

EFFECTS OF INCREASED INTRAMUSCULAR TEMPERATURE
ON CHARACTERISTICS OF MUSCULAR FATIGUE IN VIVO

by

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ABSTRACT

Shortwave diathermy was used to elevate the intramuscular temperature of human elbow flexor muscles before measurements of strength, isometric endurance, and the fatigue induced by dynamic exercise. The test of strength involved three maximal voluntary contractions (MVC's) facilitated by visual feedback of force and verbal encouragement. Isometric endurance was examined during three contractions of $2/3$ MVC sustained until exhaustion. Dynamic exercise involved a standardized submaximal dynamic task of five and a half minutes duration. The effects of this exercise were assessed by means of three isometric contractions of $2/3$ MVC sustained until exhaustion. Results indicated that increasing intramuscular temperature above 40 degrees C temporarily depressed all three measures of physiological work.

An integrated electromyogram (IEMG) was recorded during each sustained contraction and converted to an equivalent force (FIEMG) by means of data obtained in a calibration experiment. This conversion was used to correct for variability of impedance and electrode placement both between experimental sessions and subjects. FIEMG was found to increase linearly with time during the progress of an

isometric contraction. The terminal FIEMG values were consistently lower than predicted maximal values, indicating both a metabolic and neurological component of fatigue. However a considerably greater terminal FIEMG obtained in the isometric contractions immediately following dynamic exercise suggested a higher metabolic/neurological ratio of fatigue in dynamic exercise.

Higher intramuscular temperatures were found to decrease the FIEMG for a given muscular force, and this variation limited the interpretation of the data obtained during isometric work. However, after corrections were made for the depressing effect of temperature on FIEMG, a higher FIEMG was found at the beginning of isometric contractions following diathermy. Evidently greater motor unit activity was necessary to produce the required force ($2/3$ MVC) at higher intramuscular temperatures.

A higher rate of oxygen uptake was observed during dynamic exercise at higher intramuscular temperatures, particularly at the beginning of the exercise task. A direct correlation was found between increased oxygen uptake and decreased isometric endurance following dynamic exercise. This suggests that the increased oxygen consumption was a means of compensating partially for an inefficiency of an

energy transducing process within the heated muscle. This reflects either increased utilization of adenosine triphosphate (ATP) at the myofibrillar level, to perform the same exercise task, or some uncoupling of ATP production from electron oxygen transport in the mitochondria. However, decreases in both strength and isometric endurance suggest the myofibrils as the most likely site of inefficiency. These results confirm an important role for the effects of temperature in the mechanisms whereby muscular effort results in fatigue.

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MEMO:

If you believe all events in nature have reason, and there is reason to believe they do, then the purpose of science is firstly to hypothesize the reasons, and secondly to test the hypotheses.

- Author

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CHAPTER I

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INTRODUCTION

The influence of temperature on muscular function is a subject of controversy. Whereas increased intramuscular temperatures have been cited as being beneficial for subsequent exercise (Astrand and Rodahl, 1970), other investigators have viewed it as a component of fatigue (Davison et al., 1974).

Intramuscular temperature can be elevated by prior activity or passive heating. Studies which have used preliminary exercise to warm the active muscles are difficult to interpret due to a large number of other physiological responses associated with exercise. In order to distinguish effects of temperature from other physiological effects of activity a number of investigators have attempted to determine the effects of passive heating on the contractile strength and endurance of different muscles and muscle groups.

Temperatures have been increased in intact human muscle by the use of infrared lamps (Saunders, 1963), hot showers (Robbins, 1942), water baths (Clarke et al., 1958; Edwards

et al, 1972) and shortwave diathermy (Asmussen and Boje, 1945; Muido, 1946; Nukada, 1955; Sedgwick and Whalen, 1964; Michielli, 1965). Needless to say, these techniques produce very different physiological responses dependent upon the attitude of the subject (Smith and Boxymowski, 1965), the body area to which the heat is applied and the intensity of the heat application (Wright, 1959). The results of these studies are also affected by variation in the application procedures and subsequent exercise tasks. Hot showers are inappropriate for comparison since their generalised warming effect produces different physiological responses than does localised heating. Infrared radiation and water bath techniques have made a valuable contribution to the understanding of muscular function but have one major limitation. Studies which have recorded intramuscular temperatures demonstrate that the heating is primarily of the superficial skin layer rather than the muscle itself. Edwards et al., (1972) report that the temperature of the muscle at a depth of 3-6 cms. was only 38.6 degrees C, after immersion in a water bath at 44 degrees C for 45 minutes. This was only 1.4 degrees C higher than the normal resting temperature, despite the fact that it is the longest immersion time reported in the literature.

Diathermy has been reported to elicit the highest artificially induced intramuscular temperatures (Lehmann et al., 1969; Lehmann et al., 1974) and has been reported to have a more specific heating effect (Lehmann et al., 1969) and vasodilatory response (Downey et al., 1970) than other methods of heating. The intramuscular temperatures reported by Lehmann et al. (1969), Guy et al. (1973) and Lehmann et al., (1974) of 40-42 degrees C simulate closely the maximal intramuscular temperatures which can be estimated following prolonged endurance exercise. Robinson (1942) and Costill (1972) both report body core temperatures above 41 degrees C following a marathon race. Although intramuscular temperatures were not recorded, it would seem reasonable to predict that they must be slightly higher than the body core temperature. Although the effects of increased body temperature on fatigue have been well documented (reviewed by Hardy et al., 1971), the localised effects of intramuscular temperatures similar to those elicited under conditions of prolonged high intensity exercise have not been well studied. Only five studies have investigated the effect of diathermy on subsequent exercise. These studies did not standardize applications on different experimental occasions and did not use procedures designed to elicit the highest tolerable intramuscular temperatures.

This study has used standardized procedures designed to elicit temperatures simulating those produced by prolonged high intensity exercise. In an attempt to isolate the muscular systems affected by temperature the study examined the influence of increased intramuscular temperature on strength, isometric endurance and dynamic exercise.

The strength experiments used visual feedback of force during maximal voluntary contraction (MVC), in an attempt to reduce the influence of psychological inhibition and therefore provide greater precision than previous studies.

Isometric contractions were sustained at a contractile force (two thirds of MVC) where intramuscular pressure is high (Sylvest and Hvid, 1959) and muscular blood flow is essentially arrested (Royce, 1960; Lind et al., 1964). Consequently this eliminates the effects of oxidative metabolism during the contraction. An electromyogram recorded during the sustained contractions was a further attempt to delineate the criteria affecting performance.

The development of fatigue during dynamic exercise was assessed by a sustained isometric contraction (two thirds of MVC) following a standardized dynamic exercise task. A

similar technique has previously been used to assess the efficiency of different pedalling frequencies on a bicycle ergometer (Petrofsky et al., 1974). The present technique was chosen first because a submaximal dynamic exercise task could be performed which nevertheless allowed a readily definable point of exhaustion. Secondly, the myoelectrical activity recorded during a sustained contraction is more readily analyzed than in dynamic conditions. Oxygen uptake was measured during the dynamic exercise load to assess the contribution of oxidative metabolism to increased energy utilization.

Studies of human performance have shown that it is profitable to use the integrated electromyogram (IEMG) as a measure of neuromuscular activity. Although exceptions have been reported (Lippold et al., 1960; Chapman and Troup, 1970), most muscles exhibit increased IEMG activity if a submaximal isometric contraction is sustained at a specified force over a period of time (Scherrer and Bourguignon, 1959; Eason, 1960; deVries, 1968a; Kuroda et al., 1970). Most investigators agree that the primary factor leading to a rise in electrical activity with respect to time as the muscle fatigues is a combination of recruitment and increased frequency of neuromuscular stimulation needed to compensate for the decreased tension generated by each

fibre. Other investigators have suggested that synchronization of motor unit potentials (Buchthal and Madsen, 1950; Lloyd, 1971) and recruitment of higher threshold motor units (Kugelberg and Skoglund, 1946; Lloyd, 1971) could also contribute to the rise in myoelectrical activity as a function of time. A frequency analysis of the electromyogram during a sustained isometric contraction suggests that there is also a loss of low threshold motor units during a sustained contraction (Lloyd, 1971). It is of considerable interest that, with the exception of this last hypothesis similar factors have also been suggested to contribute to the increased IEMG with respect to increasing muscular tension (Lippold, 1952; Lenman, 1959; Kudora et al., 1970; Coggshall and Bekey, 1970). It is consequently surprising that no previously reported studies have investigated the relationship between IEMG during fatigue and its equivalent force in an unfatigued condition, for a study of this design would test the hypothesis that loss of motor unit activity occurs with fatigue during sustained contractions. Although this was not the purpose of the present study, this procedure was used to correct for variations in impedance and electrode placement on different experimental occasions. The force equivalent of the IEMG (FIEMG) could then be used to assess the electrical activity required to sustain the required force. Both the initial

degree of electrical activity (Edwards and Lippold, 1956) and the rate of increasing electrical activity (deVries, 1968a) have been previously used to assess fatigue. The test-retest correlation coefficient of the linear slope determined by deVries (1968a) was 0.934 when 15 minutes rest intervened between the two contractions, and 0.827 on different experimental sessions.

The hypotheses which can be formulated regarding the physiological effects of increased temperature on muscular function are numerable and complex. Increased temperature could potentially improve certain forms of muscular performance (especially dynamic exercise) by:

- 1) Vasodilatory effect and improved blood flow to the muscle (Barcroft and Edholm, 1946; Downey et al., 1970; Greenburg, 1972).

- 2) Increased permeability of membranes (Lehmann et al., 1950; Hoare, 1972) could allow an increased diffusion rate of substrates to, and metabolic waste products from the muscle. It should perhaps also be noted that increased permeability could cause a loss of potassium ions (Brown and von Euler, 1938) and a detrimental effect on exercise performance.

3) An increased rate of oxidative metabolism and therefore a potentially more rapid adaptation to the oxygen requirements of the task.

4) A decreased viscosity resulting in a decreased internal resistance (Buchta et al., 1944) could increase the efficiency of dynamic exercise although it might also decrease the efficiency of an isometric contraction, as explained later.

5) The increased activity of enzymes associated with increased temperature might lead to an increased myosin ATPase activity and a more rapid cross-bridge turnover.

Whereas this last mechanism could potentially improve the velocity and strength of muscular contraction, the first four mechanisms would specifically favour dynamic exercise. However, there are also a number of other reasons why increased temperature could be detrimental to all forms of muscular work. These could include:

1) The possibility of protein denaturation. Unpublished calculations to estimate the temperature at the mitochondria during muscular work suggest that it could be very high (Calvert, 1976). An additional thermal load and

the decreased diffusion of heat due to increased temperature of the surrounding tissues, could potentially induce denaturation of oxidative enzymes. Another possible site of denaturation is the myofibrillar proteins. There is good evidence to suggest that a temporary deformation, or denaturation, of the actin myosin complex occurs at temperatures above 40 degrees C (Hartshorne et al., 1971; Medvedeva and Ruuge, 1975; Medvedeva et al., 1975). While Hartshorne et al., (1971) suggest that the conformation of myosin at higher temperatures no longer "recognizes" troponin, Medvedeva et al. (1975) have reported that myosin binds phosphogens less effectively at higher temperatures.

2) Increased intramuscular temperature leads to an increased distance between the actin and myosin filaments (Medvedeva and Ruuge, 1975) which could lead to an inefficiency of crossbridge function. Differential efficiencies of crossbridge function have been implied from studies comparing fast- and slow-twitch muscle. The increased fluctuation of sarcomere length in fast-twitch muscle (Goldspink et al., 1970) presumably contributes to an increased rate of ATP utilization per unit of force during sustained contractions (Davies et al., 1970).

3) The increased rate of rise and fall, and decreased duration of tension in an isometric twitch at higher intramuscular temperatures (MacLagan and Zaimis, 1957; Close and Hoh, 1968) probably reflects the increased rate of release (Kaufman and Fleckenstein, 1965) and removal (Inesi and Watanabe, 1967) of calcium from the myofibrillar spaces or a faster metabolism of reactions limiting the rate of crossbridge turnover. The increased rate in the development of tension should increase the velocity of contraction for the whole muscle. Although no studies have been reported on skeletal muscle, Yeatman et al. (1969) report a greater velocity of contraction in heated cat papillary muscle. The effect of the increased rate of tension development on strength is not clear. While MacLagan and Zaimis (1957) found increased twitch tension at higher intramuscular temperatures, Close and Hoh (1968) report a reduction in twitch tension in fast twitch muscles. However the reduction in twitch duration at higher temperatures would necessitate a greater frequency of motor unit activation so that the duration of activation necessary to sustain or produce a required force is comparable in both the heated and non-heated situation. Douboumopoulos and Chatfield (1959) and Truong et al. (1964) have shown that if the frequency of stimulation of isolated muscle is limited to 60 c/sec a significant reduction of isometric tetanic tension

is associated with increased temperature. The CNS and synaptic limitations to increased firing frequency may result in an earlier point of exhaustion in heated muscle. The decreased twitch duration could also be detrimental to endurance type activities where ATP is limiting, since the more frequent release and uptake of calcium, which is presumably responsible for this effect, would also involve increased energy expenditure.

4) Edwards and Hill, (1975) have reported energy conservation in the latter stages of a sustained isometric contraction and have suggested that the decreased rate of relaxation accompanying fatigue may act as an energy conserving mechanism. The results reported by Edwards et al. (1975) suggest that the decrease in relaxation time, which accompanies fatigue, is not related to the pH effect on calcium sequestration (Inesi and Watanabe, 1967). They hypothesized that the rate limiting step for myosin ATPase may determine the rate of tension decay following contraction. It is possible that the increased ATPase activity at higher temperatures may counteract the effects of the energy conserving mechanism.

5) Increased muscular temperature decreases the viscosity and increases the compliance of a muscle (Buchta

et al, 1944 and Buchtal and Kaiser, 1944). While this effect could reduce the internal resistance and consequently improve the efficiency of muscular movement, it effectively adds a compliance to the muscle and could increase the distance of crossbridge movement necessary to generate the same tension, thereby increasing the energy cost of a sustained isometric contraction. Combined with a reduction of the time course of the active state, the increased elasticity could also result in a decrease in the rate of development of tension during a maximal voluntary contraction. A report by Hajdu (1951) indicates that when frog sartorius muscle was increased from 15-35 degrees C the decrease in contractile strength at higher temperatures was more rapid for contractions which allowed greater muscle movement. This effect could be partly accounted for by the increased elastic properties of the muscle.

6) The possibility that increased temperature leads to inefficiency of energy transducing processes has been suggested previously (Brookes et al., 1971; Saar and Cassuto, 1976). Brookes et al. (1971) found that the respiration of isolated rat skeletal muscle mitochondria was increased by over 200% when the temperature was increased from 25 to 45 degrees C. However, the P:O ratio decreased 18% between 40

and 45 degrees C. indicating a decrease in phosphorylative efficiency over this temperature range. Saar and Cassuto (1976) recorded oxygen deficit, oxygen debt and intramuscular temperatures during comparable workloads of concentric and eccentric work. The higher oxygen debt and intramuscular temperature elicited from eccentric exercise were suggested to reflect uncoupling of mitochondrial energy dependent reactions. However, it is also possible that inefficiency of energy transduction may be associated with splitting of ATP at the myosin heads. If this occurs it could be associated with any of the five hypothesized detrimental effects of increased temperature already discussed.

7) Increased intramuscular temperature might be expected to decrease the resting partial pressure of oxygen due to an increased rate of metabolism without a compensatory increased oxygen uptake. Stainsby and Otis (1964) have demonstrated that a decrease in the partial pressure of oxygen within the muscle was not compensated by oxygen uptake until a critically low oxygen partial pressure was reached, and that this value was lower in resting than in contracting muscle.

The present study was designed to determine the extent to which the above physiological mechanisms affect muscular function by investigating the capabilities and physiological responses of muscle to three different forms of physiological work and the recovery of muscle from temperatures simulating the highest physiological range.

CHAPTER II

REVIEW OF RELATED LITERATURE

For purposes of clarity the literature directly pertaining to the effect of increased intramuscular temperature on exercise performance will be discussed under headings of strength, isometric endurance and dynamic exercise.

Isometric Strength

Although the effects of increased intramuscular temperature on strength are clearly significant in their relevance to human performance, very few studies on this topic have been published. Those which have been done have yielded controversial results. A review of related literature indicates that results are specific to the temperature change, the conditions under which the muscle is activated and the type of muscle under study.

The possibility that there is an optimal temperature for strength performance is reflected in a study by Wright (1959) who raised the whole body temperature of 3 subjects 1.12 degrees C, and then a further 0.56 degrees C to 38.34

degrees C by immersing each subject in hot water for the time required to elicit the specific temperature change. Whereas a rectal temperature of 37.78 degrees C was associated with an improved grip strength, the grip strength was decreased at rectal temperatures of 38.34 degrees C compared to grip strength recorded at resting body temperature. Although it is difficult to draw conclusions regarding increased intramuscular temperature when the whole body temperature has changed, the study demonstrates the importance of temperature on muscular function.

Although studies investigating the effects of intramuscular temperature on contractile tension of isolated muscle have used temperatures corresponding to the lower physiological range of mammals, they have not investigated temperatures over 40 degrees C, corresponding to the highest physiological temperature range. All reported investigations using isolated mammalian skeletal muscle have demonstrated an increased isometric tetanic tension with an increase of temperature up to 40 degrees C, if a sufficiently high frequency of stimulation is provided. Cullingham et al. (1960) and Truong et al. (1964) found that the increase in tension with increased temperature was more rapid for indirect stimulation compared to direct stimulation of the muscle up to temperatures of

39 - 40 degrees C. A partial neuromuscular block was hypothesized at lower temperatures.

Close (1965) and Close et al. (1968) have shown an increase in tetanic tension with a temperature increase up to 35 degrees C. However the increase is much more pronounced for muscle containing a higher proportion of fast-twitch white fibres (extensor digitorum longus) than for slow-twitch red muscle (soleus). In both muscles the isometric twitch contraction time was decreased at higher temperatures, while the peak twitch tension was reduced in extensor digitorum longus. It was hypothesized that the increased intrinsic speed of shortening and more rapid removal of activating substance in fast-twitch muscle was responsible for the decreased twitch tension. It was further suggested that the repetitive stimulation of extensor digitorum longus produced a post-tetanic potentiation which allowed an increased tetanic tension despite the decrease in twitch tension. However no explanation was offered to account for the increase in tension during tetanic contractions. MacLagan and Zaimis (1957) found a similar increase in isometric tetanic tension and a decrease in twitch duration with increased temperature over the range 30 - 36 degrees C. Over this temperature range they also found an increased peak twitch tension at

higher temperatures which could account for the increase in isometric tetanic tension.

The studies of temperature on strength in vivo are more controversial. Apart from the study of Wright (1959) already mentioned, only Hall et al. (1947) and Sedgwick and Whalen (1964) have found a significant reduction in strength at higher intramuscular temperatures. Hall et al. (1947) applied hot packs to the elbow flexors of human subjects which resulted in a skin temperature of 41-43 degrees C and a decrease in strength of 10%. Sedgwick and Whalen (1964) applied shortwave diathermy to the elbow flexors, followed by a maximal voluntary contraction thirty seconds after heating. The intramuscular temperatures recorded for two subjects were both above 40 degrees C. No other studies have recorded such high temperatures before a test of strength. Michielli (1965) who applied a mild dose of shortwave diathermy to elevate intramuscular temperatures to 39.3 degrees C observed a slight decrease in strength although their results were not statistically significant.

Clarke et al. (1958) and Saunders (1963) both report no significant effect of increased intramuscular temperature on strength. Clarke et al. (1958) tested forearm grip strength after the forearm was immersed in a water bath of 42 degrees

C, while Saunders (1963) used an infra-red lamp to increase the temperature of the elbow flexors before flexion strength was measured by a cable tensiometer.

These studies are challenged by the results of Asmussen et al. (1974) who found an 8% increase of isometric strength of human biceps brachii, triceps surae and quadriceps femoris when the temperature of the muscle was increased from 30 degrees C to 40 degrees C. They attributed their findings to an increased rate of cross-bridge activity at higher temperatures. This hypothesis was given support by their observation that the speed of tension development over the same temperature range increased by 35%.

It is apparent that while the literature is controversial, only one study by Sedgwick and Whalen (1964) has examined strength at temperatures corresponding to those produced as a by-product of prolonged high intensity submaximal exercise. No explanation was offered for the impaired strength at higher temperatures, and the reversibility of the impairment was not tested.

Isometric Endurance

Most studies reporting the effects of increased intramuscular temperature on the ability to sustain isometric contractions have been performed on human subjects. Although one study reports no significant effect (Michielli, 1965), other investigations have found that increasing intramuscular temperature above resting levels was detrimental to isometric endurance.

Despite the scarcity of experiments relating to increased intramuscular temperature in isolated preparations one of the first experiments on intramuscular temperature and endurance were performed on isolated muscle. Hall et al. (1944) found a more rapid decline in tension produced by a muscle during repetitive stimulation when the intramuscular temperature was elevated by 3.3 degrees C. The baseline values for intramuscular temperature were not reported.

Nukada (1955) used both shortwave diathermy and hot waterbath techniques to elevate intramuscular temperatures before a sustained isometric endurance task. Although interpretation of the results is limited by data from only one subject, there was found to be a decrease in endurance after heating regardless of the technique used. He

attributed the decrease in endurance time to a shift of blood flow from the muscles to the skin. The experiment was extended to test the recovery of endurance 5, 10 and 20 minutes after application of diathermy. Endurance was not affected by diathermy when any of the above recovery periods were introduced.

Clarke, Hellon and Lind (1958) found that the duration of contractions sustained to fatigue with a force of one third of maximal voluntary contraction (MVC) was longest at an intramuscular temperature of 27 degrees C. A follow-up study by Lind (1959) consisted of a series of sustained contractions at one third MVC at set intervals following immersion of the forearm in water at 18 degrees C. in one experimental session and at 34 degrees C. in another session. When the interval between the contractions was kept constant at a given value, the durations of these final contractions were always longer after immersion at the lower temperature. They concluded that metabolites not associated with muscle contraction accumulated more rapidly at higher temperatures.

Edwards et al. (1972) confirmed by a muscular biopsy technique that the resting levels of glycolytic intermediates were higher at 38.6 degrees C. than at 31.6

degrees C. However, taking into account these initial values they determined that the rate of glycolysis was greater in the heated muscle from the fact that the levels of accumulated metabolic by-products in the heated and non-heated muscle were similar at exhaustion despite the decreased endurance of the heated muscle. They suggested that the decreased endurance time was due to an inefficiency of ATP utilization by the myofibrils. The observation that at exhaustion ATP and Phosphocreatine levels were respectively 100% and 23% of those recorded before the contraction eliminated the possibility that energy supplies were limiting. However the study exhibited one obvious limitation in that the assumption was made that the intramuscular partial pressures of oxygen were unaltered by the increased resting metabolism. The possibility of this mechanism as a major cause for decreased endurance seems less likely however, in view of the fact that endurance was also decreased on successive contractions at 20 second intervals.

Dynamic Exercise

Most of the effects of increased temperature which could be beneficial to muscular performance are likely to be more effective under conditions of dynamic aerobic exercise.

While the results of studies using active warm-up are controversial (Bonner, 1972) the most frequently cited experiments using passive heating (Asmussen and Boje, 1945; Muido, 1946) have reported it to be beneficial to subsequent dynamic exercise. Despite the questionable reliability of the performance criteria used in these studies the dynamic phase of a "warm-up" before competitive athletic events has been largely based on these experimental results (Karpovich, 1968; Astrand and Rodahl, 1970).

Asmussen and Boje (1945) observed that passive heating by either shortwave diathermy or by hot showers had a beneficial effect on physical performance proportional to the recorded intramuscular temperature. Working with four trained athletes they found a decrease in the time required to complete a standardized exercise task on a bicycle ergometer by 3.9% to 7.6% following diathermy and 5.0% to 7.2% following hot showers. The intramuscular temperatures ranged from 38 - 39.4 degrees C after diathermy and 37.4 to 37.9 degrees C following hot showers.

Muido (1946) and Carlisle (1956) both reported improved swimming times following different forms of passive warm-up. Muido (1946) used hot baths, shortwave diathermy and turkish baths, and Carlisle (1956) used hot showers. However,

whereas Muido (1946) attributed the improved performance to an increased blood temperature, Carlisle (1956) reported that the improved performance in his experiments were not closely related to rectal temperature. He suggested that this finding supported the observation of Assmussen and Boje (1945) that the increased performance was related to increased muscular temperature.

Challenging the results of these studies are two investigations which measured the rate of onset of fatigue by the criterion of tension exerted during intermittent hand grip contractions. While Grose (1958) found a more rapid onset of fatigue in heated muscle, Sedgwick and Whalen (1964) found no significant effect of heating. Grose (1958) heated the muscles of the forearm by eight minutes immersion in water of 48 degrees C. Although Grose (1958) did not record intramuscular temperatures Sedgwick and Whalen (1964) reported maximum readings of 39.0 degrees C, 38.2 degrees C and 38.0 degrees C following five minutes of shortwave diathermy applied to the whole length of the forearm.

Kaijser (1970) investigated the effect of cooling on the dynamic forearm exercise on a hand ergometer. The intramuscular temperature was not recorded but the deep forearm vein temperature was lowered from 34.1 degrees C to

32.7 degrees C before an exhaustive exercise task. The decreased temperature caused a 33% reduction in the endurance time to exhaustion. It was also found that at lower temperatures the oxygen saturation in the deep venous blood at exhaustion was less whereas the lactate concentration did not differ consistently. This suggested that a decreased aerobic metabolic rate was the most likely explanation of the decreased endurance time.

Brooks et al. (1971) demonstrated an increased oxidative metabolism at higher intramuscular temperatures, while Horstman et al. (1976) reported an increased capacity for oxidative metabolism with improved oxygen supply to the muscle. These findings suggest that the anaerobic component of dynamic exercise could potentially be reduced. It is therefore surprising that no studies have been reported on the effects of passive heating on the ratio of anaerobic/aerobic energy expenditure. However, Watt and Hodgson (1975) found an increased oxygen consumption during a one minute run to exhaustion after an active warm-up consisting of walking 5.6 kph at 10% grade for 10 minutes. A rest period of 4 to 5 minutes between the warm-up and the run allowed some recovery of the accumulated fatigue effects from the warm-up. Intramuscular temperatures following the warm-up were not recorded but according to the results of

Saltin and Hermansen (1966), they can be estimated to be within the range of 37.5 - 39.0 degrees C. There would, however, have been considerable variation between subjects because the warm up was not graded relative to the subject's maximal oxygen uptake (Saltin and Hermansen, 1966). The higher oxygen consumption following warm-up was suggested to reflect a reduction in the anaerobic component of the exercise task, with a consequent improvement in work capacity.

CHAPTER III

MATERIALS, METHODS, AND PROCEDURES

MATERIAL

Subjects

Ten healthy male university students, ranging in age from 20 to 31 years volunteered as subjects. All ten subjects completed the strength experiments, nine completed the isometric experiments and eight completed the experiments on dynamic exercise. All subjects were right-handed and, although some exercised regularly, none were engaged in progressive resistance exercises.

Experimental Muscle Group

The elbow flexors were selected as the experimental muscle group for the following reasons: a) They are frequently used and are consequently relatively well trained. b) They are capable of dynamic exercise tasks. c) The monode diathermy applicator, preferred because of its capabilities in selectively increasing intramuscular temperature higher than the temperature of the superficial tissues (Lehman et al., 1969), cannot distribute heat over a

large muscle group. d) Subcutaneous layers of fat, which insulate and produce larger temperature gradients within a muscle (Lehmann et al., 1969), are relatively thin over this muscle group. The mid-bicep skinfold for the subjects of this experiment ranged from 2.7mm. to 4.4mm., with a mean of 3.3mm.

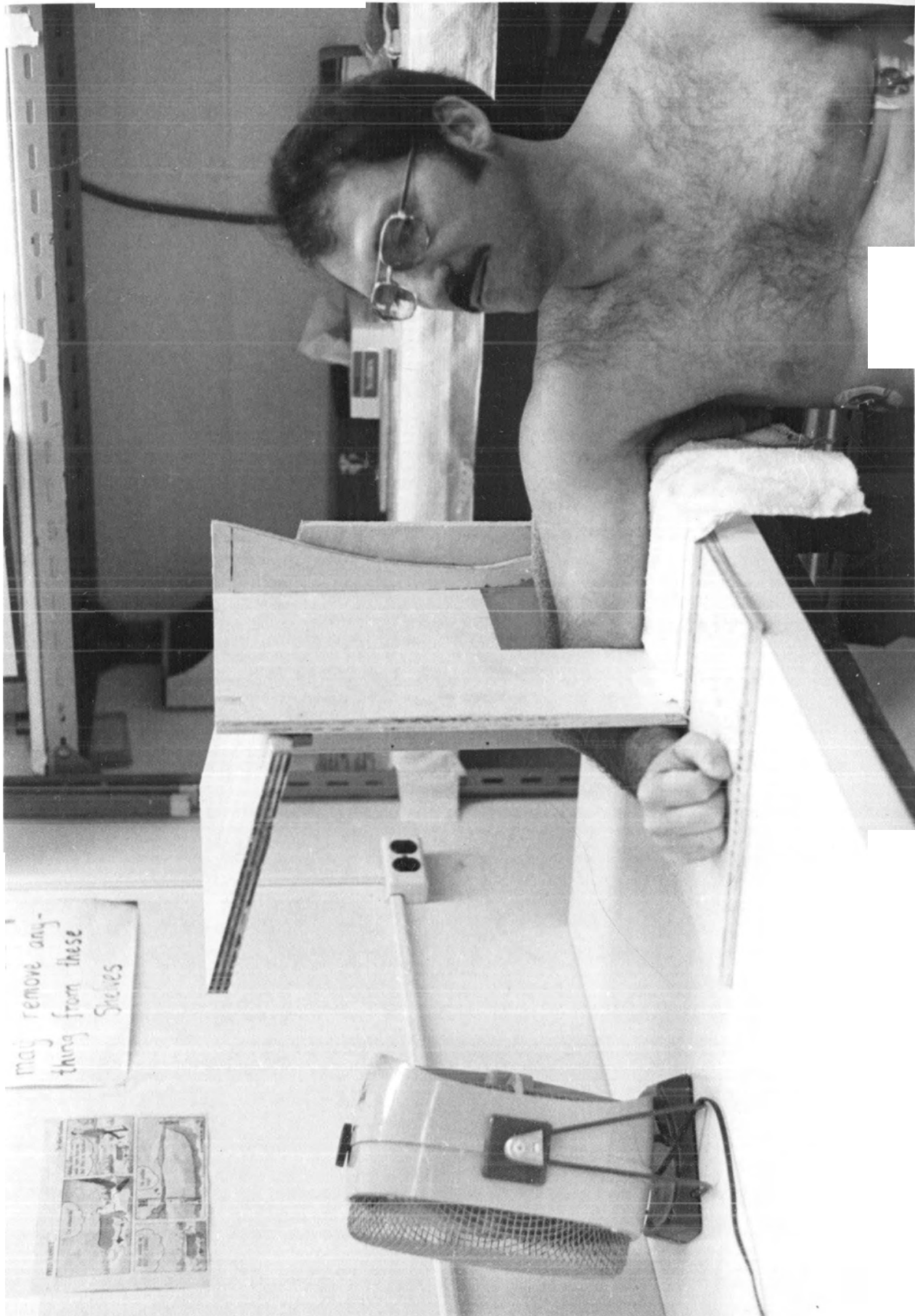
METHODS

Application of Shortwave Diathermy

A 27.12 MHz. shortwave diathermy apparatus (manufactured by Siemens Ltd.) with a maximum output of 400 watts was used to increase the intramuscular temperature. A monode applicator (manufactured by Siemens Ltd.), containing a compact induction coil was selected because of its capacity to produce the most intense field distribution of any induction coil applicator (Lehmann et al., 1968; Guy et al., 1974). This is especially so when it is positioned so that the side of the applicator with four elements is placed directly over the muscle such that the muscle length forms a cord of the circumference of the applicator (Lehman et al., 1968). This position was standardized for each subject by using a positioning guide for the arm (Figure 1), and standardizing the distance

FIGURE 1

The photograph shows the positioning of the arm for diathermy. The position was standardized on different experimental occasions by maintaining the lower arm in contact with the positioning apparatus with the hand in the prone position. The elbow was maintained at right angles by positioning the posterior aspect of the upper arm along another positioning board obscured by the arm in the photograph. An electric fan shown on the left was placed so that the air flow was channelled towards the area of application.



May remove anything from these Series



from the positioning guide to the centre of the applicator and the alignment of the applicator relative to the arm on each experimental session (Figure 2). The distance between the face of the applicator and the skin surface was 1.8 cm. and was standardized on each experimental session by temporarily inserting a wooden spacer. An electric fan was directed to the surface of the application area in order to reduce the temperature of the superficial tissues and to prevent the accumulation of sweat droplets which could induce a burn injury.

Positioning of Subject for Performance of Strength, Isometric and Dynamic Work Tasks

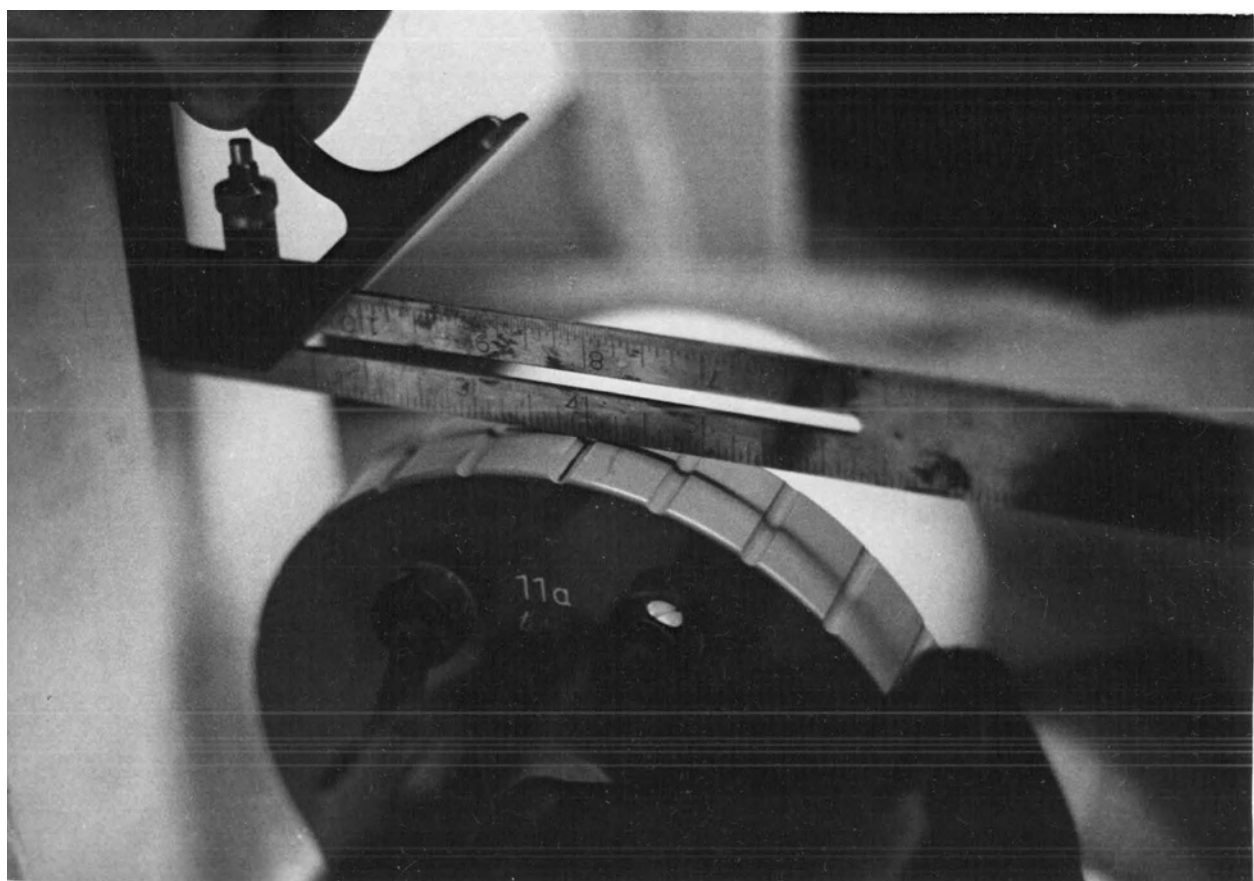
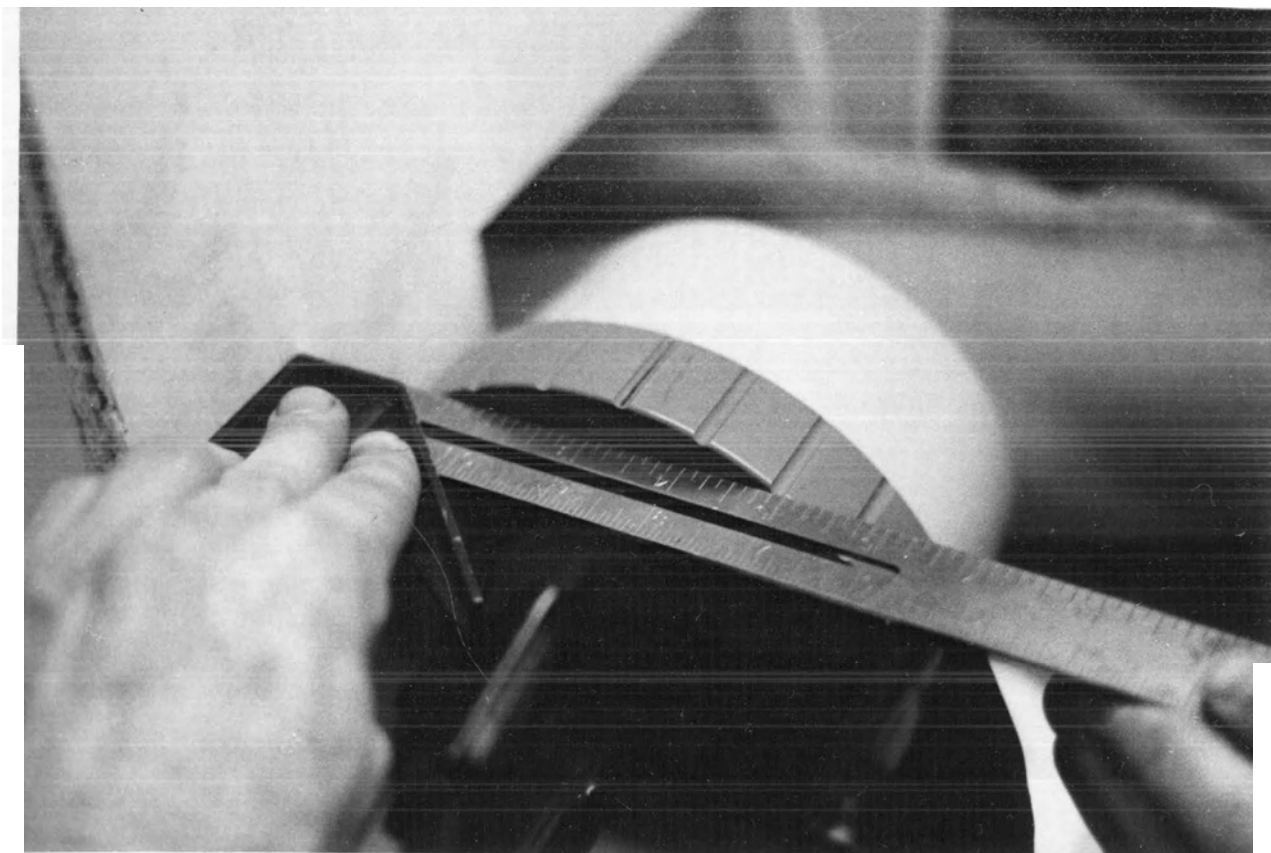
All performances of strength, sustained contractions and dynamic exercise were performed with the subject seated on a chair adjusted in height so that the thigh was parallel to the floor. The torso was stabilized by a support adjusted horizontally onto the anterior part of the subject's chest. The right humerus was maintained horizontal in the saggital plane. The support under the upper arm was adjusted so that the axis of rctation of the elbow joint was common with that of the beam which extended,

FIGURE 2

The photographs show how the position of the applicator was standardized on each experimental session by:

1) Measuring the distance from the positioning board for the lower arm (top photograph).

2) Aligning the back of the applicator at right angles to the positioning board for the lower arm (bottom photograph).



parallel to the lower arm. A handle which extended horizontally from the top of the beam was adjusted so that the hand could comfortably grasp it. Figure 3 shows the right arm in the experimental position. All adjustments were recorded for each subject and used to standardize his position on each experimental session.

The beam was capable of rotating through 30 to 110 degrees (lower values representing extension of the elbow) from a horizontal position in the saggital plane. The beam and a lever were both attached to a common axle (Figure 4). When the dynamic lever was locked in the horizontal position (Figure 5) the beam was vertical for strength and sustained isometric contractions. Dynamic exercise tasks were assigned by adjusting a weight on the dynamic lever. A bicycle pump buffered the fall of the lever as the arm was extended and both stops of the lever were padded with foam rubber.

Detection and Transduction of Torque

The torque on the beam was detected by four strain gauges (type WA-06-250BA-120, manufactured by Micro Measurements, Mich.) on the beam. The use of four gauges minimized the effect of ambient temperature (all four would be affected equally thereby increasing the stability) and

FIGURE 3

The photograph shows the experimental arm adjusted to the apparatus for measuring strength and isometric endurance. The handle and support for the upper arm were adjusted for individual differences between subjects, so that the elbow joint and the beam to which the handle is attached formed a common axis of rotation.

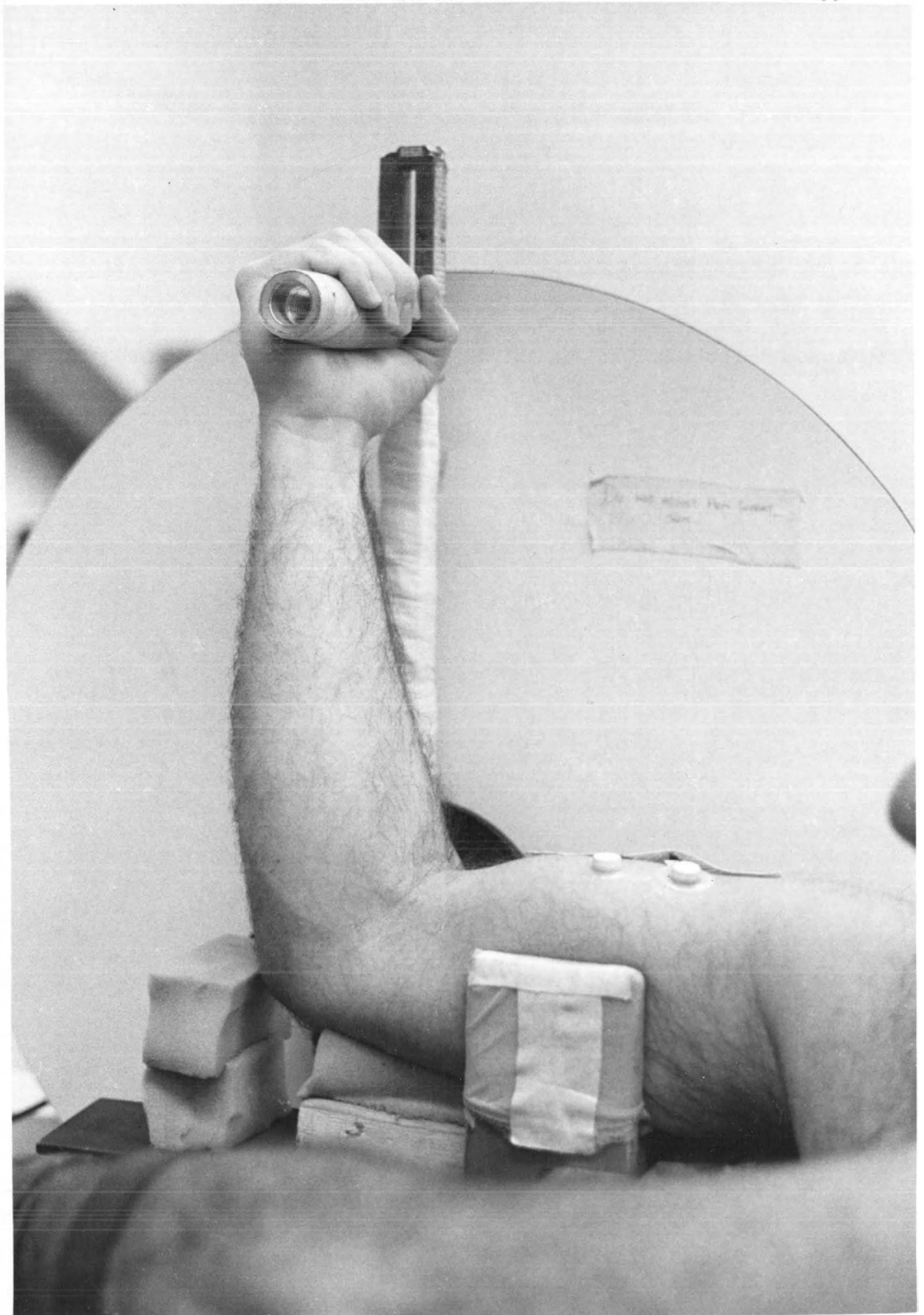


FIGURE 4

The photograph shows the beam being held on the left and the dynamic lever on the right connected by a common axle. This is the position of the apparatus during the dynamic exercise task when the elbow was flexed 110 degrees from a maximally extended position.



FIGURE 5

The photograph shows the dynamic lever maintained in the horizontal position so that the beam (not shown) on which work was performed, was in a vertical position. During dynamic exercise the stop maintaining the lever was removed which allowed movement up to the stop on the wall at the top of the photograph and down to another stop (not shown) on the floor.



allowed for greater resolution of the applied torque as two of the gauges were subject to strain while the other two were subject to compression.

The power supply to each transducer and amplification of its output voltage was controlled by separate strain gauge amplifiers (type AD6) mounted in a single integrated unit (type TE4, manufactured by TECA Corp., White Plains, N.Y.).

A series of known torques, exceeding the range expected in the experiments, were applied to the beam by hanging a number of different weights from the handle, with the beam fixed in a horizontal position. There was no detectable deviation from linearity between the applied torques and the output voltage.

Detection and Transduction of Myoelectric Signals

i) Electrodes

A bipolar electrode system was used throughout all isometric and dynamic experiments. The active electrodes were silver/silver chloride surface electrodes (manufactured by IMI., Newport Beach, Cal., U.S.A.) five

millimeters (5 mm.) in diameter, while an ECG plate electrode was used as the ground electrode on the volar aspect of the wrist. Low chloride gel (IMI Low Chloride Gel, manufactured by IMI., Newport Beach, Cal., U.S.A.) was used as electrode jelly between the skin and the electrodes.

In order to reduce impedance the electrode sites were shaved free of surface hair and loose skin, and cleaned with alcohol before the position for diathermy was assumed. The active electrodes were placed so that they formed a line parallel with the muscle fibres over the belly of biceps brachii.

The integrated unit (type TE4) which contained the strain gauge amplifiers, also incorporated a modular electromyographic system which was used to amplify the myoelectric signals. There were two amplifying modules. The myoelectrical activity was first amplified by a preamplifier placed close enough to the subject's right arm to reduce bad capacitance effects, and secondly, by the main amplifying unit (type AA6, manufactured by TECA Corp., White Plains, N.Y.). The main amplifier had its filter control set for a bandwidth from 32 - 1600 Hz. and its gain setting varied between subjects from 500 mV/cm. to 1 V/cm. division on the display scope of the TE4 system.

An electronic integrator (type I-6, manufactured by TECA Corp., White Plains, N.Y.) was incorporated as a module of the TE4 system, and used to rectify and integrate the myoelectric waveform. The time constant used for integration was 1.0 second.

The amplitude of a sine wave input (300 Hz) generated from a function generator (type 3310A, manufactured by Hewlett-Packard) was linearly related to output voltage from the integration, when amplified within the range of the display scope on the TE4 system.

Permanent Recording of Torque, Electromyogram (EMG) and Integrated Electromyogram (IEMG)

Two methods were employed to make permanent recordings of torque and electromyographic activity:

i) The output voltage for torque, EMG and IEMG from three respective channels of the TE4 system, separately powered three different galvanometers (type 7-326, manufactured by Bell-Howell, Basingstoke, U.K.) within an ultra-violet recording oscillograph (type 5-127, manufactured by Bell-Howell, Basingstoke, U.K.). Each galvanometer deflected an ultra-violet beam of light a

distance proportional to the input voltage.

ii) The output voltage from each channel of the TE4 system was separately recorded through three separate channels of an F.M. tape recorder (type 3096A, manufactured by Hewlett-Packard, Colorado, U.S.A.) onto low noise magnetic instrumentation tape (manufactured by Phillips, Vancouver, Can.) run at a speed of 38.1 cm/sec. The input and output voltages were adjusted within the linear response range of the amplifiers (full scale 0 - 2.5v) by using the input and output gain controls.

Analysis of the relationship between IEMG and force.

The force of each of the eight levels held for the determination of the force/IEMG relationship was calculated from the U/V trace, using the calibration data, and expressed as a percentage of each subject's MVC. The ultra-violet beam of light was directed onto U/V sensitive paper (type 2022, Linograph Direct Print Paper, manufactured by Eastman Kodak Corp., Rochester) run at a speed of 3.8 cm/sec.

Analysis of IEMG recorded during sustained isometric contractions

The analogue signal of IEMG on magnetic tape was transformed to digital data at a sampling rate of 25 samples per second by an analogue to digital converter (type ADC, manufactured by Digital Equipment Corp., Mass., U.S.A.). The digitized data was stored on magnetic tape (type DECTAPE, manufactured by Digital Equipment Corp., Mass., U.S.A.). The mean digital value of IEMG was calculated for one second every three seconds on a minicomputer (type PDP-8e, manufactured by Digital Equipment Corp., Mass., U.S.A.).

Recordings of Oxygen Uptake

Oxygen uptake during dynamic exercise was calculated from measurements of the expired air volume per minute of exercise, its temperature and gaseous composition. The subject inspired room air through a mouth piece attached to a valve which directed the expired air along a connecting tube to a mixing chamber (volume 5 litres). The gas leaving the mixing chamber was directed along another connecting tube to a volume meter and thermometer, where expired gas volume and temperature were recorded.

The composition of the expired gas was measured by a mass spectrometer (type Medspect 1, manufactured by Scientific Research Instrument Corp., Maryland, U.S.A.) which sampled mixed expired gas through a catheter as it left the mixing chamber.

Recordings of expired gas volume, temperature and composition were taken at the beginning and end of every completed minute of the 5.5 minute dynamic exercise task and at the beginning and end of the last minute of a five minute rest period before dynamic exercise.

Visual Feedback of Force and Electromyographic Activity

An oscilloscope, placed in front of the subject, was used to provide him with information regarding the generation of force by his elbow flexors. The beam of the unused input channel was used to indicate to each subject the magnitude of his maximal voluntary contraction (MVC) in the strength experiments and two thirds of MVC during the sustained contractions of the isometric and dynamic experiments.

The oscilloscope was also used to provide visual feedback of myoelectrical activity of biceps brachii during the dynamic exercise task, so that the subject could more effectively relax between contractions.

Calibration

i) Torque

Calibration of torque in each experiment was conducted by recording the difference in output voltage before and after a known weight was hung from the handle of the beam. The beam was fixed in a horizontal position to the floor and the handle was adjusted to the appropriate position determined for each subject.

ii) Mass Spectrometer

Calibration of the mass spectrometer was conducted before each of the experimental sessions of dynamic exercise. The total of the partial pressure readings of nitrogen, oxygen and carbon dioxide were adjusted to total the barometric pressure. The ratio of the three readings were then adjusted using a known gas mixture of nitrogen, oxygen and carbon dioxide. The settings were checked using a similar gas mixture of different ratios.

PROCEDURES

There were 10 experimental sessions each separated by a period of at least 7 days. The order and nature of each experimental session is outlined in Table 1. As far as possible the time of day for each experimental session remained unaltered for any one subject.

The purpose of the first session was to locate accurately the subject relative to the apparatus, to determine his initial value of MVC, to calculate his dynamic workload and to familiarize the subject with the experimental procedures of the study. Following the adjustment of the apparatus to the measurements of the subject he was instructed to maintain a fixed position of the wrist and to "pull as forcefully as possible on the handle without jerking." The verbal stimulus from the investigator during the contraction was the command, "one and pull." The beam of the unused channel on the oscilloscope (marker beam) was adjusted to mark the greatest output voltage, representing the subject's greatest MVC.

The subject was then prepared for recording EMG and the dynamic workload was adjusted so that when the beam was vertical in a stationary position (the position of greatest

TABLE I

An outline of the procedures for each of the ten experimental sessions. The three sessions on strength (sessions 2-4), isometric endurance (sessions 5-7), and dynamic exercise (sessions 8-10) were each randomized as described in the text.

Session	Nature of experiment
1	a) 3 determinations of MVC b) Dynamic work load c) First sustained isometric contraction at 2/3 MVC d) Two minutes recovery e) Second sustained isometric contraction at 2/3 MVC
2-4	a) 3 determinations of MVC b) Either: Application of diathermy to pain producing level followed by further application at one dosage level below this level OR: Positioning of the arm for application without application of diathermy c) 3 determinations of MVC
5-7	a) Either: 20 minutes of diathermy application at one dosage level below the pain producing level OR: 20 minutes of positioning for diathermy without application b) Placement of electrodes over belly of biceps brachii c) First sustained isometric contraction at 2/3 MVC d) Two minutes recovery e) Second sustained isometric contraction at 2/3 MVC f) Twenty minutes recovery g) Third sustained isometric contraction at 2/3 MVC h) Twelve minutes recovery i) Determination of Force/IEMG relationship
8-10	a) and b) as for sessions 5-7 c) Dynamic work load d) e) to i) as for sessions 5-7

torque), the torque recorded represented 15 - 20% of that generated during a MVC. A metronome was set at 80 beats/sec so that the subject could perform 40 dynamic concentric contractions every minute. Visual feedback of EMG activity was provided through the oscilloscope and the subject was encouraged to relax and eliminate EMG activity as the elbow was extended by the external load.

The dynamic exercise task was continued for 5.5 minutes. Ten seconds following the completion of dynamic exercise the subject sustained an isometric contraction at $2/3$ MVC until exhaustion. The marker beam on the oscilloscope had previously been lowered to represent $2/3$ of the output voltage generated from the torque of his MVC (determined previously). The force of the sustained contraction was maintained by attempting to hold the other beam on the oscilloscope, indicating torque, coincident with the marker beam. After a recovery period of 2 minutes a second isometric contraction was sustained.

The next nine experimental sessions will, for the sake of convenience, be considered as three groups of three relating respectively to the study of strength, isometric endurance and dynamic exercise.

Strength (Sessions 2 - 4)

On these experimental sessions the subject was placed in the experimental position for work and the marker beam on the oscilloscope was adjusted to represent the MVC recorded in the first experimental session. This value was retained even when the subject exceeded it. The subject performed 3 MVC's accompanied by verbal stimuli from the investigator. A two minute rest period followed each contraction.

Following the contractions the experimental position for diathermy was assumed. In one session (control) the subject sat for 20 minutes without diathermy and in the other two sessions (experimental) diathermy was applied. The order of the control session was randomized so that it was session 2 for three subjects, session 3 for four subjects, and session 4 for the other 3 subjects.

In the first session of application a middle range dosage level (dosage grade 3 on the diathermy apparatus) was initially selected. If no surface discomfort or deep pain developed within the first ten minutes of application the dosage was increased stepwise for ten minutes at each level. This procedure eventually developed deep pain in seven of the ten subjects. As soon as discomfort or pain developed

the dosage was lowered one level and continued for a further five minutes.

In the second session the initial dosage was first set at the pain or discomfort producing level. Despite the fact that all subjects were unaware of the dosage level six of the ten subjects experienced the same pain or discomfort reported in the first session. The dosage level was increased one level for the other two subjects and both experienced deep pain at this level. One of these two subjects had not experienced pain in the first session which means that eight of the ten subjects experienced this sensation. Diathermy application was continued, at a dosage immediately below the pain producing level, to complete 20 minutes of application. This dosage level was selected for all subsequent applications of diathermy in sessions relating to the study of isometric and dynamic exercise.

Immediately following the application, or following 20 minutes in the application position without diathermy, the subject resumed the experimental position for work and three further MVC's were performed, each separated in time by a 2 minute rest period. The time between the end of diathermy and the first contraction was approximately 10 seconds.

Isometric Endurance (Sessions 5 - 7)

Three contractions of $2/3$ MVC were sustained following both 20 minutes of positioning for diathermy without application (control) and 20 minutes of application (experimental). Five subjects repeated the session without diathermy application and the other four repeated the session with diathermy. The three sessions were performed in random order.

At the beginning of each session the skin over the right biceps brachii was prepared for electrode placement and the ground electrode was attached to the wrist. The active electrodes were attached in position immediately following diathermy and the subject assumed the experimental position for work. There was approximately 30 seconds of elapsed time between the end of diathermy application and the beginning of the first sustained contraction. The second sustained contraction began after 2 minutes of recovery and the third sustained contraction began after a further 20 minutes of recovery.

The subject rested for 12 minutes following the third contraction and then procedures began for determining the force/ IEMG relationship. The marker beam on the

oscilloscope was used to assign eight different forces within the range of the subject's MVC. The forces were assigned in randomized order every two minutes and were sustained for a period of time sufficient to allow the mean voltage of the IEMG to reach a steady level. The investigator was careful to ensure that the force was generated smoothly to the assigned level. Preliminary experiments had shown that the level of IEMG recorded from this muscle was lower when force was rapidly generated. This effect was possibly due to a reduction in the maximal stimulation frequency with more rapid contractions (Milner et al., 1973).

Dynamic Exercise (Sessions 8 - 10)

Five minutes and thirty seconds of dynamic exercise were completed following both 20 minutes of positioning for diathermy without application (control) and 20 minutes of application (experimental). Four subjects repeated the session without diathermy application and the other four repeated the session with diathermy. The order of performance for each experimental session was randomized. The procedures for application of diathermy and placement of electrodes are identical to those of the isometric experiments. The first sustained isometric contraction

followed the dynamic exercise task by precisely 10 seconds. The timing of the second and third contraction and timing and procedures for the determination of the force/IEMG relationship were identical to that described for the the isometric experiments.

CHAPTER IV

RESULTS

Strength

Initially each value of force applied at the handle was expressed as a percentage of the average force of all contractions performed before positioning for diathermy on all three experimental sessions. The mean of the percentage values of the first contractions on the two sessions with diathermy yielded the single percentage value for the first contraction with diathermy. The percentage values of the second and third contractions before, and the three contractions after diathermy were obtained in a similar manner. The mean values and standard deviations of the three contractions before and after both positioning with diathermy and positioning without diathermy are shown in Table Ia. A paired correlative 2-tailed t-test determined the significance of differences between these twelve values, seen in Table Ib.

It is apparent that the maximal force produced in the first and second contractions after diathermy was significantly less ($p < 0.01$ and $p < 0.05$ respectively) than all six contractions before diathermy and before positioning

TABLE Ia

Effects of diathermy and positioning without diathermy on strength. Values are expressed as a percentage of the average force recorded before diathermy and positioning without diathermy. Means and standard deviations before and after diathermy were calculated from the averaged values of two experimental sessions whereas the means and standard deviations before and after positioning without diathermy were calculated from one experimental session (n=10).

Conditions	Contraction Number	No Diathermy (34 - 37°C)		Diathermy		
		Mean	S.D.	Mean	S.D.	Estimated Temp. °C
BEFORE POSITIONING	1	100.43	2.35	99.52	2.56	34-37
	2	99.57	1.65	100.17	1.71	34-37
	3	100.33	2.04	99.98	1.83	34-37
AFTER POSITIONING	1	97.49	3.08	95.61	3.31	41
	2	99.84	1.76	96.64	3.65	38.5-39.5
	3	98.33	2.27	98.44	1.85	38-39

TABLE Ib

Differences between the means of strength values before and after diathermy and before and after positioning without diathermy. Positive values indicate that the mean strength in the column condition is greater than that in the row condition. Significant differences are marked (*).

Time Conditions and Contraction No.	B E F O R E						A F T E R					
	No Diathermy			Diathermy			No Diathermy			Diathermy		
	1	2	3	1	2	3	1	2	3	1	2	
A F T E R	3	1.99	1.13	1.89*	1.08	1.73	1.54	-0.95	1.4	-0.11	-2.83*	-1.8
	2	3.80*	2.93*	3.70*	2.89*	3.54*	3.34*	0.85	3.2*	1.70	-1.03	
	1	4.82**	3.96**	4.72**	3.91**	4.56**	4.37**	1.88	4.23*	2.72		
B E F O R E	3	2.10	1.23	2.00	1.19	1.84*	1.65	-0.85	1.50			
	2	0.60	-0.27	0.49	-0.31	0.34	0.14	-2.35*				
	1	2.94*	2.08	2.84*	2.03	2.68	2.49					
B E F O R E	3	-0.45	-0.41	0.35	-0.46	0.19						
	2	-0.26	-0.61	0.16	-0.65							
	1	-0.91	3.04	0.81								
No Diathermy	3	0.1	-0.76									
	2	0.86										

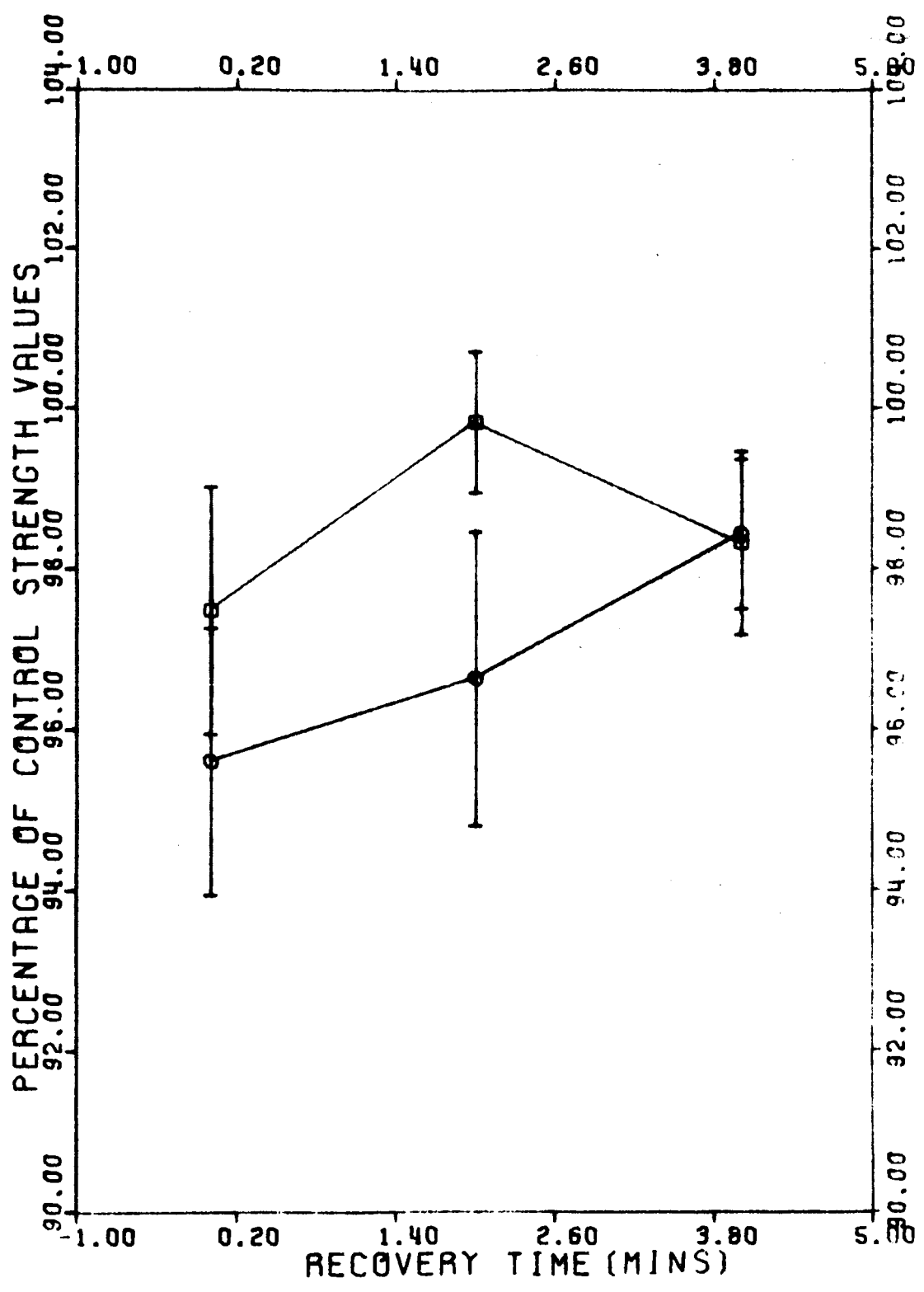
** p < .01
* p < .05

without diathermy. Although the significance of the difference was greater for the first contraction there was no significant difference between the first two contractions after diathermy. The first contraction after positioning without diathermy was significantly ($p < 0.05$) lower than the first and third contractions before positioning without diathermy. The temporary nature of this small impairment to strength after positioning without diathermy is reflected by a significant increase of strength between the first and second contractions after positioning without diathermy. This relationship is seen in Figure 1a which compares the percentage force for the three contractions after diathermy with the three contractions after positioning without diathermy.

Although the third contraction after diathermy is significantly lower ($p < 0.05$) than the third contraction before positioning without diathermy, it is still significantly greater than the first contraction following diathermy. The third contraction after positioning without diathermy was significantly lower ($p < 0.05$) than the second contraction before diathermy.

FIGURE 1a

The effects of diathermy on strength as a function of the time following diathermy (shown by circles) and positioning without diathermy (shown by squares) (n=10). This time is referred to as recovery time to depict recovery from increased temperature and, in the case of the second two contractions, recovery from the combined effects of heat and the previous maximal contraction(s). Strength is expressed as a percentage of the mean of all contractions so that 100% represents the mean strength in an unfatigued condition.



Isometric Endurance

The endurance times were standardized by expressing each as a percentage of the greatest endurance time for that subject, irrespective of the conditions under which the greatest endurance time was obtained. As each subject had two trials under either the experimental or control conditions the value of endurance time for that subject was obtained as the mean of the repeated trials. Six sets of data were obtained from the endurance times of three sustained contractions which followed either diathermy or positioning without diathermy at intervals of 0.5, 2.5 and 20.5 minutes. The mean endurance times, expressed as a percentage of the greatest endurance time, and pooled over subjects are tabulated in Table IIa and plotted against time after cessation of positioning for diathermy (recovery time) in Figure 2b.

A paired correlative 2-tailed t-test was used to determine the significance of the difference between values of percentage endurance time (Table IIb). The percentage endurance time of the first sustained contraction immediately following diathermy was lower (6.41%; $p < 0.01$) than the first sustained contraction without diathermy. No other significant differences were found between experimental and corresponding control endurance times.

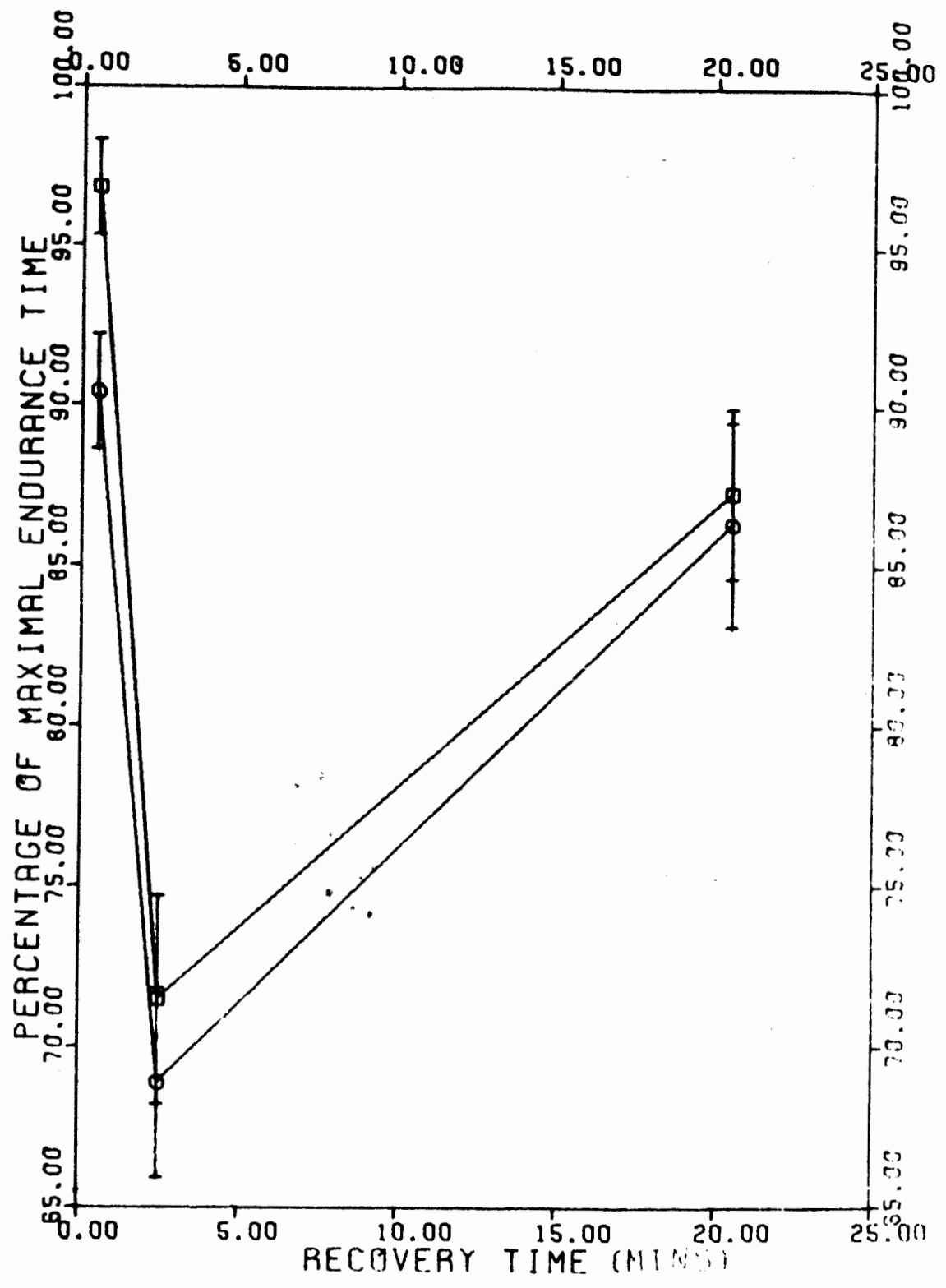
TABLE IIa

Effects of diathermy and positioning without diathermy on endurance for the first, second and third sustained isometric contractions. Values shown are means and standard deviations expressed as a percentage of the greatest endurance time for each subject (n=9). Estimated values of intramuscular temperature were extrapolated from the data of Lehmann et al. (1974). The intramuscular temperature for the third contraction was estimated to be at the upper range of resting muscle temperature since blood flow would still be elevated (Downey et al., 1970).

Contraction Number	No Diathermy (34 - 37°C)		Diathermy		
	Raw Values		Raw Values		Estimated Temp. °C
	Mean	S.D.	Mean	S.D.	
1	96.82	3.00	90.41	3.57	41
2	71.47	6.47	68.88	5.89	38.5-39.5
3	87.30	5.32	86.33	6.37	34-37

FIGURE 2a

The effects of diathermy (shown by circles) and positioning without diathermy (shown by squares) on isometric endurance as a function of the time following application ($n = 9$). This time is referred to as recovery time to depict recovery from increased temperature and, in the case of the second two contractions, its combined effect with previous isometric work.



The endurance time of the second sustained contraction was lower than the first and third contractions in both experimental and control conditions. However, the endurance time of the first sustained contraction was significantly greater than that of the third contraction only when positioning without diathermy preceded the contractions.

The relationship between force and IEMG was found to be non-linear (Figure 2b), and was fitted by a polynomial of the form $\text{Force} = \text{Constant} + A(\text{IEMG}) + B(\text{IEMG})^2 + C(\text{IEMG})^3$. This equation was used to calculate the force equivalent of the IEMG (FIEMG) recorded for one second every three seconds during each of the sustained isometric contractions. Although IEMG with respect to time often demonstrated some deviation from linearity, its expression as FIEMG showed an approximately linear relationship with respect to time (Figure 2c). The rate of increase was found to be inversely proportional to the endurance time of the contraction (Figure 2d). However, the FIEMG of one subject showed an initial increase and then a decrease during all three contractions. The data of this subject was excluded from pooled data analysis as it deviated considerably from that of all other subjects. However, consideration of the data of this aberrant subject is discussed in detail in Chapter V.

TABLE IIb

Differences between means of percentage endurance times of the first, second and third isometric contractions. Positive values indicate that the mean endurance time in the column condition was greater than that in the row condition. Significant values are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	10.49***	-14.86***	0.97	4.08*	*** -17.45
	2	27.94***	2.59	18.42***	21.53***	
	1	6.41**	-18.94***	-3.1		
No Diathermy	3	9.52***	-15.83**			
	2	25.35***				

*** p \leq .005

** p \leq .01

* p \leq .05

FIGURE 2b

An example of the relationship between IEMG recorded from biceps brachii and force of muscle contraction. The IEMG is expressed in arbitrary units and plotted with respect to the percentage of the subject's maximal voluntary contraction.

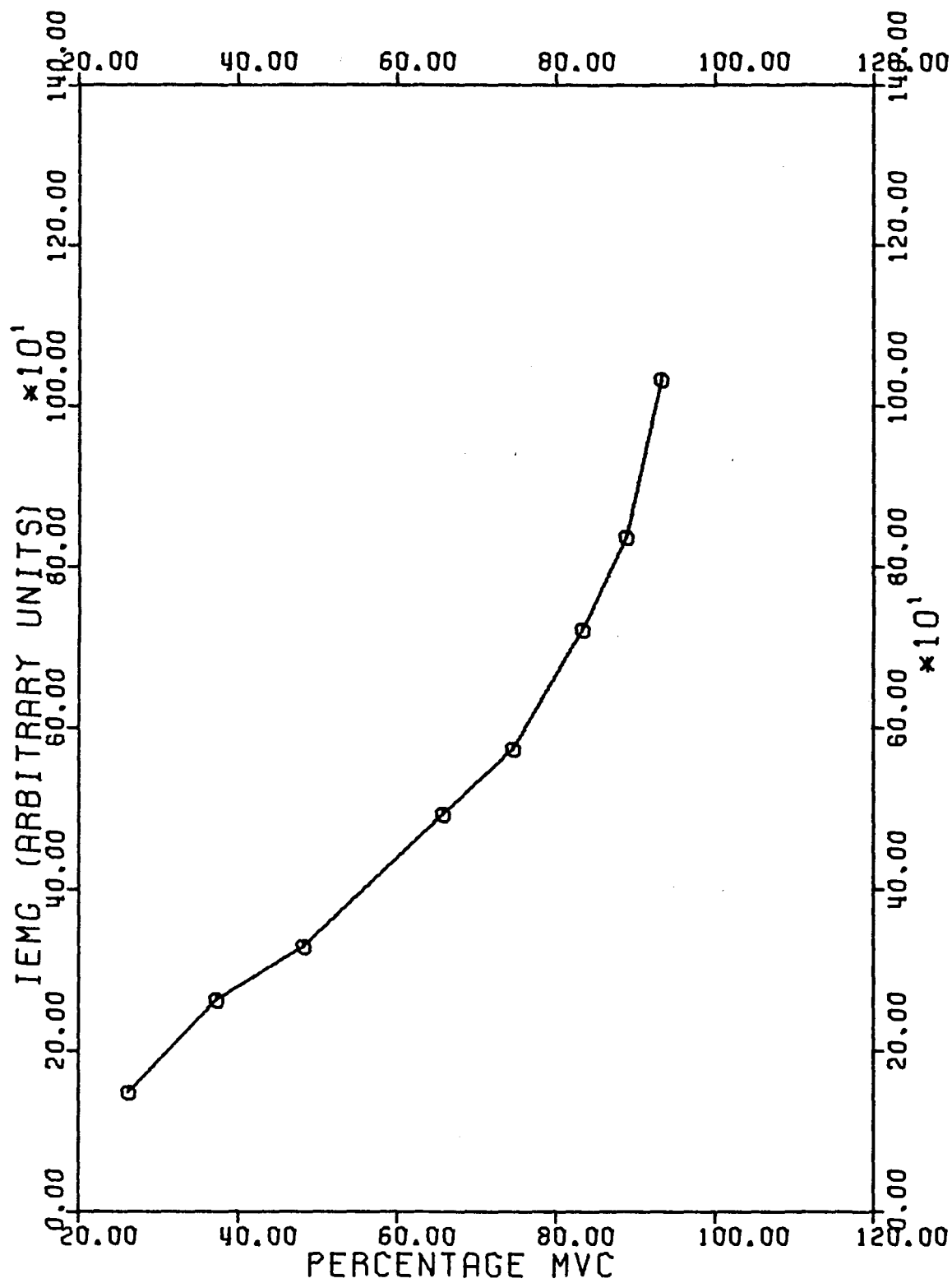


FIGURE 2c

An example of the effect of expressing IEMG as its force equivalent (FIEMG) on the nature of the increasing myoelectrical activity with respect to time. The IEMG values (shown by squares) were recorded from biceps brachii. The FIEMG values (shown by circles) were calculated from the recorded IEMG values and the IEMG/force relationship shown in Figure 2b. The IEMG is expressed in arbitrary units and the FIEMG as a percentage of its maximal value. Both values are plotted with respect to the subject's endurance time.

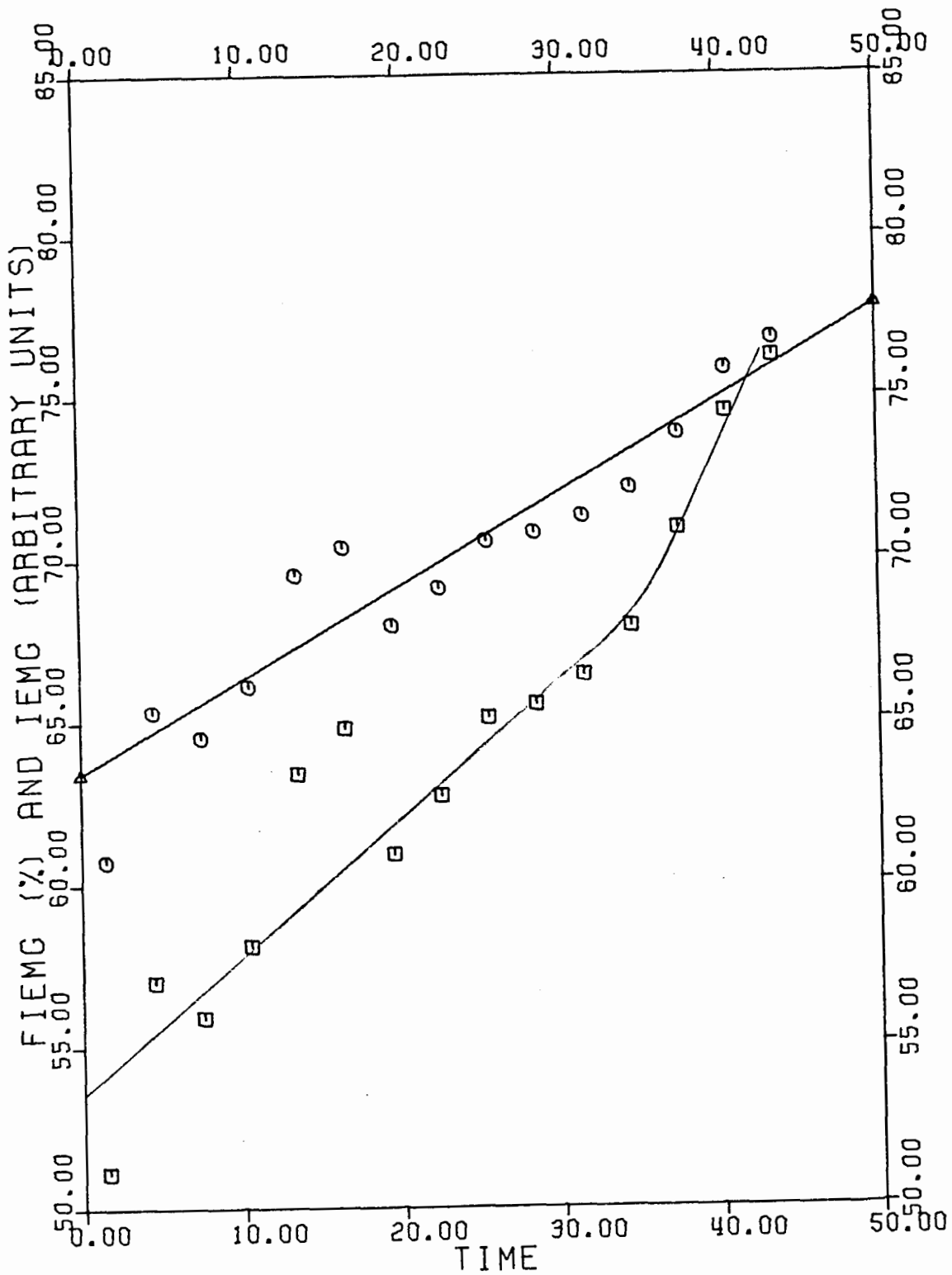
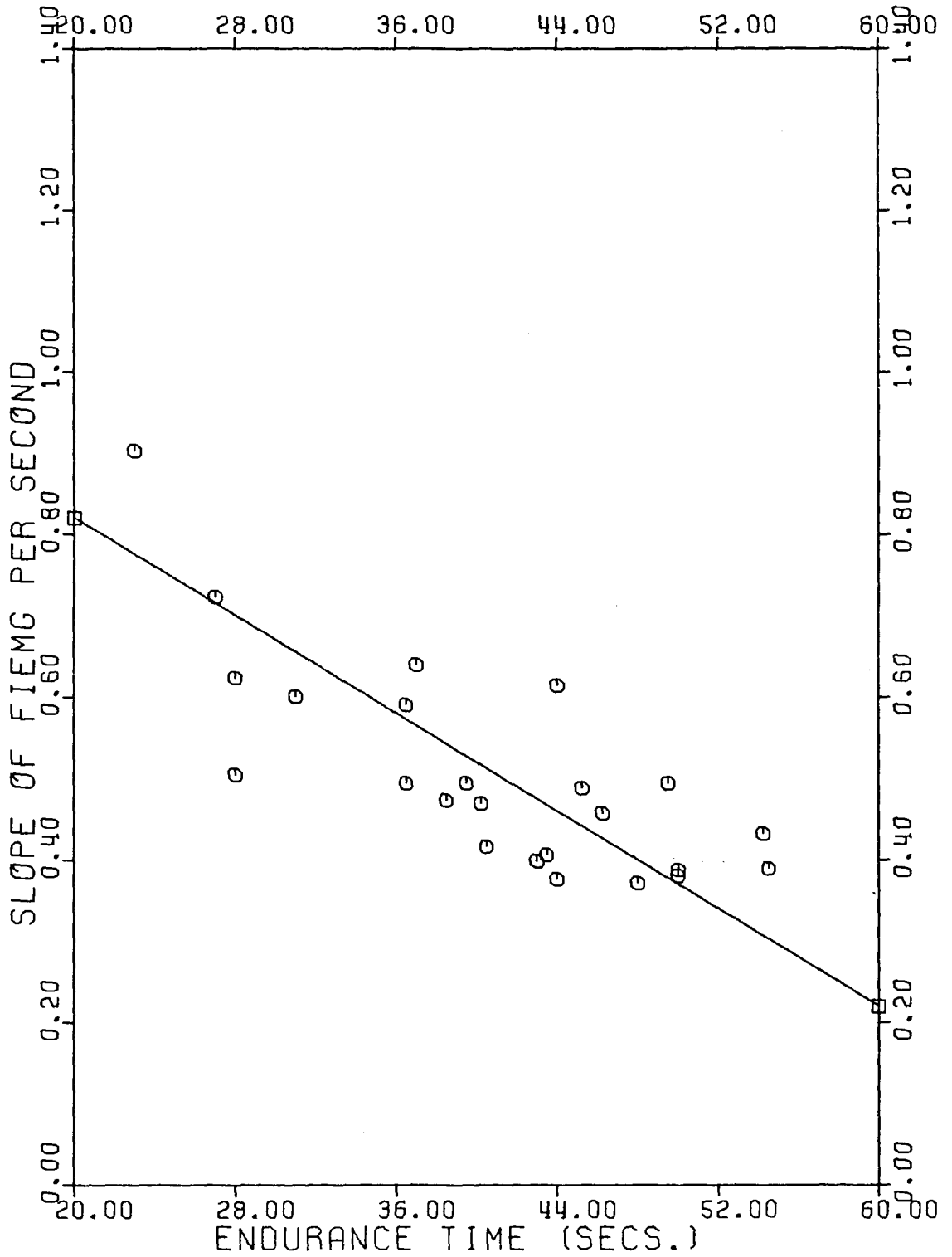


FIGURE 2d

The relationship between the rate at which FIEMG increased and endurance time of individual subjects for the first, second and third isometric contractions after positioning without diathermy. These contractions demonstrate that a more rapid increase in FIEMG generally leads to a reduced contraction time. The correlation coefficient of the relationship was -0.71 ($n=24$).



Linear regressions of FIEMG with respect to both absolute time and percentage of contraction time were calculated for each of the three contractions after both diathermy and positioning without diathermy. Where subjects repeated trials, the FIEMG data from both trials were used to calculate the single linear regression for each condition. The mean correlation coefficients of the linear regressions for the first, second and third contractions was respectively 0.906, 0.921 and 0.918 after positioning without diathermy, and 0.884, 0.909 and 0.871 after diathermy. The mean correlation coefficients between FIEMG values obtained from repeated trials under the same experimental conditions were respectively 0.845, 0.794 and 0.810 for the first, second and third contractions.

Five categories of FIEMG data were analysed from the linear regression treatment. The pooled mean values and standard deviations of the slope of FIEMG's with respect to both time (category 1) and percentage endurance time (category 2) are seen in Table IIc. The pooled mean values and standard deviations of average FIEMG (category 3) and intercepts of FIEMG's on the axes representing zero time (category 4) and time of exhaustion (category 5) are seen in Table IIId.

TABLE IIc

Effects of diathermy and positioning without diathermy on the slope of FIEMG with respect to both time and percentage of contraction time for the first, second and third sustained isometric contractions. Values are expressed as the mean and standard deviation of all means (n=9) calculated for each subject. The mean correlation coefficients of the linear regressions are shown for each contraction. Estimated values of intramuscular temperature were extrapolated from the data of Lehmann et al. (1974).

Contraction Number	No Diathermy (32-37°C)						Diathermy					
	Slope respect to time		Slope respect to % contraction		Mean cor- co- efficient	Mean cor- co- efficient	Slope respect to time		Slope respect to % contraction		Mean cor- co- efficient	Estimated Temp. °C
	Mean	S.D.	Mean	S.D.			Mean	S.D.	Mean	S.D.		
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean cor- co- efficient	Estimated Temp. °C
1	0.4696	0.0945	0.2136	0.0448	0.906	0.3820	0.1337	0.1365	0.0341	0.884	41	
2	0.5896	0.1750	0.1837	0.0345	0.921	0.5321	0.1615	0.1574	0.0319	0.909	38.5-39.5	
3	0.4585	0.0912	0.1815	0.0403	0.918	0.4912	0.1608	0.1737	0.0411	0.871	37	

TABLE IID

Effects of diathermy and positioning without diathermy on the mean FIEMG and the raw and corrected values (diathermy only) of the intercept of the FIEMG on the axis representing zero time for the first, second and third isometric contractions. Values are expressed as the mean and standard deviation of means (n=9) calculated for each subject. Estimated values of intramuscular temperature for the first and second contraction after diathermy were extrapolated from the data of Lehmann et al., (1974). The third contraction after diathermy was estimated to be at the higher range of resting values, since blood flow would still be elevated at this time (Downey et al., 1970).

Contraction Number	No Diathermy (32-37°C)						Diathermy						Estimated Temp. °C		
	Mean FIEMG		Intercept FIEMG (exhaustion)		Intercept FIEMG (zero time)		Mean FIEMG		Intercept FIEMG (exhaustion)		Intercept FIEMG (zero time)			Corrected Intercept FIEMG (zero time)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.		Mean	S.D.
1	71.64	2.20	82.45	3.04	60.84	2.56	69.57	1.97	76.39	2.35	62.74	2.84	64.82	3.44	41
2	74.21	1.78	84.56	1.54	63.88	3.62	74.20	3.25	82.08	3.84	66.33	3.39	66.35	2.21	38.5-39.5
3	72.09	1.72	81.92	2.65	62.26	3.39	72.81	1.61	82.61	5.00	63.02	2.63	62.30	4.63	37

The intercept of FIEMG on the axis corresponding to zero time of the first contraction after diathermy was corrected for the depressive effect of temperature on the recorded myoelectrical activity. This was achieved by normalizing the mean FIEMG of the first contraction after diathermy to the mean FIEMG of the first contraction after positioning without diathermy for each subject, and then reassessing the intercept. The result of this analysis demonstrated that the corrected intercept of FIEMG on the axis corresponding to zero time was greater following diathermy (3.19%; $p < .005$). A paired correlative t-test was used to determine the significance of the differences between means of the first, second and third contractions following both diathermy and positioning without diathermy within each of these five categories of data. These differences and their statistical significance are seen in Tables IIe, II f, II g, II h and III i respectively for mean FIEMG, intercept of FIEMG's at zero time, intercept of FIEMG's at the time of exhaustion, slope of FIEMG's with respect to time and with respect to percentage of contraction time. Figure 2e shows FIEMG values with respect to percentage of endurance time recorded during the first contraction following diathermy and the first contraction after positioning without diathermy. The plotted linear regressions demonstrate the reduced slope of the FIEMG with respect to percentage of endurance time

TABLE IIe

Differences between mean FIEMG for the first, second and third sustained isometric contractions (n=8). Positive values indicate that the mean FIEMG in the column condition was greater than that in the row condition. Significant values are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	-1.17	1.41	-0.72	-3.25**	1.39
	2	-2.56	0.01	-2.11	-4.64**	
	1	2.07	4.65**	2.52*		
No Diathermy	3	-0.45	2.12			
	2	-2.58				

** $p < .01$

* $p < .05$

TABLE II f

Differences between mean intercepts of FIEMG on the axis representing zero time for the first, second and third sustained isometric contractions (n=8). Positive values indicate that the mean intercept in the column condition was greater than that in the row condition. The difference between intercepts following normalization of FIEMG is indicated for the first contraction after diathermy, and after positioning without diathermy. This procedure did not affect the significance between experimental and control values for the other two contractions. Significant values are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	-2.18	0.86	-0.75	-0.27	3.32
	2	-5.49**	-2.46	-4.07*	-3.59*	
	1	-1.90+	1.13	-0.48		
No Diathermy	3	-1.42	1.62			
	2	-3.04				

+ = -3.98*** when the average FIEMG of the first contraction after diathermy is normalized to the average FIEMG of the first contraction after positioning without diathermy.

*** $p < .005$

** $p < .01$

* $p < .05$

TABLE IIg

Differences between the mean intercept of FIEMG'S on the axis representing the time of exhaustion for the first, second and third isometric contractions (n=8). Positive values indicate that the mean intercept in the column condition was greater than that in the row condition. Significant values are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	-0.17	1.95	-0.69	-6.22***	-0.53
	2	0.37	2.48	-0.15	-5.68	
	1	6.05***	8.17***	5.53***		
No Diathermy	3	0.52	2.64*			
	2	-2.11				

*** $p < .005$

** $p < .01$

* $p < .05$

TABLE IIh

Differences between mean slopes of FIEMG calculated as a function of the time for the first, second and third isometric contractions (n=8). Positive values indicate that the mean slope in the column condition was greater than that in the row condition. Significant values are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	-0.0216	0.0694	-0.0327	-0.1092*	0.0409
	2	-0.0625	0.0285	-0.0736	-0.1501*	
	1	0.0876*	0.1786*	0.0765		
No Diathermy	3	0.0111	0.1021*			
	2	-0.1200*				

* $p < .05$

TABLE III

Differences between mean slopes of FIEMG calculated as a function of the percentage of endurance time for the first, second and third isometric contractions (n=8). Positive values indicate that the mean slope in the column condition was greater than that in the row condition. Significant values are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	0.0142*	0.01	0.0079	*** -0.0372	0.0162
	2	0.0562**	0.0263	0.0241	-0.0209	
	1	0.0772***	0.0472*	0.0451*		
No Diathermy	3	0.0321	0.0022			
	2	0.0299*				

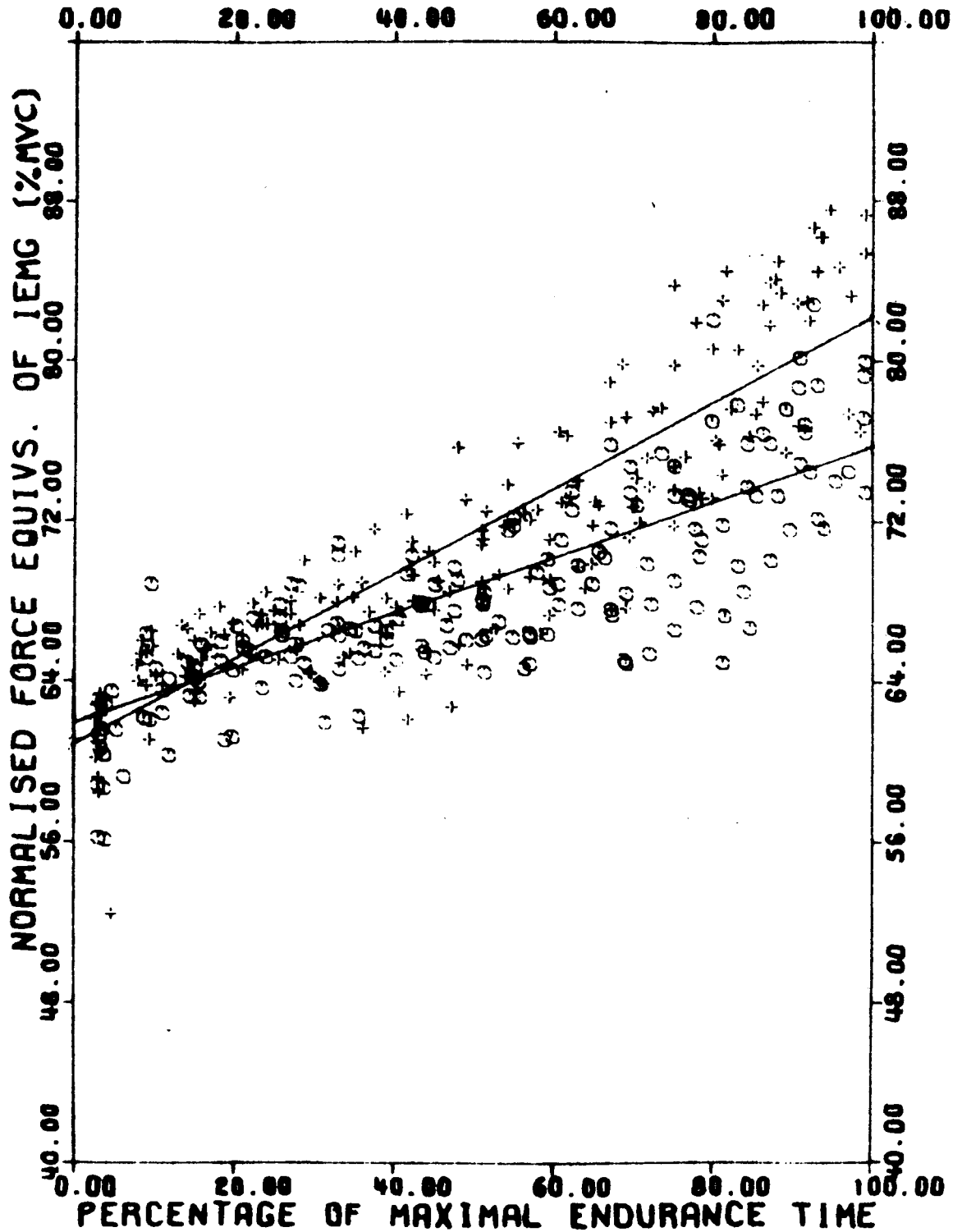
*** $p < .005$

** $p < .01$

* $p < .05$

FIGURE 2e

The effects of increased intramuscular temperature on myoelectrical activity recorded from biceps brachii during the first sustained isometric contraction. The values shown are force equivalents of IEMG (FIEMG) plotted against percentage of endurance time after diathermy (shown by circles) and after no diathermy (shown by crosses), (n=8).



following diathermy. For the purposes of display (and not analysis) the mean FIEMG values obtained both with and without diathermy were normalized for each subject so that the intercept of FIEMG on the axis representing zero time corresponded with the mean pooled value for the group.

Dynamic Exercise

The endurance times were standardized by expressing each as a percentage of the greatest endurance time recorded in the isometric experiments for each subject. As each subject had two trials under either the experimental or control conditions, the value of the endurance time for that subject was obtained as the mean of the repeated trials. Six sets of data were obtained from the endurance times of three sustained contractions which followed either diathermy and the dynamic work task, at intervals of 10 seconds, 2 minutes 10 seconds and 20 minutes 10 seconds. The mean values for percentage endurance time are seen in Table IIIa.

A paired correlative 2-tailed t-test was used to determine the significance of the difference between these endurance values. The percentage endurance time of the first sustained contraction immediately following the dynamic work task after diathermy was lower (5.63%, $p < 0.05$)

TABLE IIIa

Effects of diathermy and positioning without diathermy followed by 5.5 minutes of dynamic work on values of endurance time for the first, second and third sustained isometric contractions. Values shown are means and standard deviations expressed as a percentage of the greatest endurance time recorded in the isometric experiments for each subject (n=8). Significant values are marked (*).

Contraction Number	No Diathermy		Diathermy	
	Raw Values		Raw Values	
	Mean	S.D.	Mean	S.D.
1	41.91	15.38	36.28	21.11
2	59.62	7.23	59.42	9.29
3	83.29	6.34	81.78	8.08

than that of the first sustained contraction following dynamic work without diathermy. The percentage endurance times of the first, second and third contractions were significantly different from each other in both the experimental and control situation. All differences of percentage endurance time along with their statistical significance are seen in Table IIIb. Figure 3a shows the mean experimental and control percentage endurance times plotted against time after the dynamic work task (recovery time).

The percentage endurance values of the first sustained contraction were analysed further for individual subjects. The impairment following diathermy was measured indirectly by determining the difference between the first sustained contractions in the experimental and control situation for each subject following dynamic work. The dynamic work load was assessed by the percentage of endurance time sustained during the first isometric contraction following positioning without diathermy and the dynamic work task. It was assumed that a shorter isometric endurance time indicated that the preceding dynamic workload was more demanding. It can be seen that the greater impairment from the application of diathermy was directly related to the fatigue induced by the dynamic workload (Figure 3b).

TABLE IIIb

Differences between means of percentage values of endurance time for the first, second and third sustained contractions following dynamic work after diathermy and positioning without diathermy. Positive values indicate that the mean endurance time in the column condition was greater than that in the row condition. Significant differences are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	-39.87***	*** -22.16	1.50	-45.5*** ***	*** -22.37
	2	-17.51*	0.20	23.87***	-24.08	
	1	5.63*	23.34*	47.01***		
No Diathermy	3	-41.38***	*** -23.67			
	2	-17.71*				

*** $p < .005$

* $p < .05$

FIGURE 3a

The effect of diathermy on dynamic work. The values shown are the percentage endurance times for three isometric contractions after a standardized dynamic work task. The recovery time against which the values are plotted indicates the time after either diathermy (shown by circles) or positioning without diathermy (shown by squares) and the dynamic work task (n=8).

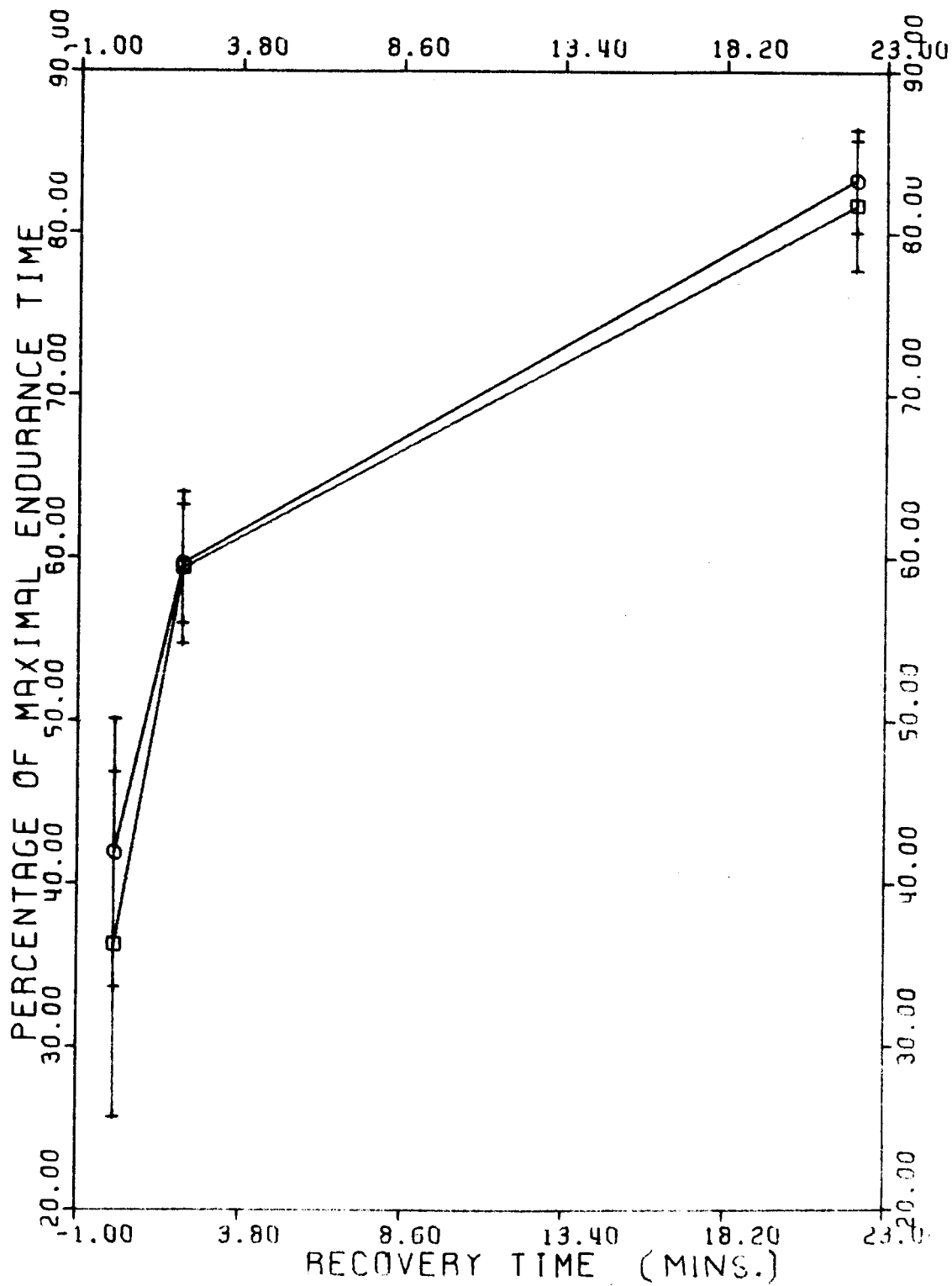
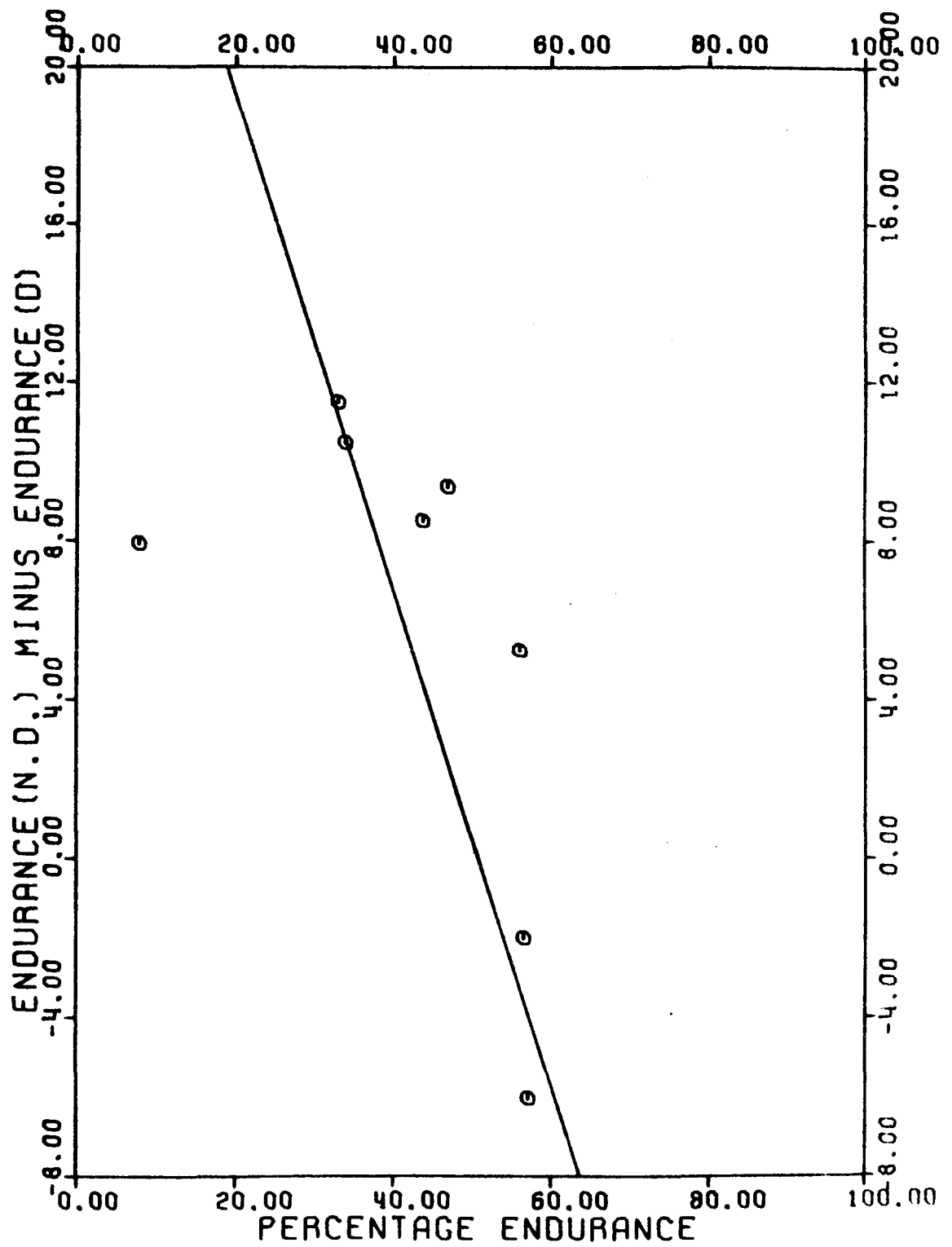


FIGURE 3b

The relationship between the impairment of work following diathermy and the extent to which the dynamic workload induced fatigue for individual subjects. The difference between percentage endurance of the heated and non-heated muscle for individual subjects is plotted against the endurance time of the first sustained contraction following dynamic work in the non-heated condition. The correlation coefficient of the relationship is -0.59 ($p < 0.1$)



The non-linear relationship between force and IFMG was similar to that found from the isometric experiments. This data was treated and used to calculate the FIEMG which was found to approximate a linear increase with respect to time for all subjects. Linear regressions of FIEMG with respect to both time and percentage of contraction time were calculated for each of the three sustained contractions in both the experimental and control situation. Where subjects repeated trials, the FIEMG data from both trials was used to calculate the single linear regression of FIEMG for each condition.

Five categories of FIEMG data were analysed from the linear regression treatment. The pooled mean values and standard deviations of the slope of FIEMG's with respect to both time (category 1) and percentage endurance time (category 2) are seen in Table IIIc. The pooled mean values and standard deviations of average FIEMG (category 3) and intercepts of FIEMG's on the axes representing zero time (category 4) and time of exhaustion (category 5) are seen in Table IIIId.

A paired correlative t-test was used to determine the significance of the differences between means of the three contractions following the experimental and control

TABLE IIIc

Effect of diathermy and dynamic work on means and standard deviations (S.D.) for the slope of FIEMG as a function of time and as a function of percentage of contraction time of the first, second and third sustained contractions after dynamic work (n=7 for the first contraction; n=8 for the second and third contractions).

Contraction No.	No Diathermy				Diathermy			
	Slope FIEMG (time)		Slope FIEMG (% Contr.Time)		Slope FIEMG (time)		Slope FIEMG (% Contr.Time)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	1.349	0.921	0.1489	0.0395	1.210	1.358	0.1450	0.0523
2	0.6187	0.311	0.1411	0.0476	0.681	0.206	0.1596	0.0589
3	0.4677	0.105	0.1657	0.0427	0.556	0.084	0.1819	0.0418

TABLE IIIId

Effect of diathermy and dynamic work on means and standard deviations (S.D.) of average FIEMG and intercept of FIEMG on the axes representing zero time and time of exhaustion for the first, second and third sustained contractions after dynamic work (n=7 for the first contraction; n=8 for the second and third contractions).

Contraction Number	No Diathermy						Diathermy					
	Average FIEMG		Intercept FIEMG (zero time)		Intercept FIEMG (exhaustion)		Average FIEMG		Intercept FIEMG (zero time)		Intercept FIEMG (exhaustion)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	81.92	3.32	74.47	4.07	91.19	4.95	82.67	2.73	75.42	3.48	89.92	4.06
2	80.83	3.84	73.78	4.88	87.89	4.13	80.51	3.98	72.53	4.95	88.49	4.95
3	73.50	2.58	65.22	3.80	81.79	2.82	73.02	3.31	63.93	4.74	82.12	2.87

situation within each of these five categories of data. Although the slope against time was greater (0.214, $p < .05$) for the second contraction after diathermy and dynamic work compared to the third contraction after positioning without diathermy and dynamic work, there were no significant differences between contractions for the slope with respect to percentage endurance time. The differences and statistical significance between contractions for slope with respect to time and slope with respect to percentage endurance time are seen respectively in Tables IIIe and IIIf.

The analysis of the differences between contractions for average FIEMG, and intercept of FIEMG on the axes representing zero time and time of exhaustion reflect a similar pattern for both categories of data. Whereas no significant differences exist between corresponding contraction numbers after the experimental and control situation, all three measures are significantly higher for the first and second contractions after both diathermy and dynamic work and positioning without diathermy and dynamic work. Figure 3c demonstrates this effect using FIEMG data from the first and third contractions following positioning without diathermy and dynamic work. The differences and statistical significance between contractions for average

TABLE IIIe

Differences between mean slopes of FIEMG calculated as a function of the time for the first, second and third contractions following the dynamic work task after diathermy and positioning without diathermy. Positive values indicate that the mean FIEMG in the column condition was greater than that in the row condition. Significant values are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	0.817	0.063	-0.088	0.678	0.125
	2	0.699	-0.063	-0.214*	0.560	
	1	0.139	-0.576	-0.761		
No Diathermy	3	0.900	0.151			
	2	0.715				

* $p < .05$

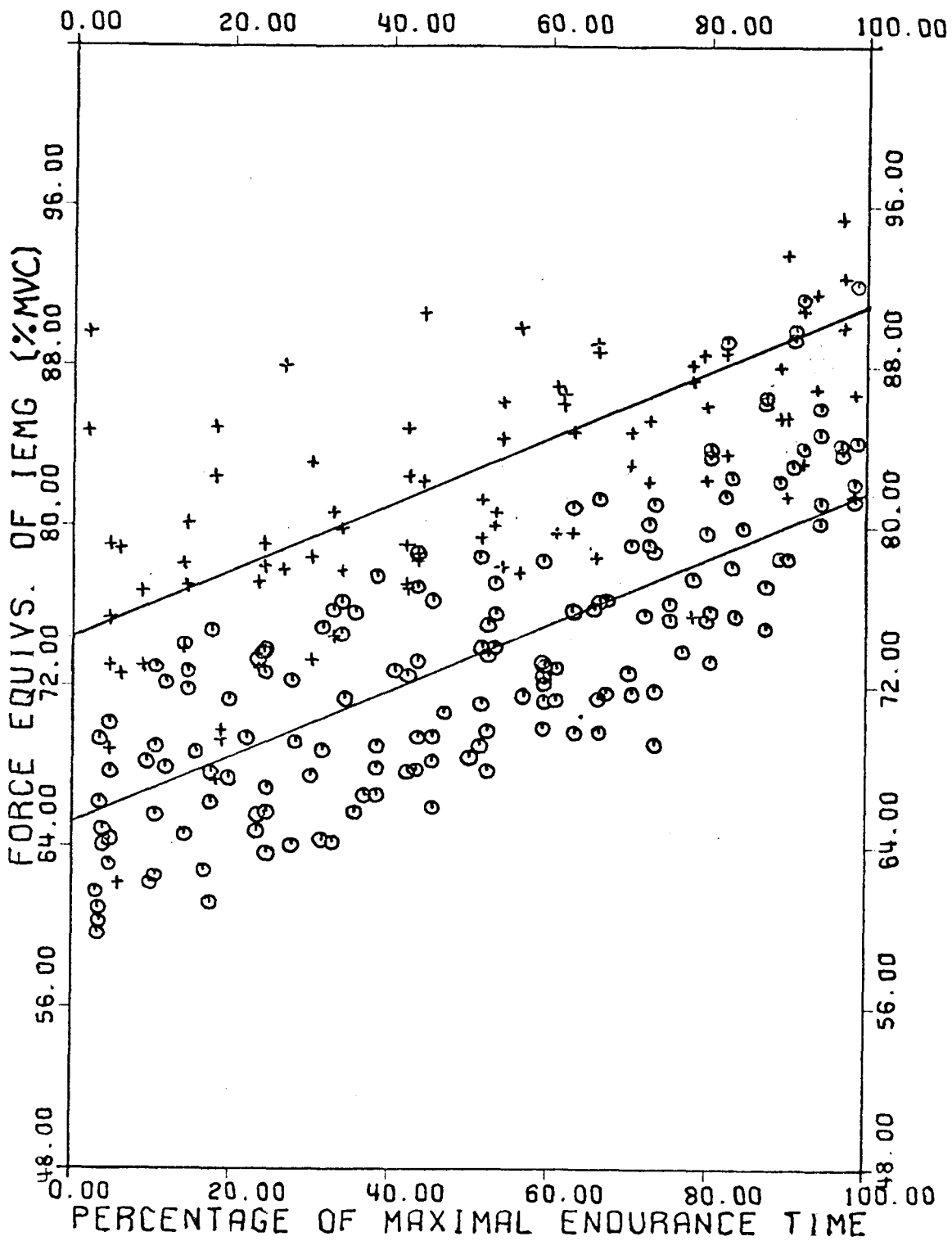
TABLE IIIf

Differences between mean slopes of FIEMG calculated as a function of the percentage of endurance time for the first, second and third contractions following the dynamic work task after diathermy and positioning without diathermy. Positive values indicate that the mean FIEMG in the column condition was greater than that in the row condition. There were no significant differences.

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	-0.8169	-0.0408	-0.0162	-0.0277	-0.0223
	2	-0.0166	-0.0185	0.0061	0.0204	
	1	0.0038	-0.0012	0.0189		
No Diathermy	3	-0.0151	-0.0246			
	2	0.0050				

FIGURE 3c

The effect of dynamic work of the elbow flexors on the myoelectrical activity recorded from biceps brachii during the first isometric contraction following dynamic work after positioning without diathermy. FIEMG values shown are plotted against the percentage of endurance time for sustained isometric contractions immediately following (shown by crosses) and 22 minutes after (shown by circles) dynamic work.



FIEMG and intercept of FIEMG on axes representing zero time and time of exhaustion are shown respectively in Tables IIIg, IIIh and IIIi.

The oxygen uptake at rest and at the end of the first, second, third, fourth and fifth minutes of the dynamic work task were calculated and expressed as a multiple of the resting value (Table IIIj). These values were observed to increase with respect to time of the dynamic work task. The relationship was close to linear between values recorded at the end of the first and fifth minutes following the commencement of the dynamic work task. A linear regression was calculated with respect to time both following diathermy and following the control situation for each subject. Where subjects repeated trials the oxygen uptake data from both trials was used for the calculation of the linear regression. The mean correlation coefficient of the straight line for both experimental and control values was 0.916. The oxygen uptake values for all subjects in both the experimental and control situation and the calculated linear regressions are plotted against time in Figure 3d. The correlation coefficient of the linear regression, and the means and standard deviations of the average oxygen uptake, slope of oxygen uptake with respect to time, and intercept of the

FIGURE 3d

The effect of diathermy on oxygen uptake recorded during the dynamic work. Values shown are a multiple of the oxygen consumption recorded at rest. These values are plotted against the time of dynamic work following both diathermy (shown by circles) and positioning without diathermy (shown by squares). The average linear regression lines are shown to demonstrate the higher oxygen uptake values at the beginning of dynamic work following diathermy (n = 8).

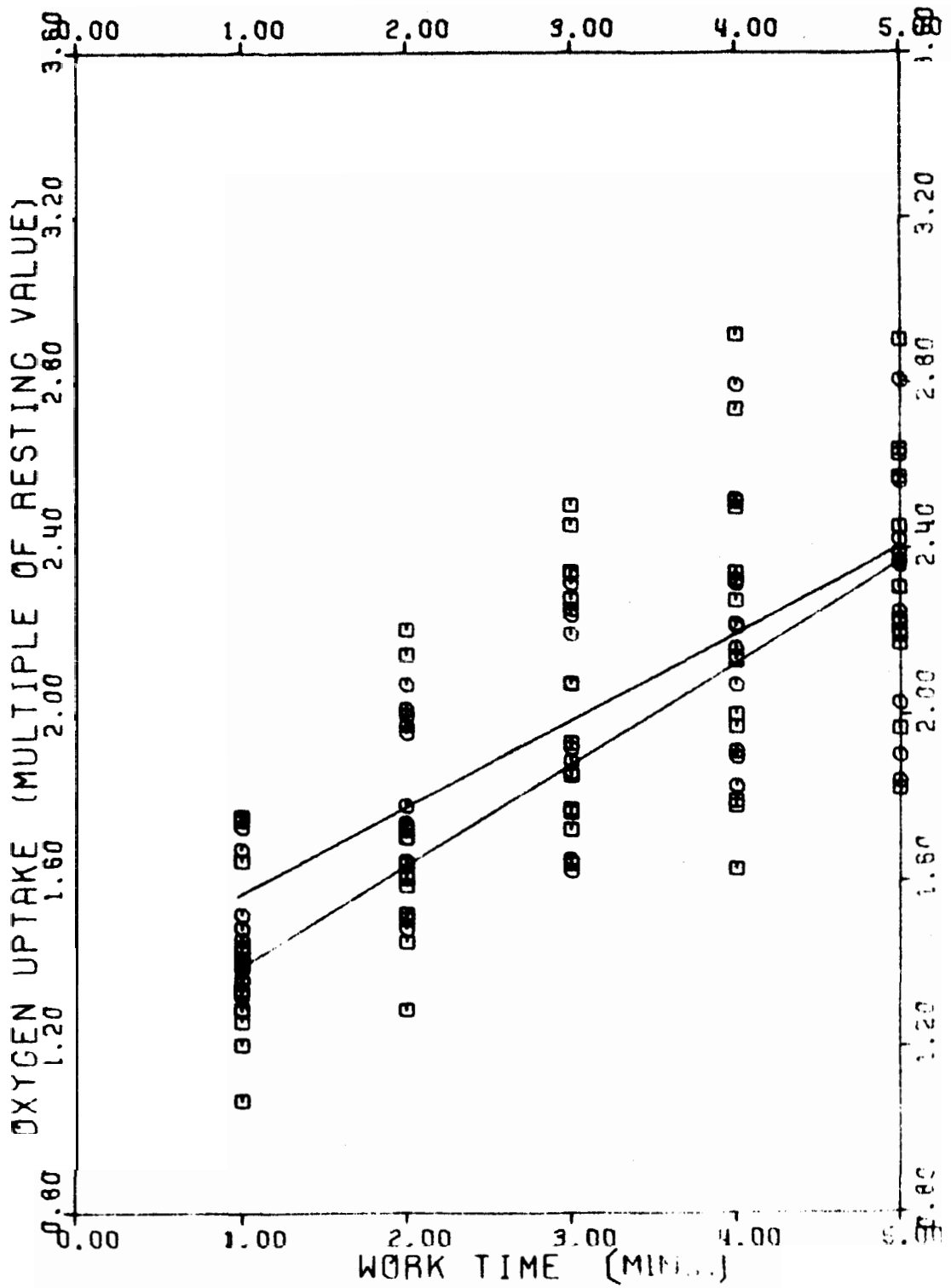


TABLE IIIg

Differences between means of average FIEMG for the first, second and third contractions following the dynamic work task after diathermy and positioning without diathermy. Positive values indicate that the mean FIEMG in the column condition was greater than that in the row condition. Significant values are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	8.89***	7.81***	0.48	9.64***	7.49***
	2	1.08	0.32	-7.01***	1.83	
	1	-0.75	-1.28	-8.75***		
No Diathermy	3	8.00***	7.33***			
	2	0.53				

*** $p < .005$

TABLE IIIh

Differences between the means of the intercept of FIEMG on the axis representing zero time for the first, second and third contractions following the dynamic work after diathermy and positioning without diathermy. Positive values indicate that the mean intercept in the column condition was greater than that in the row condition. Significant values are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	10.54***	9.85***	1.29	11.39***	8.60***
	2	1.94	1.25	-7.31***	2.89	
	1	-0.95	-1.22	-9.69***		
No Diathermy	3	9.25***	8.56***			
	2	0.69				

*** $p < .005$

TABLE IIIi

Differences between the means of the intercept of FIEMG on the axis representing the time of exhaustion for the first, second and third contractions following the dynamic work task after diathermy and positioning without diathermy. Positive values indicate that the mean intercept in the column condition was greater than that in the row condition. Significant values are marked (*).

Conditions and Contraction No.		No Diathermy			Diathermy	
		1	2	3	1	2
Diathermy	3	9.07 ^{**}	5.77 [*]	-0.33	7.80 ^{***}	6.37 ^{**}
	2	2.70	-0.60	-6.70 [*]	1.43	
	1	1.27	-2.03	-8.13 [*]		
No Diathermy	3	9.40 ^{***}	6.10 ^{***}			
	2	3.30				

*** p \leq .005

** p \leq .01

* p \leq .05

TABLE IIIj

Effect of diathermy on the means and standard deviations (S.D.) of oxygen uptake, during dynamic exercise, expressed as a multiple of the resting value (n=8).

Minute of Exercise	No Diathermy		Diathermy	
	Mean	S.D.	Mean	S.D.
1	1.376	0.184	1.496	0.147
2	1.677	0.265	1.803	0.198
3	2.008	0.313	2.038	0.247
4	2.217	0.401	2.201	0.272
5	2.341	0.308	2.288	0.270

relationship between the linear regression of oxygen uptake and time of the first recording (1 minute) during the dynamic work task were calculated (Table IIIk). A paired correlative t-test showed a significantly higher intercept following diathermy whereas the slope with respect to time was significantly greater for the control values of oxygen uptake ($p < 0.02$; $p < 0.05$).

The intercept values of oxygen uptake were analysed further for individual subjects. The effect of diathermy on oxygen uptake was assessed from the difference in the intercept of the linear regression calculated from oxygen uptake values recorded in the experimental and control sessions during dynamic work. The fatigue induced by the dynamic work task was assessed by the percentage of endurance time sustained during the first isometric contraction following positioning without diathermy and the dynamic work task. It was assumed that a shorter isometric endurance time indicated a more fatiguing dynamic work load. It can be seen that the higher oxygen consumption after diathermy was related to more fatiguing dynamic work loads (Figure 3e). Furthermore, there was a direct relationship between the higher oxygen consumption and the component of fatigue induced by diathermy (Figure IIIf).

TABLE IIIk

Means and standard deviations for:

- 1) average oxygen uptake
- 2) value of the intercept (at one minute) of the relationship between oxygen uptake and time (intercept), (see Figure 3d.)
- 3) slope of oxygen uptake with respect to time of dynamic work [slope(t)]
- 4) correlation coefficient of the regression of oxygen uptake against time (Corr. Coeff.)

Significant differences between corresponding values recorded after diathermy and those recorded after positioning without diathermy are indicated (*).

Factor	No Diathermy		Diathermy		Significance of difference between means
	Mean	S.D.	Mean	S.D.	
Average $\dot{V}O_2$	1.885	0.243	1.985	0.207	*
Intercept	1.397	0.144	1.568	0.111	**
Slope (t)	0.2437	0.0674	0.2085	0.0722	
Corr. Coeff.	0.908	0.0533	0.924	0.0442	

* $p < .05$ (1 tailed)

** $p < .02$

FIGURE 3e

The relationship between the effect of diathermy on the initial oxygen uptake values and fatigue induced by the dynamic work load. The difference between the intercepts of oxygen uptake values after 1 min. of exercise recorded in the heated and non-heated condition for individual subjects were plotted against the endurance time of the first sustained isometric contraction following dynamic work in the non-heated condition. The correlation coefficient of the inverse relationship is 0.81 ($p < 0.05$).

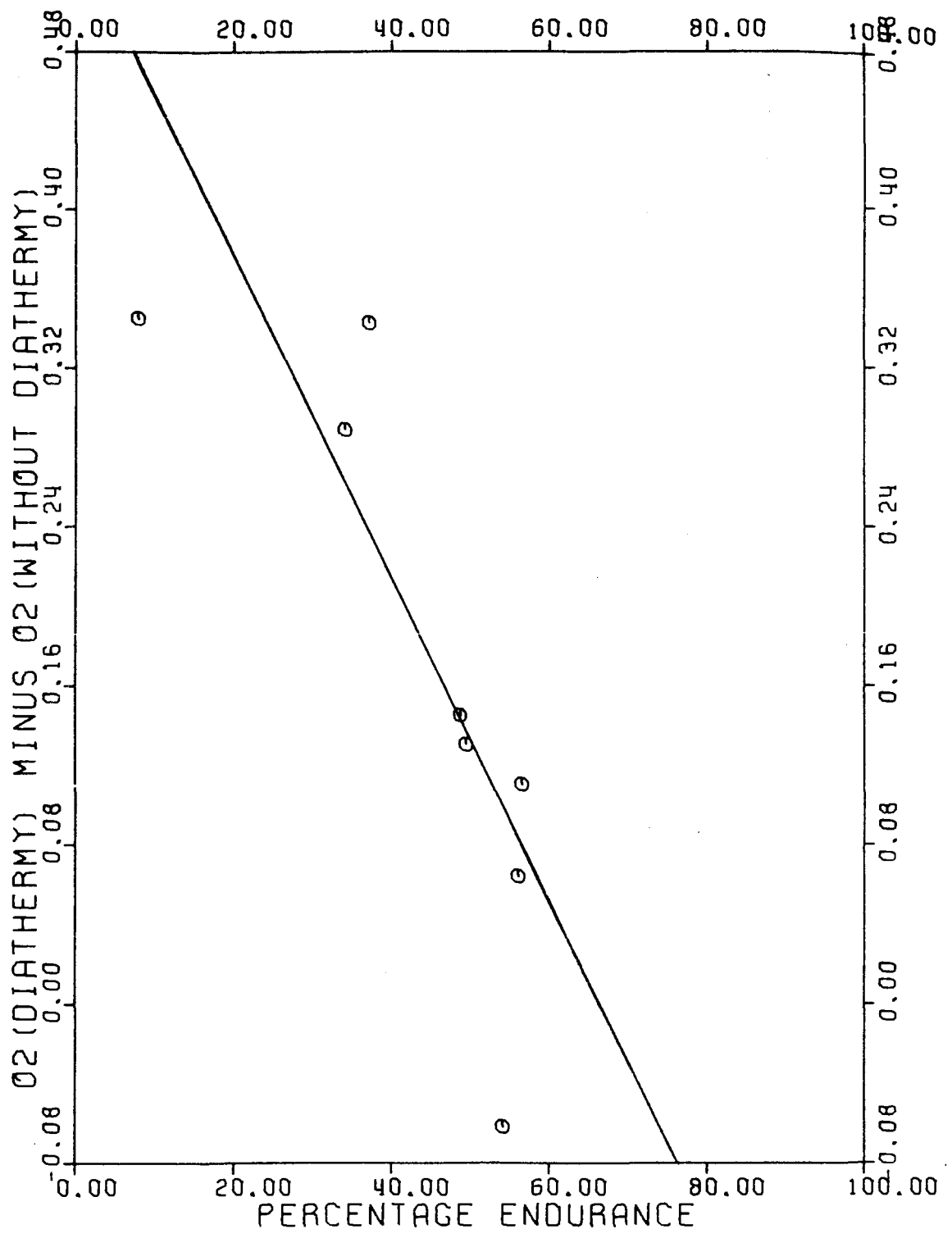
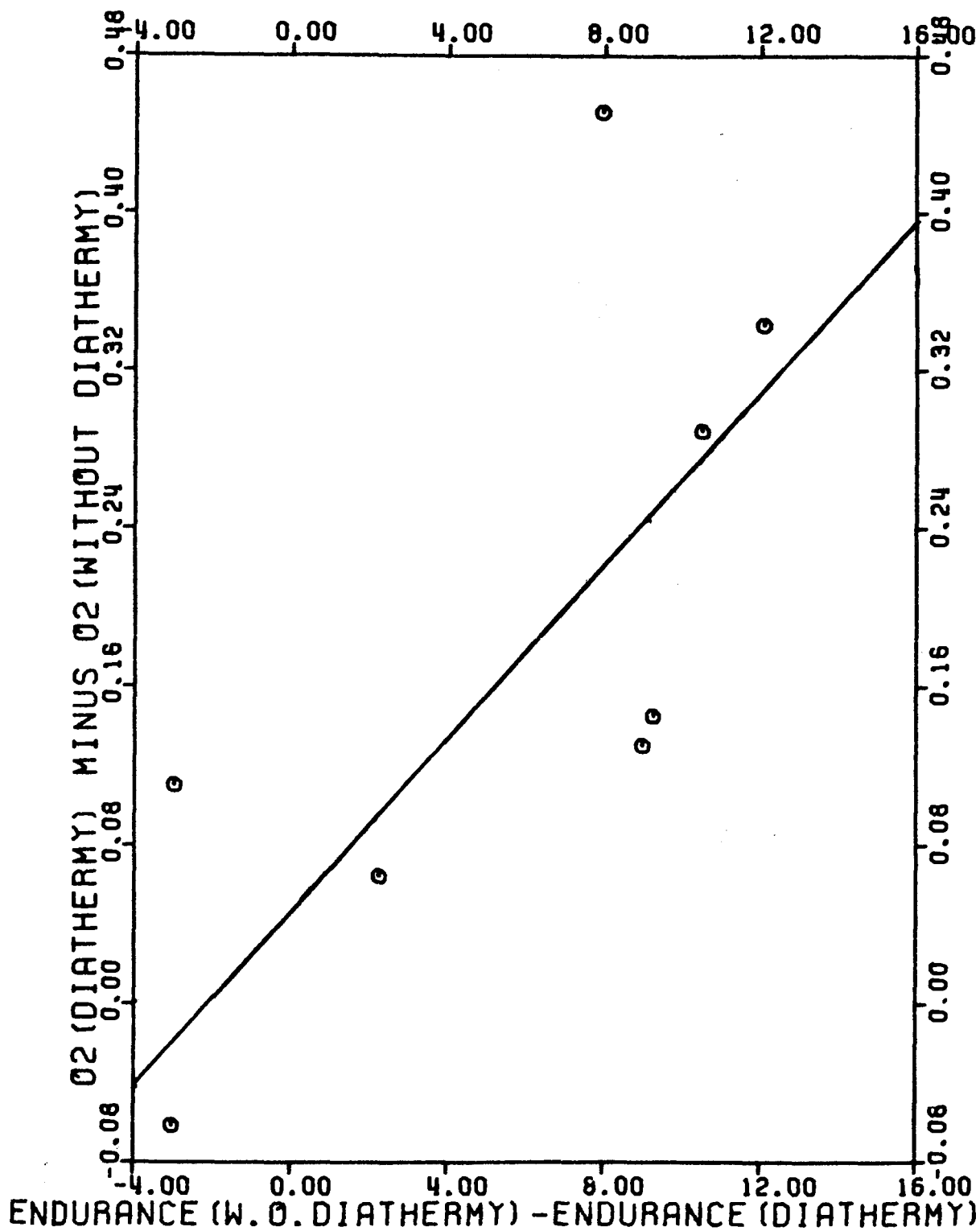


FIGURE 3f

The relationship between the effect of diathermy on the initial oxygen uptake values (determined from the difference in the intercept of oxygen uptake values after 1 min. of exercise) and the component of fatigue induced by diathermy (determined by the difference between the first sustained contractions, after diathermy and dynamic work, and after positioning without diathermy and dynamic work). The correlation coefficient of the relationship is 0.71 ($p < 0.05$).



CHAPTER V

DISCUSSION

Isometric Strength

Figure 1a shows that diathermy decreased strength for the first two contractions following its application although the first contraction after positioning without diathermy also shows some evidence of a suppressive effect. Similar strength values for the third contraction after either conditions indicate that the suppressive effects of diathermy last only 2 - 4 minutes.

A significant decrease in contractile strength agrees with the findings of Sedgwick and Whalen (1964) who induced similar intramuscular temperatures to those estimated in this study. The greater level of significance found in this study may have been due to the visual feedback of force and/or the more standardized conditions for application of diathermy. However the second and third contractions are within the estimated temperature range where previous investigators (Cullingham et al., 1960, and Truong et al., 1964) have found increased contractile strength of isolated muscle, and yet the second contraction was significantly

lower and the third contraction no different from the respectively timed contractions after positioning without diathermy. Two hypotheses can be considered to account for these apparent contradictions:

1) The deleterious effect of diathermy on muscular strength combined with the potential enhancement of fatigue induced in the first contraction after diathermy may lead to a slower recovery rate than would be obtained if the muscle temperature alone was initially elevated to 38 - 39 degrees C. Medvedeva et al., (1975) have demonstrated a change in the configuration of myosin at temperatures above 40 degrees C. It is interesting to speculate that the recovery to normal configuration may be slower than the rate of decrease in intramuscular temperature in this study.

2) The factors influencing muscular strength in vivo are different from those operative in isolated muscle. Close and Hoh (1968) have shown that whereas temperature increases the twitch tension, the isometric twitch contraction time is decreased. On this basis one would expect an increased frequency of motor unit activation to be necessary for development of maximal tension at higher temperatures. In isolated preparations the synchronization with a standardized electrical impulse is potentially much

greater than that which occurs during a maximal voluntary contraction in vivo. This hypothesis is even more attractive when it is extrapolated to account for the greater speed of tension development at higher temperatures in vivo (Asmussen and Bonde-Petersen, 1974) when increased velocity does not depend upon synchronization of motor unit activation. Yeatman et al. (1969) have shown an increased velocity of shortening at zero load and decreased maximum tension with increased temperature of isolated ventricular papillary muscles of the cat. Differences in the activation system of cardiac muscle compared to skeletal muscle may account for the decreased maximum tension, despite the fact that the muscle was artificially stimulated. Another factor for consideration in isolated muscle preparations (compared to physiological stimulation) is the superior ability to maintain or adjust to an increased rate of stimulation necessary to compensate for a reduced twitch time at higher intramuscular temperatures (Truong et al., 1964).

It is quite apparent that strength is also suppressed merely as a consequence of positioning without diathermy. It is possible that this effect may have been caused by relative circulatory stasis. In support of this hypothesis, other studies have shown a linear relationship between

force and muscle blood flow in isolated muscle of once the flow is reduced beyond a critical level (Hirvonen and Sonnenschein, 1962; Jobsis and Duffield, 1967) In view of the increased blood flow at higher intramuscular temperatures (Downey et. al., 1970) this effect would not be expected to affect strength following diathermy. The insignificant difference between the first and second contractions following diathermy (Table Ib) further supports this hypothesis.

Isometric Endurance

The decreased isometric endurance time of the first contraction following diathermy agrees with reports from Nukada (1955), Clarke et. al. (1958), Saunders (1963) and Edwards et al., (1972). However there was no significant decrease of endurance time for the second contraction at an estimated intramuscular temperature (38.5 - 39.5 degrees C.) corresponding to the range reported by Clarke et al. (1958) and Edwards et al. (1972). A further disagreement between the results of this study and those of Clarke et al. (1958) and Edwards et al., (1972) is the recovery of muscular function after heating. Both previous research groups found decreased isometric endurance two minutes following the first

contraction. Although the endurance time of the second contraction after diathermy in this experiment was less than the second contraction after positioning without diathermy the difference was not significant. These apparent contradictions could result from the different method of heating employed in this study. Michielli (1965), who found no significant effect of a mild application of diathermy on isometric endurance, suggested that diathermy was more specific in heating the muscle than waterbath techniques, and that in his experiments the detrimental effects of temperature were compensated for, during the contraction, by a more rapid removal of waste products. Due to the large intramuscular temperature gradient produced by waterbath heating techniques (Edwards et al., 1972), the hyperemic response associated with higher intramuscular temperatures (Barcroft and Edholm, 1946) would largely be directed towards the superficial vasculature (Rowell et al., 1971). Although the magnitude of the force sustained in this study occluded blood flow and therefore prevented recovery during the contraction, it is feasible that an increased recovery rate from the first contraction after diathermy may have compensated for the detrimental effects of increased temperature during the second contraction.

In view of the slow rate of recovery 20 minutes after a sustained isometric contraction (Funderburk, 1974), and the fact that the metabolic by-products from the contraction have largely diffused from the muscle at this time (Karlssen et al., 1975), it is most unlikely that the insignificant difference in endurance time between the third sustained contraction in the heated and non-heated condition could reflect a differential recovery rate. Consequently this suggests that no detectable long term damage results from the intramuscular temperatures elicited by shortwave diathermy in this experiment.

It is apparent from the relatively small standard deviations of all FIEMG values (for any particular contraction number and experimental condition) that the expression of IEMG values as FIEMG is an effective method of correcting for the effects of different electrode placement and variable impedance both between subjects and experimental sessions. Correlation coefficients of 0.845, 0.794 and 0.810 respectively for FIEMG values of the first, second and third contractions on two different experimental sessions under the same conditions is comparable to the correlation of IEMG on different experimental occasions reported by deVries (1968a). If the EMG was perfect we would expect to see the intercept of FIEMG at zero time to

be equal to 66.67%. The fact that the intercept of FIEMG was consistently lower than this value could reflect the extent of fatigue at the time the force/IEMG relationship was determined. In the unfatigued state, when the intercept was obtained, less EMG activity would be required to sustain 66.67% of MVC. However when this level is referred to the curve obtained after all the contractions the small accumulated effect of fatigue would naturally yield a level of force below 66.67% (Edwards and Lippold, 1956).

The non-linear relationship between IEMG and force found in this study (Figure 2a) supports the findings of Nightingale (1960), Zuniga and Simons (1969), Kuroda et al. (1970), Gottlieb and Agarwal (1971) and Troup and Chapman (1972). In contrast, Lippold (1952), Edwards and Lippold (1956), Lenman (1959), Eason (1960), Liberson et al., (1962) and deVries (1968b) have found a linear relationship between the measured electrical activity and muscle tension. It is perhaps relevant that Lippold (1952) provided external indirect stimulation to the muscle and Edwards and Lippold (1956) only reported the relationship with tensions up to 44% MVC. With few exceptions a straight line could well represent the relationship between force and IEMG at lower

percentages of MVC in the present study. Kuroda et al. (1970), who obtained similar results, suggests that as the frequency of stimulation of each motor unit increases, the force exerted increases proportionately to the frequency within a certain submaximal force level, but beyond this point the force generated per given increase in frequency becomes proportionately less. This hypothesis is supported by studies which have determined the relationship between stimulation frequency and tension development in isolated muscle (Merton, 1954).

The progressive increase of myoelectrical activity during sustained contractions in this study supports the findings of previous studies (Scherrer and Bourguignon, 1959; Eason, 1960; deVries, 1968a; Kuroda et al., 1970). Most previous studies report a non-linear increase in IEMG during a sustained isometric contraction (Edwards and Lippold, 1956; Eason, 1960; Kuroda et al., 1970). Kuroda et al. (1970) found a "linear-plus-exponential" relationship of IEMG with respect to time during sustained contractions of 57% and 28% MVC. A greater exponential component at 28% MVC may have reflected a larger reserve of high threshold motor units available for recruitment. The linear relationship between FIEMG and contraction time determined in this study was partly

possible because of the higher force sustained but also because of the expression of IEMG in "force equivalents." Figure 2b demonstrates how a non-linear increase in IEMG during a sustained contraction approximates linearity when expressed as FIEMG.

Of particular interest is the aberrant subject where the FIEMG initially increased and then decreased with respect to time. This result is comparable with those of Chapman and Troup (1970) who found a decrease in IEMG from the lumbar musculature during a sustained contraction of 30% MVC. Lippold et al. (1960) also recorded a decrease in electrical output from the extensor digitorum in isometric extensor activity of the forefinger. Whereas Chapman and Troup (1970) suggested the decrease in IEMG to be due to selective recruitment of deeper fibres, Lippold et al. (1960) found that the extensor activity was being transferred to extensor indicis. The decline of IEMG activity recorded towards the end of the contraction in this study may have reflected a peculiar pattern of recruitment for the subject concerned whereby flexor IEMG activity is transferred either from the superficial to deeper fibres of biceps brachii or from the biceps to brachioradialis.

The original reason for recording IEMG was to provide an objective criterion of motor unit activity within the muscle. It has been proposed that whereas the intercept of FIEMG on the axis representing zero time indicates the combined effect of initial firing frequency and number of operational motor units, the slope of FIEMG with respect to time largely reflects the rate of recruitment (Kuroda et al., 1970). This hypothesis is supported by the findings of this study and those of Eason (1960) that the rate of increase in FIEMG is inversely proportional to the contraction time (Figure 2c). This relationship is also demonstrated by the significantly greater mean slope for the more rapidly terminated second contraction compared to the first and third contractions after positioning without diathermy (Tables IIc and IIh). However, in the latter stages of all contractions there appears to be some other factor(s) operating, for despite the consistency of final FIEMG values they do not approach maximal values possible in a non-fatigued contraction. This effect is probably even greater than the results indicate, since the decreased conduction velocity associated with muscular fatigue could potentially increase the recorded myoelectrical activity (Lindstrom et al., 1970; Mortimer et al., 1970). The possibility of synaptic inhibition or some CNS control preventing fatigued motor units from firing are probably

the only factors which could account for such a large deficit in the terminal FIEMG at exhaustion. Studies where maximal voluntary contractions have been sustained have observed that IEMG decreases during the contraction in close proximity to the decrease in force (Kogi and Hakamada, 1962; Stephens and Taylor, 1970), suggesting progressive synaptic impairment. A number of studies suggest that the neuro-muscular block is at least in part attributable to the effects of ischemia (Paul, 1961; Lundborg, 1970; Dahlback et al., 1970). Dahlback et al. (1970) report that ischemia increased the time interval between action potentials from two muscle fibres belonging to the same motor unit and on this evidence suggested that the block occurs due to emptying of acetylcholine stores. The hyperpolarizing effect of decreased pH may also be a factor responsible for impaired synaptic transmission (Guyton, 1974). On the other hand, Missiuro et al. (1962) suggest a CNS component of fatigue, and others attribute a loss of motor activation to increased pressure on the motor neuron (Reid, 1928; Lloyd, 1971).

The maximum FIEMG reached was greater (2.64%; $p < 0.05$) in the second than the third contraction following positioning without diathermy (Table II) indicating either a

decreased neural fatigue in the second contraction or loss of motivation in the third contraction. Whereas the decreased endurance time may reduce the neural component of fatigue in the second contraction, the time involved waiting for the third contraction may have led to loss of motivation. Consequently either of these explanations seem tenable. However the lower maximum FIEMG reached for the first sustained contraction following diathermy cannot be explained on this basis. Although the endurance time was greater for the first contraction without diathermy compared to the first contraction after diathermy (Figure 2c), the slope with respect to time was greater without diathermy. An explanation of this finding is not tenable on the basis that the rate of increase in FIEMG reflects the rate of motor recruitment. In addition the mean FIEMG of the first contraction following diathermy was lower than all other contractions (Table II f). It is unlikely that increased temperature could enhance the onset of neural fatigue, since it is more likely to facilitate motor neuron and neuro-muscular transmission (Paintal, 1965; Poole, 1972). Therefore the results suggest that for the first contraction after diathermy the increased temperature decreased the externally measured electrical activity (expressed as FIEMG) for a given degree of muscle activation. This hypothesis is compatible with the results of Frauendorf et al. (1974)

who found a decrease of IEMG by approximately 8% in a non-fatigued contraction after heating. These findings are further elaborated in the results of Edelwejn (1964), who found that the duration of single polyphasic potentials was reduced in heated isolated rabbit muscle. This effect was suggested to be caused by an increased rate of depolarization at higher temperatures. However the results of Clarke et al. (1958) who reported a more rapid increase of IEMG with increased intramuscular temperature, contradicts the results of this experiment. This may have been due to the fact that in their experiments, the IEMG was not corrected for variable impedance and electrode placement on different experimental occasions. A further difference for consideration was the method of heating and the lower percentage MVC sustained (33% MVC). The lower intramuscular temperatures elicited from water bath heating and the possibility of blood flow and subsequent cooling during a contraction of 33% MVC (Lind et al., 1974) may have contributed to the increased slope of IEMG reported by Clarke et al. (1958).

Whereas the slope of FIEMG per unit time has been proposed to represent the combined effects of recruitment and increased firing frequency of motor units (deVries, 1968a), the initial FIEMG, reflected by its intercept on the

axis representing zero time, supposedly represents the initial metabolic state (Edwards and Lippold, 1956) and/or the efficiency of the myofibrils (deVries, 1968b). On the basis of this hypothesis, the decreased endurance time of the second sustained contraction after positioning without diathermy results from the need for more rapid recruitment. However the decreased endurance time that results from the effect of heating suggests the presence of some limiting factor at the beginning of the contraction because, after allowances were made for the effect of heating on the myoelectrical activity, the initial FIEMG values of the first contraction were higher after diathermy (Table II f). This conclusion, supported by the decreased strength values following diathermy, strengthens the suggestion made by Edwards et al. (1972) that increased temperature affects the efficiency of myofibrillar function.

Dynamic Exercise

The endurance times of the first sustained contraction indicate that higher intramuscular temperatures during the preceding dynamic work task induced lower efficiency of isometric muscle function (Figure 3a). The detrimental effect is associated with dynamic workloads which are more fatiguing (Figure 3b) and accompanied by higher values of oxygen consumption (Figure 3f).

It may be argued that the reduction in endurance of the first sustained contraction following diathermy and dynamic work may reflect the effect of diathermy on the sustained contraction itself and not the dynamic work task. However this explanation is unacceptable for the following reasons:

1) The results from the isometric endurance section of this study suggest that the effects of diathermy have dissipated within two and a half minutes following its application.

2) The slope of FIEMG with respect to time for the first sustained contraction was not significantly different in experimental and control situations, indicating no difference in the rate limiting factors between these two contractions.

However if the metabolic state of the muscle was more impaired following diathermy and dynamic work compared to the corresponding time in the control situation one would expect a higher FIEMG at the beginning of the first sustained contraction (Edwards and Lippold, 1956; deVries, 1968b). Although the intercept was higher (Tables IIIId and IIIh) the significance of the difference may have been obscured by the more obvious effect of dynamic work on the FIEMG. This effect will be discussed in detail later.

Grose (1958) has reported the only previous study which measured the effects of increased intramuscular temperature on muscle fatigue during dynamic work, and in agreement with the results of this study there was a reduction in the amount of work accomplished. The magnitude of the decreased work output was 5.8% which corresponds closely to the 6.59% decrease in isometric endurance following diathermy and dynamic work in these experiments. On the other hand Asmussen and Boje (1945) who report an improved performance time for a specific dynamic workload at higher intramuscular temperatures, did not assess fatigue. Whereas the experimental muscle group was heavily loaded in the present experiments and those conducted by Grose (1958), the criterion of performance in the experiments by Asmussen and Boje (1945) was velocity of contraction. Yeatman et al., (1969), working with isolated ventricular papillary muscles of cat, found an increased maximum velocity of shortening at zero load and decreased maximum tension with increased temperature. Although it is not possible to compare directly cardiac and skeletal muscle it is reasonable to hypothesize that a similar effect may result when the temperature of skeletal muscle is increased. Should this hypothesis be correct the reduction in efficiency during dynamic work can be related to that part of the series elastic component residing in the contractile mechanism

(Assmussen et al., 1976). An inefficiency of some physiological process involved in dynamic work is suggested from the finding that the greatest impairment due to heating was found when the dynamic workload was most demanding (Figure 3b). This relationship is impressive when one considers that an increased oxygen uptake should benefit those subjects with a larger anaerobic component to the dynamic work task, or in other words the subjects which have demonstrated the greatest impairment from higher intramuscular temperatures. One limitation in the interpretation of the above results is that the sensitivity of the muscle to fatigue is increased as the extent of fatigue increases. This is reflected by a more rapid recovery following conditions where the muscle is more extensively fatigued (Pastor, 1959; Clarke, 1971; Funderburk, 1974). Consequently some reservation is necessary when comparing the relationship of fatigue induced by increased temperature to intensity of the dynamic work task.

The increased oxygen consumption at higher intramuscular temperatures may reflect either an increased rate of metabolism, an increased blood flow or both. Kaijser (1970) concluded that oxygen consumption was limited by the rate of metabolism whereas the results of Horstman et

al. (1976) indicate that consumption is limited by the rate of supply. The question is raised as to whether the observed increase in oxygen uptake may not reflect a higher oxygen uptake in resting muscle immediately prior to the dynamic work task. Evidence for this possibility has been reported by Stainsby and Otis (1964) who found that oxygen uptake in resting isolated muscle was not altered by changes in blood flow or blood oxygen tension, except when these values were reduced below critical values. In view of these findings it is possible that the greater oxygen consumption at higher temperatures may have been a compensatory increase in oxygen consumption due to the increased anaerobic component developed from an increased metabolic rate at rest. However, the fact that the greatest increase in oxygen uptake due to heating occurred with those subjects where workloads were most demanding to the physiological systems involved in muscular work (Figure 3e), is indirect evidence against the possibility that the higher oxygen consumption may reflect processes unrelated to the work task. Therefore, it appears most likely that the higher oxygen consumption at the beginning of the work task indicates either a lower amount of ATP generated per unit of oxygen consumed (P:O ratio) due to an inefficiency of an energy transducing process in the mitochondria, or an increased requirement for ATP for a given work task,

reflecting diminished efficiency of the myofibrils. Whatever the mechanism responsible for lost efficiency, this study clearly indicates that oxygen uptake during a standardized work task does not always inversely relate to the anaerobic component of the work task as suggested by Watt and Hodgkin (1974).

The possibility of an uncoupling of the respiratory chain has previously been suggested by Brookes et al. (1971) and Saar and Cassuto (1976). However results of experiments in this study on strength and isometric endurance suggest that the site of inefficiency of energy transducing processes is more likely to be the myofibrils, and is limiting from the beginning of a sustained contraction. The possibility that the major cause of inefficiency is a temperature effect on the energy conserving process of the increased relaxation time accompanying the onset of fatigue (Edwards and Hill, 1975; Edwards et al., 1975) is incompatible with these results, for in this case inefficiency would be most apparent towards the end of a contraction.

One of the hypotheses on which these experiments were designed was that the already high temperatures of active mitochondria might be further elevated by additive

temperature effects from diathermy, and the reduction in heat dissipation with higher surrounding intramuscular temperatures. However the higher oxygen uptake values at the beginning and throughout dynamic work following diathermy is indirect evidence to suggest that the activities of mitochondrial oxidative systems were not decreased although if the coupling mechanisms became disengaged, the combination of increased oxygen uptake with decreased endurance would be explained. Denaturation of some oxidative enzymes is known to occur at temperatures approximating 44 - 45 degrees C. On the basis of this evidence the increased oxygen uptake observed in this study would appear contradictory unless certain factors have been overlooked in predictions of mitochondrial temperature during physical work (Calvert, 1976). Atha and Ackers (1974) have reported a temperature dependent endothermic reaction in haemoglobin which acts as a "heat sink". The present results open the possibility that certain unknown mitochondrial reaction(s) may also be temperature dependent and endothermic.

Considering the relative high intensity and duration of the dynamic work load it is surprising that the oxygen uptake values continued to increase throughout the dynamic work task without any indications of a steady state being

reached. This effect may have indicated an unnoticed gradual recruitment of other muscles not directly involved in the work task as the subject became fatigued. However it is unlikely that this possible artifact could have contributed to differences in oxygen consumption between the experimental and control dynamic work tasks since the greatest difference in values is at the beginning of work when the contribution from this possible artifact would be minimal.

The influence of dynamic work on increasing FIEMG (Figure 3c) closer to maximal values is a factor which would be of considerable importance in quantifying IEMG measurements involving dynamic work. This phenomenon cannot be explained on the basis of changed electrical skin resistance with increased blood flow (Fraundorf et al., 1974), and therefore it seems more plausible that the dynamic work task elicited some metabolic change within the muscle necessitating greater electrical activation during subsequent isometric contractions. The depletion of glycogen is much greater following prolonged heavy submaximal dynamic work (Costill et al., 1973) than that after sustained isometric contractions to fatigue (Gollnick et al., 1974a). The higher FIEMG after dynamic work could reflect greater glycogen depletion, so that a greater motor

recruitment is necessary to supply ATP for contraction before electrical impairment occurs due to lactic acid accumulation (Guyton, 1974), acetylcholine depletion (Dahlback et al., 1970), or increased pressure on the motor neuron (Reid, 1928; Lloyd, 1972). Whatever the mechanism of electrical impairment associated with sustained isometric contractions, it does not appear to occur (at least not to the same extent) during dynamic work. Whereas submaximal dynamic work selectively depletes glycogen from slow-twitch fibres (Gollnick et al., 1974b), sustained isometric contractions, above 20% MVC, selectively depletes glycogen from fast-twitch fibres (Gollnick et al., 1974a). The fact that glycogen depletion is not noticeable in slow-twitch fibres may suggest a selective impairment of these fibres, rather than preferential recruitment of fast-twitch fibres, suggested by the authors of these studies. The hypothesis that impaired activation of slow-twitch fibres is responsible for the lower terminal FIEMG values during isometric contractions, not preceded by dynamic work, supports the findings of Lloyd (1971), who suggested a 'drop out' of high frequency motor units was responsible for changes in the waveform of the electromyogram during sustained isometric contractions.

CHAPTER VI

SUMMARY AND CONCLUSIONS

This study investigated characteristics of muscular fatigue resulting from elevation of intramuscular temperature. Evaluations were made at estimated temperatures above 40 degrees C, and at lower estimated temperatures during recovery. Some of the findings of the study have implications not specifically concerned with temperature effects. These are;

1) The FIEMG increased linearly during sustained isometric contractions of two thirds MVC. However the FIEMG at the point of exhaustion was only 81.92 -84.56 percent of the maximal FIEMG recorded in a brief unfatigued maximal contraction. Whereas the increase of FIEMG during sustained contractions probably reflects motor recruitment, the depressed values at exhaustion suggest synaptic and/or central nervous fatigue.

2) Dynamic work increased the average FIEMG recorded during subsequent sustained isometric contractions. Both the initial and final values of FIEMG were greater during

sustained isometric contractions following immediately, and two minutes after a submaximal dynamic work task.

3) The rate at which the FIEMG increased was inversely related to the endurance time of a sustained contraction.

The findings of the study specifically relating to the effect of increased intramuscular temperature on fatigue are;

1) Increased intramuscular temperature, estimated above 40 degrees C, decreased strength, and accelerated onset of fatigue during isometric and dynamic contractions. There was a rapid recovery of muscle function, assessed by these performance criteria, once intramuscular temperatures had fallen below an estimated 39 degrees C.

2) At elevated temperatures the FIEMG increased less rapidly. Should the FIEMG reflect motor recruitment there should have been a more rapid increase at higher temperatures corresponding to the decreased endurance time. It was suggested that this apparent contradiction resulted from an increased rate of depolarization along individual muscle fibres which minimized the effects of changing recruitment.

3) When corrections were made for the depressed FIEMG values at higher temperatures there was found to be a higher initial FIEMG at the beginning of sustained isometric contractions of heated muscle. This finding, and the decrease in strength, suggests that the tension produced by the muscle is less for a given level of motor recruitment.

4) The more fatiguing the dynamic work task the greater the impairment resulting from increased intramuscular temperatures.

5) The rate of oxygen uptake was greater at the beginning of a dynamic work task at higher temperatures. This effect was greatest when the isometric endurance following the dynamic work task was most impaired.

It is apparent from the findings of this study that elevation of intramuscular temperature to an extreme physiological range facilitates at least one physiological response which is detrimental to strength, sustained isometric contractions and dynamic work. The hypotheses presented in the introduction to this study suggest that physiological mechanisms relating to muscle contraction could either be beneficial or detrimental depending on the criteria of performance measured and the extent of the

temperature increase. It is plausible that several mechanisms may be operative resulting in either a combined or counter-balancing effect. However, certain conclusions can be made regarding the relative influence of these mechanisms. The potentially beneficial effects of increased temperature would facilitate dynamic work and possibly strength. As both of these factors were temporarily impaired at high temperatures we can conclude that at these temperatures the detrimental aspects overruled any potentially beneficial effects. The possibility that impairment results from systemic effects of heating on the work task is unlikely in view of the positive relationship between the increased oxygen uptake and demand of the assigned work task on the physiological systems involved. Furthermore, the hypothesis that denaturation of enzyme proteins may limit the rate of metabolism, and hence work rate, is not apparent in these experiments since impaired strength could not be attributed to this possibility. The integrity of the enzymes involved in oxidative metabolism at higher temperatures is further supported by an increased oxygen consumption under these conditions, although a decreased phosphorylative efficiency is feasible. It does appear that the impairment involves an inefficient transduction of chemical to mechanical energy, but the following findings suggest that this involves impaired

function of the myofibrils:

1) A reduction in contractile strength.

2) A higher estimated force equivalent of IEMG at the beginning of sustained contractions of heated muscle before glycolytic energy systems are likely to become involved.

Unfortunately it is not possible from the results of this study to distinguish the exact nature of this transduction inefficiency. Possible mechanisms could involve a change in the conformation of the contractile proteins, a decreased twitch time, or an increased crossbridge turnover necessary to produce a given force. Further research should be designed to differentiate these effects. The rapid recovery of muscle function, observed in this study, even when temperatures are still above normal resting muscle temperature, suggests either the insensitivity of the physiological characteristics studied to a reduced impairment, or a rapid reversal and a specific temperature threshold for the detrimental effect(s). Taken together the results of these studies confirm an important role for the effects of increased temperature whereby muscular effort results in fatigue.

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