCE (kg)

	Core Temperature Increment (°C)									
	0.0		0.3		0.6		0.9		1.2	
Subject	B	E	B	E	B	E	B	E	B	E
1	19.5	17.6	16.7	14.9	15.3	13.2	16.6	13.0	17.4	13.0
2	22.5	17.7	21.5	19.4	22.5	21.4	21.8	21.2	23.7	20.5
3	20.6	20.0	23.5	19.2	18.0	17.7	24.3	21.0	23.6	19.5
4	15.6	18.3	13.2	11.8	16.1	16.1	15.1	13.1	14.4	11.9
5	18.9	15.6	17.0	14.8	17.5	15.3	16.3	14.9	16.1	15.6
Avg.	19.4	17.8	18.4	16.0	17.9	16.7	18.8	16.6	19.0	16.1

B - average of first five MVC's at beginning of series
E - average of last five MVC's at end of series

The differences between the averages are shown below for each temperature:

Temperature (°C)	0.0	0.3	0.6	0.9	1.2
Begin - End (kg)	1.6	2.4	1.2	2.2	2.9

Although there was an increased difference (2.9 vs. 1.6 kg) when going from 0.0 °C to 1.2 °C, its significance is again masked by the large variability in the data. Due to this fact, further analysis was not performed.

Physiological Measurements

The information obtained from the measurement of heart rate and skin temperature was minimal. Heart rate provided a good indication of the severity of the treadmill work task and of the hot environment, and was used primarily as a safety measure. Changes in heart rate occurred rapidly following any change in the work load or environmental temperature. Slight increases in heart rate (5 to 10 beats/min) occurred during each MVC measurement and during the endurance test. At the higher core temperature levels, heart rates of the different subjects remained high, even after recovery from the treadmill exercise.

In general, skin temperature changes followed changes in the environmental temperature. There was a very high correlation between the measured dry-bulb temperature and the mean skin temperature. This is in agreement with Nielsen (1969) who stated that the average skin temperature is a linear function of the ambient air temperature and is relatively independent of the level of exercise.

An increase in the temperature at the surface of the thigh was observed in most subjects during treadmill exercise. However, this was often masked by the larger changes in environmental temperature.

The same was true of changes in the temperature of the surface of the lower arm during static contractions. Although an increase in the lower arm temperature was observed in most of the subjects during the endurance test, the magnitude of the change compared with changes in the chamber temperature prevented an accurate analysis. In fact, it was easily detected only during the 0.0 $^{\circ}$C trials. The differences between the surface temperatures of the working forearm and the non-working forearm did not follow any systematic pattern. Again, the magnitude of the environmental temperature changes was larger than the differences between the temperatures at the two sites, thus preventing further analysis.

Summary

Tables 17 and 18 summarize the major results of the investigation. Table 17 provides the Pearson correlation coefficients for the experimental variables. In spite of the difficulties in controlling core temperature for some of the trials, there was a high correlation (0.96) between the target and actual temperatures.

Table 17

TABLE OF CORRELATION COEFFICIENTS

	TCT	ACT	PRE	POST	P-P	END
TCT	1.00	0.96	0.04	-0.13	0.53	-0.32
ACT	0.96	1.00	0.08	-0.07	0.48	-0.32
PRE	0.04	0.08	1.00	0.95	-0.06	-0.44
POST	-0.13	-0.07	0.95	1.00	-0.37	-0.32
P-P	0.53	0.48	-0.06	-0.37	1.00	-0.27
END	-0.32	-0.32	-0.44	-0.32	-0.27	1.00

TCT - Target Core Temperature
ACT - Actual Core Temperature
PRE - Preliminary Strength
POST - Post-Exercise Strength
P-P - (Pre-Post) Strength
END - Endurance

Also, the correlations between the target values and the various dependent variables did not differ appreciably from the correlations between the actual core temperatures and the dependent variables.

The correlations between the core temperatures and the preliminary and post-exercise strength values were essentially zero. However, the correlations between the core temperatures and the pre-post score were on the order of 0.5 which was significant at an alpha of 0.01. This reinforced the relationship between the change in strength and the core temperature level. The correlations between the core temperatures and endurance were negative (-Ø.32), indicating a decrease in endurance time with increasing core temperature.

The correlation between the preliminary and post-exercise MVC's was high (Ø.95) due to the large differences between subjects combined with the small changes from pre to post-exercise. Finally, the correlation between preliminary grip strength and endurance was negative (-Ø.44), implying that the subjects with greater initial strength had less endurance.

Table 18 shows which factors had a significant effect on each of the dependent variables. When examining the data from both the preliminary and post-exercise MVC's, it was evident that a large variation between subjects existed. However, by calculating a (pre-post) strength score, this variability was reduced, thus revealing a marginally significant effect due to the core temperature level.

With respect to endurance, a highly significant difference between subjects was again observed. However, the effect of core temperature was also highly significant. In general, the control condition of Ø.Ø $^{\circ}$C produced significantly longer endurance times than any of the heat stress levels.

Table 18

SUMMARY OF SIGNIFICANT EFFECTS

Criterion Measure	FACTOR		
	Core Temp.	Subject	Trial Order
Prelim. MVC		***	
Post-Ex MVC		***	
Pre-Post MVC	*		
Endurance	***	***	

*   - Marginally Significant
*** - Highly Significant

CHAPTER V

CONCLUSIONS

The purpose of this study was to investigate the effects of changes in body core temperature on the strength and endurance of static hand-grip contractions. This was done by increasing each subject's core temperature in fixed steps and measuring changes in strength and endurance at each level.

Due to the expected small changes in performance, it was essential to maintain precise experimental control over the strength and endurance measurements. To achieve this objective, a special apparatus was constructed to accurately measure the desired forces. The successful use of this apparatus was demonstrated by the consistency of the preliminary strength values throughout the second week of testing.

Precise control of each subject's core temperature was also highly desirable. However, results in this area were less successful. Comparison of the baseline data from week 1 and week 2 showed little change in resting core temperature. Thus, the daily change in resting core temperature was a minimal source of variation in generating the desired level of heat strain. A greater source of variation existed with respect to the ability to control core temperatures. Some of the reasons for the difficulty were discussed in Chapter IV.

Although rather large percentage errors in core temperature occurred in a few of the trials, the final conclusions were insensitive to the errors. This was demonstrated by comparing the results obtained using the full data set with those obtained with the partial data set in which the trials with an error in core temperature exceeding 10% were removed from the analysis. In most cases, the only difference between the results from the two data sets was in the level of significance of the F-ratios.

With respect to grip strength, there was only a slight increase from week 1 to week 2. However, the differences in strength between the preliminary and post-exercise measurements were also small in comparison with the differences between subjects. This necessitated an analysis of the pre-post difference. The magnitude of this difference increased with increasing temperature (to a maximum of 8%), but the change was only significant at a level of 0.16. There was no significant difference due to subjects or trial sequence. The practical significance of the change is questionable.

More significant changes occurred with respect to endurance. At the 1.2 ^{o}C core temperature increment, there was almost a 60% decrease in the length of time an individual could exert 1/3 of his maximum strength. The change at other core temperature levels was almost as great, indicating that a significant change in endurance occurs when working in a hot environment, regardless of the level of heat stress.

The fact that there was no evidence of change in the MVC series indicates no difference in the level of fatigue at the end of the endurance test for the different temperature levels. The length of time that force was exerted in the hotter environments was significantly less than in the cooler environments. Thus, the 6-minute rest period represented a higher percentage of the total exertion time for the hotter temperatures. It is likely that this allowed an equivalent degree of recovery for the various temperature levels.

A comparison with the results of Clarke, Hellon and Lind (1958) can be made by making some assumptions which relate their water bath temperatures with the current core temperature changes. The 0.0 ^{o}C neutral environment is comparable to the 26 ^{o}C water bath temperature in that minimum conductive and convective heat transfers with the environment occur under these conditions. The higher core temperatures are comparable to the 42 ^{o}C water bath temperature, again in terms of the expected conductive and convective heat transfers.

Based on these assumptions, a comparison of grip strength results reveals that Clarke et al. found no difference in strength between the 26 °C and the 42 °C water baths, while in this study, an 8% decrease in strength was observed from the 0.0 °C to the 1.2 °C core temperature increment. However, the change was marginally significant.

In terms of endurance, Clarke et al. observed an average endurance time of 230 seconds at a bath temperature of 26 °C and an endurance time of 120 seconds at a bath temperature of 42 °C. This amounts to a decrease in endurance of 49%. In comparison, the endurance times in this study ranged from 906 seconds at 0.0 °C to 385 seconds at the 1.2 °C level, amounting to a decrease of 58%.

In general, the results obtained in this investigation were very similar to those in Lind's studies. Although measurements of changes in blood flow and muscle temperature were not made in this study, the hypotheses of Lind provide a satisfactory explanation for the results. In Lind's opinion, a more rapid accumulation of metabolites occurs within the muscle due to a reduced flow of blood to and from the muscle itself. This buildup of metabolites reduces the length of the endurance time at higher temperatures.

The results obtained in this investigation must be applied cautiously. It is essential to remember that the subjects employed in the study were partially acclimatized females in good to excellent physical condition. Care must be taken in generalizing the results to other populations. What should be stressed is the large decline in continuous hold endurance under all levels of heat stress. Although various work/rest periods were not specifically investigated, work/rest scheduling for all workers should take into account the reduction in time available for sustained static work while exposed to a hot environment.

Recommendations for Further Research

The major recommendation for additional research in this area is for verification of the present findings using other muscle groups. The use of hand-grip contractions allows tighter control over the actual muscle group performing the exercise. With other muscle groups, difficulties in precisely measuring the forces exerted may obscure possible changes in strength and endurance. However, similar investigations should be performed to determine if larger muscle masses yield similar results. The studies should also employ a larger and more diverse subject population.

Additional refinement of the procedure used to control core temperature would also be helpful. This would include a more sophisticated interactive program to make the fine adjustments necessary to keep core temperature stabilized for individual subjects. An effective real-time predictive model would ensure more accurate control of the desired core temperature levels.

Further studies should be performed to verify the observed phenomenon of a large decrease in endurance at the Ø.3 °C increment followed by a relative increase in endurance at the Ø.6 °C level. Although the pattern may be unique to this particular data set, the fact that it occurred in four of the five subjects indicates that additional investigation is necessary.

Finally, additional research needs to be conducted to determine the underlying physiological mechanisms responsible for the changes in endurance. One serious drawback of the current study was the lack of information about blood flows and muscle temperatures. This information is essential in isolating the causes of the endurance decrement. Also of importance is an evaluation of the psychological factors involved, especially differences in motivational levels.

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