INFORMATION TO USERS

This material was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.

2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.

3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in "sectioning" the material. It is customary to begin photoing at the upper left hand corner of a large sheet and to continue photoing from left to right in equal sections with a small overlap. If necessary, sectioning is continued again — beginning below the first row and continuing on until complete.

4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from "photographs" if essential to the understanding of the dissertation. Silver prints of "photographs" may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.

5. PLEASE NOTE: Some pages may have indistinct print. Filmed as received.

Xerox University Microfilms
300 North Zeeb Road
Ann Arbor, Michigan 48106

73-24,661

QUIGLEY, Brian Maxwell, 1935-
RELATIONSHIPS AMONG ISOMETRIC MUSCULAR STRENGTH, RELATIVE-LOAD ENDURANCE, AND SELECTED CARDIOVASCULAR AND ELECTROMYOGRAPHIC VARIABLES.

The University of Michigan, Ph.D., 1973
Education, physical

University Microfilms, A XEROX Company, Ann Arbor, Michigan

THIS DISSERTATION HAS BEEN MICROFILMED EXACTLY AS RECEIVED.

RELATIONSHIPS AMONG ISOMETRIC MUSCULAR STRENGTH, RELATIVE-LOAD ENDURANCE, AND SELECTED CARDIOVASCULAR AND ELECTROMYOGRAPHIC VARIABLES

by

Brian Maxwell Quigley

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Education)
in The University of Michigan
1973

Doctoral Committee

Associate Professor Merle L. Foss, Co-Chairman
Associate Professor Don B. Chaffin, Co-Chairman
Professor John A. Faulkner
Professor Paul Hunsicker
Associate Professor Richard A. Schmidt

DEDICATION

To my mother

AGNES MAY QUIGLEY

whose life was dedicated to
the education of her three sons

ACKNOWLEDGEMENTS

Special thanks are given to the following people for their invaluable assistance and, without exception, for the friendly spirit with which it was given.

Dr. Merle L. Foss and Dr. Don B. Chaffin and their wives Peg and Barbara for their friendship, guidance, support, hospitality, and patience.

Dr. John A. Faulkner, Dr. Paul Hunsicker and Dr. Richard A. Schmidt for their professional skill and personal concern as committee members.

Miss Diane Ross, Mr. Hugh Fox, and Mr. Curt Whitcomb for their attention to detail and their personal qualities as friends and assistants.

Mr. David Farrar, Mr. James Foulke, Mr. Seth Feinberg, and Mr. Robert Wolters for their technical expertise, friendly support, and untiring efforts in the collection and processing of the data.

Dr. Guy Reiff, Dr. M. Anthony Schork, and Dr. Leigh Whitlock for their generous encouragement and support, each in his own way.

Mrs. Rebecka Andress for her typing excellence and calm charm.

All forty subjects for the enthusiasm and interest with which they went through agony.

Financial assistance was provided for computer programming and data processing by a grant from the Western Electric Company and HEW Grant No. 1-P07-FR00417-01 COM. The subjects were paid from a University of Michigan Graduate Student Dissertation Research Grant.

TABLE OF CONTENTS

		Page
DEDICATION		ii
ACKNOWLEDGEMENTS		iii
LIST OF TABLES		vi
LIST OF FIGURES		viii
LIST OF APPENDICES		x
CHAPTER		
I	INTRODUCTION	1
	Need for the Study	1
	Purpose of the Study	3
	Definition of Terms	4
II	REVIEW OF LITERATURE	7
	Strength vs. Endurance Relationships	7
	Cardiovascular Responses	11
	Electromyographic Responses	16
III	METHODS	25
	Subjects	25
	Test Procedures	25
	Anthropometric Measurements	34
	Test Order	35
	Data Collection	36
	Force	36
	Time	38
	Blood Pressure	38
	Electrocardiogram	38
	Electromyogram	39
	Data Processing	40
	Anthropometric Variables, Force, Time, and Blood Pressure	40

CHAPTER Page

III Cont.
Data Processing, cont.
Electrocardiogram 40
Electromyogram 43
Statistical Analysis 44

IV RESULTS 45

Descriptive Data 45
Repeatability of the Data 48
Strength Measurements (MVC) 48
Endurance Measurements 49
Cardiovascular Measurements 51
Electromyographic Measurements 51
Strength vs. Endurance Relationships 52
Maximum Endurance Time (MET) 52
Isometric Work (F × T) 60
Cardiovascular Responses 63
Blood Pressure 63
Heart Rate 75
Electromyographic Responses 82
Relationships with Endurance 89
Specific EMG Responses 89

V DISCUSSION 92

Strength vs. Endurance Relationships 92
Comparative Endurance of Swimmers 95
Evaluation of Endurance Performance 96
Evaluation of Group Strength Differences . . . 97
Relationships between Endurance Times and Physiological Variables 98
Physiological Hypotheses 99
Cardiovascular Responses 103
Static Contractions and Cardiac Health 104
Electromyographic Responses 106

VI CONCLUSIONS 110

REFERENCES 112

APPENDICES 121

LIST OF TABLES

Table		Page
1	Summary of Physical Characteristics of Subjects: Group Means and Standard Deviations	46
2	Group Strength Means Showing Differences Among Groups Before and After Adjustment for Covariance	46
3	Product-Moment Correlation Coefficients Showing Day-to-Day Repeatability of Maximum Strength Measurements	48
4	Test-Retest Repeatability of all Variables at 25% MVC . .	50
5	Relationship of Maximum Endurance Time to Strength: Individual Regression Analysis and Analysis of Variance of Group Means	55
6	Relationship of Isometric Work to Strength: Individual Regression Analysis and Analysis of Variance of Group Means	62
7	Relationship of Peak Systolic Blood Pressure to Strength: Individual Regression Analysis and Analysis of Variance of Group Means	70
8	Relationship of Peak Diastolic Pressure to Strength: Individual Regression Analysis and Analysis of Variance of Group Means	71
9	Relationship of Peak Mean Blood Pressure to Strength: Individual Regression Analysis and Analysis of Variance of Group Means	72
10	Product-Moment Correlation Coefficients Showing Relationships of all Variables to Maximum Endurance Times	76
11	Relationship of Peak Heart Rate to Strength: Individual Regression Analysis and Analysis of Variance of Group Means	80

Table Page

12 Relationship of EMG Low Frequency Power to Strength: Correlation Coefficients, Group Means and Standard Deviations 87

13 Relationship of EMG rms Voltage to Strength: Correlation Coefficients, Group Means and Standard Deviations 88

LIST OF FIGURES

Figure		Page
1	Arrangement of Subject, Investigators, and Equipment During Maximal Voluntary Contraction	27
2	Arrangement of Subject, Investigators, and Equipment During Endurance Hold	28
3	Sampling Protocol Showing Times at which Variables were Recorded Before, During, and After Maximum Voluntary Contraction	31
4	Sampling Protocol Showing Times at which Variables were Recorded During and After Endurance Holds . . .	33
5	Flow Diagram of Data Collection Equipment	37
6	Flow Diagram of Data Processing Equipment	41
7	Regression of Bodyweight on Elbow Flexion Strength . . .	47
8	Regression of Maximum Endurance Time on Strength for Static Elbow Flexion at 25% MVC	56
9	Relationship of Maximum Endurance Time to Strength Showing Group Means and Standard Deviations for High, Medium, and Low Strength Groups and Swimmers	57
10	Regression of Maximum Endurance Time on Strength for Static Elbow Flexion at 50% MVC	58
11	Regression of Maximum Endurance Time on Strength for Static Elbow Flexion at 75% MVC	59
12	Relationship of Maximum Endurance Time to Relative Tension for Continuous Static Contractions	61
13	Relationship of Isometric Work (Force × Time) to Strength Showing Group Means and Standard Deviations for High, Medium, and Low Strength Groups and Swimmers	64
14	Relationship of Isometric Work (Force × Time) to Relative Tension for Continuous Static Contractions.	65

Figure		Page
15	Group Differences in Mean Blood Pressure During a 20 Min Static Elbow Flexion at 15% MVC	66
16	Regression of Peak Mean Blood Pressure on Strength for Static Elbow Flexion at 15% MVC	68
17	Relationships of Peak Blood Pressures to Strength Showing Group Means and Standard Deviations for High, Medium, and Low Strength Groups and Swimmers	69
18	Group Differences in Mean Heart Rate During a 20 Min Static Elbow Flexion at 15% MVC	78
19	Relationship of Peak Heart Rate to Strength Showing Group Means and Standard Deviations for High, Medium, and Low Strength Groups and Swimmers	79
20	Mean Blood Pressure and Heart Rate Shown as a Function of Time for a Typical Strong Subject (Subject 25) and a Typical Weak Subject (Subject 23)	81
21	EMG Low Frequency Power and EMG rms Voltage Shown as Functions of Time for a Typical Strong Subject (Subject 25) and a Typical Weak Subject (Subject 23)	84
22	Relationships of EMG Low Frequency Power to Strength Showing Group Means and Standard Deviations for High, Medium, and Low Strength Groups and Swimmers .	85
23	Relationships of EMG rms Voltage to Strength Showing Group Means and Standard Deviations for High, Medium, and Low Strength Groups and Swimmers .	86

LIST OF APPENDICES

APPENDIX		Page
I	Randomized Order of Tests	122
II	Characteristics of Subjects	123
III	Forearm Measurements of Subjects	124
IV	Test Conditions: Test 025	125
V	Test Conditions: Test 15	126
VI	Test Conditions: Test 25	127
VII	Test Conditions: Test 50	128
VIII	Test Conditions: Test 75	129
IX	Maximum Voluntary Contraction (MVC)	130
X	Maximum Endurance Time (MET)	131
XI	Isometric work (Force × Time)	132
XII	Peak Systolic Blood Pressure	133
XIII	Peak Diastolic Blood Pressure	134
XIV	Peak Mean Blood Pressure	135
XV	Peak Pulse Pressure	136
XVI	Peak Heart Rate	137
XVII	Initial EMG Low Frequency Power	138
XVIII	Initial EMG rms Voltage	139
XIX	Final EMG Low Frequency Power	140
XX	Final EMG rms Voltage	141
XXI	EMG Low Frequency Power Increase	142

APPENDIX Page

XXII EMG rms Voltage Increase 143

XXIII Individual Coefficients of Variation for Daily Determinations of MVC 144

CHAPTER I

INTRODUCTION

Controversy has existed concerning the relationships between muscular strength and endurance since the 1950's, when Tuttle, Janney, and their co-workers, in two frequently cited studies on grip strength and leg and back strength (107,106), suggested that, for a given time, "stronger individuals can maintain a smaller porportion of their maximum strength than those with less initial strength."

Need for the Study

There is general agreement that the development of strength enables a given absolute tension (a fixed number of kilograms or pounds) to be maintained for a longer period of time. Correlation coefficients of .70 or more are common for this relationship between isometric strength and absolute isometric endurance. When the tension to be maintained is a given percentage of each individual's own maximum strength, some investigators have found that the endurance is no longer related to strength, and strong and weak subjects perform equally well (9,10,11,13,86,87,88). Others have found significant negative correlations, supporting the findings of Tuttle's group, namely, that weaker subjects out-perform stronger individuals when the load is related to each person's own maximum strength (17,18,49,72). A third group of studies is somewhat equivocal (16,71,97, 102): although only a few statistically significant relationships were

shown, correlation coefficients for the strength vs. relative endurance relationship were consistently between -.20 and -.60, with most near -.40, suggesting that there may, in fact, be a relationship which was not brought out because of experimental limitations such as samples which were too small or too homogeneous. In all the literature, the only positive correlation coefficients for strength and relative endurance are reported by Shaver (96,98), who has confused the measurement of relative and absolute endurance.

It has been suggested on one hand that there is no theoretical or physiological reason to expect a better performance by weaker subjects. Caldwell has concluded that the relative loading technique removes endurance differences related to strength and that any remaining differences are due to differences in physical conditioning, motivation, or some other variable (12). Other authors have suggested that there are strength-related differences which are related to the metabolic demands and the degree of occlusion of blood flow in the muscles (17,102). Lind and others (47,60,62) have shown that occlusion of blood flow during isometric contractions is reflected in marked changes in blood pressure and lesser changes in heart rate. Since muscular fatigue rate, oxygen supply, and the cellular metabolic apparatus have been shown to be related to muscle fiber type, and this, in turn, to be related to the pattern of recruitment of motor units within the muscle, the electromyographic study of the muscle action potentials may reveal further physiological differences which may help to explain differences in endurance performance.

The conflicting research results and the lack of an adequate theoretical basis suggested the need for:

1. explanation of the conflicting results in prior research,
2. construction of a theoretical framework to allow future research to be better directed and to allow alternative hypotheses to be tested, and
3. experimental studies directed at testing specific hypotheses to permit a more refined understanding of the influence of various anthropometric, physiological, and environmental variables on endurance and fatigue.

Purpose of the Study

The purposes of this study were, first, to determine the relationships between isometric strength and relative endurance at four levels of tension (15, 25, 50, and 75% of maximum strength) at which negligible, partial, or complete occlusion of blood flow is thought to occur, and, second, to evaluate the blood pressure, heart rate, and electromyographic responses in order to develop further hypotheses towards a physiological explanation of the findings. Subjects were chosen to represent extremes of strength and muscular endurance conditioning in the population, where, if there are consistent differences, they may be expected to be most clearly revealed.

Several basic hypotheses were tested.

1. That there is no relationship between isometric muscular strength and relative endurance, with the alternative hypothesis that there is a negative relationship.
2. That the relationship between isometric strength and relative isometric endurance is constant at various levels of tension at which negligible, partial, or complete occlusion of blood flow is thought to occur.

3. That individual differences in the elevation of blood pressure and heart rate during fatiguing isometric contractions with constant relative loads are not related to differences in strength.

4. That changes in the electrical power and frequency characteristics of the electromyogram during such contractions are not related to differences in strength.

5. That individual differences in blood pressure, heart rate, and electromyographic responses are not related to differences in endurance.

Definition of Terms

In the original studies of Tuttle et al. (106,107), maximum strength was taken as the highest value recorded during a maximum contraction maintained for 30 or 60 sec, usually at or near the beginning of the hold. Since, as Caldwell (13) has shown, this is not a good measure of the maximum force which can be exerted in an independent, brief contraction, strength is now usually defined as the maximum isometric force which can be exerted in a given position during a steady contraction of about three to eight seconds. In some cases, the peak tension recorded is taken as the maximum strength; in others, integrated or averaged values are taken over a period of from one to three seconds. There is still little agreement as to whether the highest or an average of several such measures best represents the true maximum. The value obtained is commonly referred to as the maximum voluntary contraction (MVC).

Muscular endurance may be defined as the ability to exert tension continuously or repetitively. Endurance performance is divided into two basic categories: the first, known as isometric, static, or tonic endurance, is the ability to maintain tension continuously or intermittently in a fixed position; the second, variously known as isotonic, dynamic, or

phasic endurance, is the ability to maintain tension and rate during a series of repetitive contractions through a given range of motion. Both forms of endurance may be further classified as absolute or relative according to whether the measurement is reported in absolute terms such as kilogram-seconds or foot-pounds, or whether it is related to the maximum strength of each individual, e.g., % MVC × seconds. Differences in endurance may be compared, for instance, by determining the time for which a fixed number of kilograms can be held by each subject (absolute isometric endurance), or by the maximum endurance time (MET) for which each individual can hold a given proportion of his own maximum strength (relative isometric endurance). The value obtained by integrating the force exerted over time (force × time for a constant load) is frequently used as a measure of the physiological effort expended. It is defined here as isometric work, although it must be understood that no work in the physical sense is performed in static contractions.

In this study systolic and diastolic blood pressures are defined as the cuff pressures at which the first and last Korotkoff sounds were heard. The time delay from the measurement of systolic to diastolic pressure was generally in the range of ten to thirty seconds, but they are reported as if occurring simultaneously at a time approximately midway between the two. Pulse pressure is the difference between systolic and diastolic pressures, and mean blood pressure is calculated as (diastolic pressure + 1/3 pulse pressure). Peak blood pressures and peak heart rates, defined as the highest values recorded during a given test, are measured as described in the Methods section.

EMG rms voltage is defined as the root mean square (rms) amplitude of an eight-second sample of the surface electromyogram as estimated by a Fast Fourier Transform of the digital conversion of the original analog EMG signal. It includes the power in the whole 4-200 Hertz (cycles per second) range. The percentage of the total EMG power which is determined by Fast Fourier Analysis to occur in the 4-40 Hz frequency range is referred to in this study as the EMG low frequency power. Initial and final values of these parameters at the beginning and end of the endurance hold were determined as described in the Methods section. EMG low frequency increase (LFI) and EMG rms voltage increase (VI) were obtained by subtraction of initial from final values. They indicate the changes in the EMG characteristics which occur during the course of the endurance hold.

CHAPTER II

REVIEW OF LITERATURE

Strength vs. Endurance Relationships

In 1950, Tuttle, Janney, and Thompson (107) reported a study in which the grip strength of the right and left hands of 200 normal males aged 20-30 years was measured with a dynamometer and recorded on paper over a period of one minute. Maximum strength was taken as the highest value recorded on the chart. Strength endurance was defined as the average strength for one minute expressed as pounds and measured from the area under the curve. A correlation of maximum strength with the absolute strength endurance gave correlation coefficients of .67 for the right hand and .66 for the left, indicating that the individuals with the greater maximum strength had a greater level of absolute endurance. However, when the percentage of the maximum grip strength which was maintained for one minute (an expression of relative endurance) was correlated with maximum grip strength, the coefficient for the right hand was -.40 and for the left -.41, suggesting that stronger individuals can maintain a smaller proportion of their maximum strength for a given time than those with less initial strength. A similar study of leg strength and back strength by Tuttle, Janney, and Salzano (106) in 1955 produced similar conclusions. Correlation coefficients for strength and absolute endurance were all above .90, for both 30 sec and 60 sec holds. Correlation of strength with percentage of maximum strength gave

coefficients of -.81 (30 sec) and -.48 (60 sec) for the back, and -.26 (30 sec) and -.47 (60 sec) for the legs. In both studies, the use of initial strength during an endurance hold to represent maximum strength may have given spuriously high correlation coefficients, since, as Caldwell has shown (13), decline in strength during a 60 sec hold is more closely related to initial effort than to maximum strength determined independently.

Monod (74), Monod and Scherrer (75), and Scherrer, Bourguignon, and Monod (94) showed for four different muscle groups of the arms and legs that a general hyperbolic function can be determined for the endurance time vs. force relationship and that it is independent of the different strength levels of the subjects if force is given as a percentage of maximum strength. Rohmert (86,87) drew similar conclusions from his studies using 13 holding tasks with the arms and legs. He concluded more recently (88) that the same general relationship between relative endurance and relative force for static muscle tasks was unaffected by differences in maximum strength, sex, or resting muscle length, or by isometric training. Caldwell (10), using a horizontal manual pull task, reported that relative endurance at 25, 40, 55, 70, 85, and 100% MVC was not related to strength levels in 18 men and 18 women in spite of the fact that on the average the men were twice as strong as the women. In other studies, he found a non-significant negative correlation between strength and the mean percentage of strength supported for 60 secs (13), and no relationship between strength and holding time with loads of 30, 50, 60, 70, and 80% MVC (11,14), or in 20 different body positions with a load of 80% MVC (12).

A number of investigators, in support of Tuttle et al., have found a significant negative relationship between strength and relative endurance. Clarke (24) drew conclusions similar to Tuttle's based on his own work with Irish (49), who reported a correlation coefficient of -.38 using repetitious elbow flexions. In tests of right elbow flexion in the supine position, Start and Graham (102) found a correlation coefficient of -.36 between strength and relative isometric endurance at 62.5% MVC in 30 fit college males. Analysis of variance showed insignificant differences among three groups divided according to strength. Martens and Sharkey (71) used 37.5% MVC in a similar study on 20 young men aged 18-27 years and found a correlation coefficient of -.42 between strength and relative endurance. Kroll (55), investigating fatigue patterns during serial, maximal, isometric flexions of the wrist, found that low-strength subjects showed a slower fatigue pattern than medium- and high-strength groups. With similar apparatus, McGlynn (72) tested 30 untrained controls and 30 experimental subjects before and after 20 days of isometric training. He found a negative and generally significant relationship between maximum strength and percentage of maximum strength held for 100 sec, all seven reported correlation coefficients falling between -.20 and -.63. In a study on 47 male college students divided into three groups on the basis of strength, Carlson (17) found that the low strength group was able to maintain tension levels of 50, 60, and 70% MVC longer than the high strength group but that the holding times of the three groups were almost identical on the 80% measure. In a similar study with loads of 30, 45, 60, and 75% MVC, Carlson and McCraw (18) concluded, on the basis of analysis of variance among groups, that the

weak subjects performed significantly better than the strong subjects on the light loads with no differences existing on the heavy loads. The correlation coefficients for the strength vs. relative endurance relationship at the four test levels ranged from -.46 to -.60. Byrd and Hills (8) trained six adult males for four weeks by daily isometric bouts, exerting maximum grip strength and holding it until a 50% strength decrement was observed. Using the same task as a test, they found increases in endurance occurring without concomitant increases in strength but, when there was a rapid strength increase, there was coincident with it a sharp decrease in endurance. This suggested that relative endurance may be largely dependent on factors other than strength, but that to some extent, at least, increased strength due to training may be associated with decreased relative endurance.

Shaver (95,96,98) is the only author to have reported consistently positive correlations between maximum isometric strength and relative endurance, and this is attributable to confusion in the definition and measurement of relative endurance. In one study (95,96) Shaver tested 40 young college males on repetitions of dynamic elbow flexions at 20, 25, 30, and 35% MVC and reported correlation coefficients for "maximum isometric strength" and "relative isotonic endurance" of between .04 and .81. A second study (97) on 40 college males resulted in a strength vs. "relative dynamic endurance" coefficient of -.19 on the bench press lift with 75% MVC. Elbow flexion with loads of 35, 40, and 45% MVC was used in a third study (98) on 120 college athletes divided into three groups on the basis of strength. Results were taken to indicate that "there was a positive relationship between maximum isometric strength and

relative isotonic endurance for each experimental group at all relative loading levels." The negative coefficient (r = -.19) is the only one obtained using the usual measurement of endurance time to determine relative endurance. In obtaining the positive coefficients, Shaver has used the relative loading technique for dynamic contractions, but has then taken the product of the absolute value of the force and the endurance time as the measure of relative endurance for each subject. By using the absolute force he has reverted to an absolute measure of endurance even though it was obtained using the relative loading technique. The proper conclusion from these results is that at a given relative load, stronger subjects are able to perform a greater absolute amount of work than weaker subjects. At the same time, a negative relationship is possible between strength and endurance time.

Theoretical and physiological questions suggested the need for a study with widely differing relative loads involving different levels of blood flow and motor unit recruitment. The range of strength vs. relative endurance relationships from zero to highly negative suggested that there may be a relationship, the existence and physiological basis of which may best be revealed in subjects at the extremes of strength and endurance training whose muscles have had several years to develop different characteristics.

Cardiovascular Responses

Several authors who have found relationships between strength and relative endurance have offered explanatory hypotheses, generally related to the occlusion of blood flow within the muscles during

contraction. As the first to measure forearm blood flow during static contractions, Grant (36), in 1938, concluded from his plethysmographic measurements that "a sustained contraction of the muscles compresses the vessels; the degree of compression depends on the strength of contraction; it is insufficient to prevent, but controls the degree of, dilatation and increase of flow which develop while contraction is maintained." Shortly afterwards, Barcroft and Millen (1) measured blood flow plethysmographically in the calf muscles during isometric contractions at tensions which were related to MVC. They found that blood flow was occluded at tensions as low as 20% MVC, a result which later evidence suggested was probably due to the "nipping" of blood vessels between moving and non-moving tissue (30).

In a series of papers, Lind and his associates (25,30,47,59,60, 61,62,63) reported that during continuous hand-grip contractions forearm blood flow increased at a rate which was directly related to the relative tension being exerted regardless of the size and strength of the muscles involved. The increased blood flow was attributed to a rise in both systolic and diastolic blood pressure and to an increase in heart rate. At tension levels below 15% MVC, blood flow, blood pressure, and heart rate all increased to a steady level which appeared to be adequate to meet the metabolic needs of the muscle. The level was graded according to the relative tension exerted. At tensions above 15% MVC a continued increase occurred in all three parameters until the point of fatigue, at which the absolute level of blood pressure was quite constant for an individual. However, the absolute blood flow at the point of fatigue was less at higher tension levels until, at a tension slightly above

70% MVC, it was completely occluded. The authors concluded that the blood flow requirements were determined by the metabolic activity of the muscle, which was a function of the relative tension. Below the level at which occlusion began (approximately 15% MVC in the forearm muscles), the flow was increased by a graded increase in blood pressure and heart rate. Above this level, the authors suggested, mechanical occlusion led to a rapid compensatory increase in blood pressure, which continued to rise in response to inadequate blood flow until the level of tension was no longer able to be maintained. At high levels of tension, the blood pressure and heart rate rose rapidly, but, since they were not able to overcome the mechanical occlusion, blood flow was inadequate and fatigue occurred rapidly. In that case, a marked hyperemia occurred during recovery.

Royce (90), studying fatigue curves for the forearm muscles during static contractions, found no difference between the curves obtained with and without artificial occlusion of the circulation until the force became less than 60% MVC. Below this critical level, the force exerted continued to diminish with occlusion, but levelled off without occlusion, leading the author to suggest that at that point the intra-muscular pressure was exceeded by the systolic blood pressure and occlusion due to intra-muscular compression was incomplete. Start and Holmes (103) and Start (101), investigating local isometric endurance with open and artificially occluded circulation of the elbow flexors, also found that occlusion was almost complete at 66.7% MVC. They suggested that "with occluded intramuscular circulation, there is a finite reserve of energy, the rate of dissipation of which depends on the rate of working of the

particular muscle group." Once this reserve is exhausted, or the build-up of catabolites reaches a critical concentration, "local muscular fatigue" occurs, according to these authors. They further suggested (102) that absolute isometric endurance is related to strength when tension is sufficient to cause intramuscular vascular occlusion, but that "when the tension produces only partial occlusion the local circulatory efficiency has to be considered and the relationship of endurance to strength becomes less until with very light loading the factors causing cessation of work might bear little relation to strength." If these relationships hold for absolute endurance, then relative endurance and strength should not be correlated at high relative tensions. Myers and Sullivan (77), also studying endurance of the elbow flexors with and without artificial occlusion, showed that at 25% MVC, occlusion of the flow of blood into the active muscle reduced the endurance time to less than 50% of the unoccluded value, demonstrating the importance of the intra-muscular circulation.

The fact that blood flow through the muscles is gradually occluded as tension increases has been well substantiated by a variety of methods, but the assumption by some authors that the occlusion is caused by compression of the vessels may not be justified. Nilsson and Ingvar (78) studied muscle blood flow in the anterior tibial muscles of humans during fatiguing tetanic contractions. Using the Xe^{133} clearance method to measure blood flow and an intramuscular catheter to measure intramuscular pressure, they found that muscle blood flow ceased when intramuscular pressure slowly increased to about 80 mm Hg and re-appeared when intramuscular pressure fell to about the same level. Gray et al. (37) studied

the intramuscular vessels of rats and dogs. Arteriograms and venograms made before, during, and after maximal contractions showed numerous localized compressions and pinching of both arteries and veins, but no compression of the micro-vasculature. Gray and Staub (38) found that vascular resistance increased gradually with increasing contraction strength. Mortimer et al. (76) using the Xe^{133} clearance method found that muscle blood flow in the human biceps gradually increased with tension to about 50% MVC and then gradually dropped with higher tension. Since blood pressure has been shown to rise with increasing tension, the reduced blood flow must have been due to occlusion. Gray et al. (37) suggested that the gradual increase in vascular resistance may be due to the all-or-none occlusion of individual vessels occurring at different tension levels. The fact that recovery hyperemia occurs at tension levels above, but not below, 15% MVC in many static contractions (30) suggests that this may be the level at which occlusion begins in these contractions.

There is no evidence to support the hypothesis of some authors that muscular fatigue is the result of a toxic concentration of metabolites. There is evidence to indicate that the hydrolysis of ATP for the immediate energy of contraction and the subsequent re-phosphorylation of ADP depletes the phosphocreatine stores of the muscle resulting in fatigue, or the inability to maintain the level of contraction (3,34,100).

Carlson (17,18) suggested that at the intermediate tension levels, at which circulation is apparently inadequate, the vascularity of the muscle tissue may be the important factor in explaining a negative relationship between strength and relative endurance. Roberts et al. (84)

and Wearn (108) had found that in hypertrophied hearts the size of the muscle cells had increased, with a resultant decrease in the capillary to fiber ratio. Similar findings in animal skeletal muscles by Krogh (54) led Carlson to suggest that "the relative amount of blood available to a specified portion of a muscle is greater in a weak muscle than in a strong muscle," since the strong muscle has undergone hypertrophy without a comparable increase in vascularity. After endurance training, muscular hypertrophy in animals (19) and humans (45) has been shown to be accompanied by an increased capillary-to-fiber ratio which maintains the capillary density of the muscles.

The search for a physiological explanation of strength vs. endurance relationships requires the measurement of physiological variables. Although previous studies have not included measurement of hemodynamic factors, the close relationship of blood pressure to relative loads suggests the need for study of its involvement in relative endurance performance. Peak values of blood pressure and heart rate may be useful indicators of cardiac load and potential risk.

Electromyographic Responses

In any determination of voluntary muscular strength or endurance motivation is an important variable. The poor repeatability ($r = .60$) commonly reported (9,15,18) for maximum endurance times may be due in part to motivational factors, especially at the lower tension levels, where protracted pain and boredom are problems. On the other hand, Missiuro et al. (73) recorded different EMG patterns during fatiguing contractions at very low and higher levels of tension and suggested that

there may be two different fatigue mechanisms operating at different levels. Several authors (20,21,29,53) have suggested the use of electromyographic techniques as a means of objectively evaluating the state of fatigue during muscular endurance tasks. In much the same way as they are commonly used in the evaluation of neuro-muscular disorders (2,22, 57,85), EMG techniques may also be expected to provide objective evidence of any differences in motor unit recruitment patterns and their changes during sustained contractions in muscles of different strength levels. The study of EMG changes has become a most useful means of describing and explaining physiological changes related to strength and endurance performance.

The complex wave form of the surface EMG is the result of the summated muscle action potentials of many motor units active in the section of muscle beneath the active electrode. In general, two forms of EMG analysis are employed. The simpler, and more common, is the measurement of the amplitude or power of the signal over a given sampling period. This is usually expressed as the integrated value of the amplitude over the sampling period or as the root mean square (rms) voltage. The more complex, but perhaps more revealing, method is to analyze the complex EMG wave form into its component frequencies either by passing the signal through appropriate band filters or, after converting the analog signal to digital form, by the mathematical procedure known as Fourier Analysis. The EMG wave form can be shown to be composed of the summation of an infinite number of sine waves of various frequencies and amplitudes (28, 85). A histogram, or normalized power spectrum, can then be constructed showing the percentage of the total power of the signal which can be

attributed to sine waves within a selected range of frequency bands (20, 21). The surface EMG requires analysis of a range of frequencies up to about 200 Hz (40,50,52,91).

During fatiguing contractions two characteristic changes occur in the surface EMG. Many investigators (29,32,50,51,56,67,73,94) have shown that the amplitude increases as a function of time when the muscle works against a constant load, although there is some disagreement as to whether the increase is linear or curvilinear. The increased amplitude is accompanied by a shift in the power spectrum towards the low frequencies. The modal frequency in the case of the biceps brachii shifts from approximately 40-60 Hz initially to a value frequently below 30 Hz during the course of a fatiguing contraction (20,22,26,50,52,53,66). The power increase has been shown to be concentrated in the lower frequency bands (20,52,68). A high frequency decay has also been found with both needle (50) and surface electrodes (91), although it has been suggested (50) that the low and high frequency changes are the result of different mechanisms and are not necessarily simultaneous. In studies of fatigue using EMG spectral analysis, most authors have followed the time-related changes in the relative proportions of low frequency and high frequency power. Kogi and Hakamada (53) calculated a "slow wave ratio" as the quotient of the integrated amplitude of slower components below 40 Hz divided by that of components over 40 Hz in a 15 sec EMG sample. The slow wave ratio of the m. biceps brachii increased in approximately linear fashion throughout fatiguing isometric elbow flexions with various loads. The rate of increase was closely related to the load. Kadefors, Kaiser, and Petersen (50) and Chaffin (20,21) selected fixed

bands to represent the low-frequency and high-frequency components and showed an approximately linear increase in the former and decrease in the latter. Although based on different spectral parameters, namely, the percentage of total power in the 4-30 Hz and in the 60-100 Hz bands, Chaffin's findings closely parallel those of Kogi and Hakamada in that the rate of change is closely related to the load and at the point of fatigue the relative proportions of power at low and high frequencies are fairly constant across loads.

In the preceding studies three possible methods of determining fatigue rate by objective EMG techniques have been suggested: (1) the rate of increase of EMG amplitude, (2) the rate of increase of the low-frequency components of the EMG power spectrum, and (3) the rate at which a predetermined value of slow wave ratio or percentage power in a given frequency band is reached. DeVries (29), measuring the integrated EMG of the biceps brachii, related the log transformation of the slope of the amplitude curve to maximum endurance time for 14 subjects performing right elbow flexions. He obtained correlation coefficients of -.47 at 50% MVC, -.68 at 40%, and -.62 at 30% MVC. The coefficients were increased when MVC was estimated from efficiency of electrical activity (integrated EMG vs. tension slope coefficient) rather than measured directly. The slopes showed a wide variation among individuals and considerable overlap across tension levels. Chaffin (20), finding a good relationship between percentage of power in the 4-30 Hz band and subjective discomfort up to the point of inability to sustain the contraction, suggested the use of an assumed fatigue limit, such as 43% of total power in the 4-30 Hz band, in designing industrial tasks.

The usefulness of such techniques to predict fatigue limits for a specific individual, rather than an industrial population, is limited by the considerable inter-individual variability, which may lead to prediction errors as great as 100%. This is well demonstrated by the results of Kogi and Hakamada (53), who found that increases in the slow wave ratio corresponded well with pain sensations. However, at the point of abandonment of the contraction, the terminal value of the slow wave ratio in different individuals ranged from 150 to 300% of its initial value. A further difficulty in using EMG parameters such as slopes and end-points to measure fatigue is that inter-individual differences are great not only at the point of fatigue but at the beginning of the hold. Kogi and Hakamada (53) reported distributions of amplitudes and slow wave ratios for m. biceps brachii of 223 subjects during elbow flexion at 90° with 6 kg supported at the wrist. The amplitudes ranged from 30 to 230 in arbitrary units of integrated value, while slow wave ratios ranged from .25 to .85. Initial amplitude values vary also from muscle to muscle, but show a fairly linear increase with tension in any one muscle (4,32,48,50,53,65,109). Spectral ratios such as those used by Kogi and Hakamada (53) and Chaffin (20) appear to remain fairly constant at different tension levels, but vary in different muscles (22,44).

Although a great deal remains to be done in clarifying the relationships between EMG parameters and performance and physiological variables, EMG research has thrown some light on the neuro-muscular changes occurring during fatigue. Norris and Gasteiger (79), by means of a micro-electrode technique, studied the discrete action potentials of single motor units in normal muscle. The motor unit action potentials

tended to increase in amplitude with increasing excitation and tension, a fact the authors attributed to an increase in the number of active muscle fibers in the successive discharges of a single motor unit. In weak and moderate contractions, increase of tension was accompanied by increased frequency of discharge of the active motor units and by recruitment of motor units previously inactive. At stronger tensions, new action potentials of slowly discharging motor units appeared, while the most excitable motor units tended to discharge in bursts alternating with periods of inactivity up to two seconds. The least excitable motor units were characterized by larger action potential amplitudes, lower frequencies of discharge and less "double discharges" and were considered to be supplied by high threshold neurons of large axon diameter. This is supported by the later work of Henneman and his group (41,42,43,80), who found that smaller motor units are innervated by smaller motoneurons with lower conduction velocities and smaller action potential amplitudes, and that the smaller units are recruited before larger ones as tension is increased.

The characteristic amplitude increase and low-frequency shift during the course of a contraction held to fatigue have been attributed to several possible physiological sources. It has been suggested (27, 32,51,67,94) that, as the muscle fibers fatigue, there is a decrease in the tension per fiber and that the electrical activity increases as more units are recruited to maintain a constant force. Eason (31) has offered a similar hypothesis with the suggestion that, since the action potentials of single motor units have been shown to decrease with fatigue (64), the reduced contractility of a motor unit possibly reflects the failure of

fatigued fibers within the unit to fire. Other authors (81,82) have attributed the amplitude increase to the synchronization of motor units. Since the electrical increase has been shown to be concentrated in the low-frequency band (53,68), some authors (50,68) have suggested that the low-frequency shift may be due, in part, to the dropping out of fatigued, rapidly-firing motor units and recruitment of new slower-firing units. Temporal grouping of motor unit action potentials is also considered to account for at least part of the low-frequency shift with fatigue (6,50, 67,94). Person (81,82) has shown that the EMG changes can be closely approximated by a model involving synchronization alone. Lippold, Redfearn, and Vuco (66) and Stern (104), from simultaneous mechanical and electrical records, found that the grouping of action potentials at a frequency of about 9-12 Hz was closely associated with physiological tremor. The former authors considered that this was due to oscillation in the stretch reflex servo loop. Although the changes described commonly occur in contractions above 10% MVC (50), Missiuro et al. (73) found a different response in repetitive, low-intensity, dynamic elbow flexions lasting from 40 to 140 min with a 2 kg load on a manual ergograph. In this case, the integrated EMG amplitude increased in several rising waves and then diminished before the point at which the contraction could no longer be maintained. No signs of synchronization were seen. The authors suggested the existence of two different mechanisms of fatigue: one peripheral, involving fatigue of the contractile apparatus, produced by intense exertion, and one central, involving diminished neural discharges, in long, low-intensity work.

The extent to which the EMG pattern is independent of motivation and other psychological variables is unclear. Missiuro et al. (73) found that, in states of sharp exhaustion after short, intense work, additional stimuli were unable to change the endurance time or EMG pattern, indicating a maximum level of response. At a low intensity of work, however, a sudden increase shortly before the end of the work of the impulses from the periphery, induced by ischemia, increased load, and occasionally also verbal stimulation, was able to increase the recruitment of additional motor units or intensity of the action potential discharges. Lloyd has suggested a much more prominent psychological effect on the EMG. Based on Surwillo's demonstration (105) of a significant increase in EMG amplitude when an incentive was provided during a submaximal contraction, and their own findings of a close relationship between EMG amplitude and symptoms of pain during holds of 25 and 50% MVC, Lloyd et al. (70) interpreted the point at which the EMG amplitude significantly increased to be the point at which the active muscle is fatigued. Additional contraction time was proposed to result from increased cortical recruitment, the length of which was determined by motivational elements. A later study by Lloyd (69) showed that, with auditory feedback of the EMG signal, subjects were not able to increase endurance time, but could sustain the same contraction with less electrical activity and hence, presumably, greater muscular "efficiency." Even though the EMG reflects physiological events within the muscle, it cannot be claimed with certainty that the EMG signal is entirely independent of motivational and other psychological factors.

Despite the uncertainty of the physiological mechanisms responsible for changes in the EMG signal, its relationships to the fatigue process indicate the need for further investigation of the time course of both voltage and spectral changes. In this study EMG rms voltage and EMG low frequency power (percentage of power in the 4-40 Hz frequency range) were chosen to represent both forms of analysis. Initial and final values and changes in these EMG characteristics were evaluated in relation to individual differences in performance in strength and endurance.

CHAPTER III

METHODS

Subjects

Thirty young, Caucasian, male subjects were selected so as to provide a broad range of strength levels. They were divided into three groups of ten according to elbow flexion strength. An additional fourth group was composed of ten highly trained competitive swimmers who had trained specifically for cardiovascular and muscular endurance.

Group H.--High strength: mostly weightlifters and bodybuilders, or football players with a background of several years of weight training.

Group M.--Medium strength: subjects whose strength levels fell between those of the high-strength and low-strength groups.

Group L.--Low strength: the ten subjects with the lowest strength scores determined as described below (see p. 29).

Group S.--Swimmers: trained competitive swimmers swimming over 4,000 meters daily and with at least two years previous training. These subjects were highly trained for cardiovascular and muscular endurance, particularly of the arms, but had done little or no specific strength training.

Test Procedures

Each subject was tested on five occasions, a minimum of 24 and usually at least 48 hours apart, to avoid residual fatigue effects. Anthropometric measurements were made on the first day (see p. 34).

On each occasion maximum right elbow flexion force was determined in the seated position (Figure 1), and the subject was then asked to hold a given proportion (15, 25, 50, or 75%) of this maximum voluntary contraction (MVC) for as long as possible. Surface electromyographic (EMG), electrocardiographic (ECG), blood pressure, and force measures were obtained both during the hold and for five minutes of recovery. All force measurements were made in pounds and subsequently converted to kilograms.

Tests of right elbow flexion strength were performed with the subject seated in a specially constructed chair, elbow supported at the side and flexed to 90°, forearm horizontal, and hand in the semi-prone position. Body position was fixed by means of lateral hip restraints, a seat belt, padded metal shoulder restraints, and padded elbow support. The legs were permitted to hang free or rest on a wheeled cart in a position which prevented their use for obtaining leverage.

Loads were applied to a padded wrist strap 8 cm wide, positioned with its leading edge immediately over the distal epicondyle of the radius. The wrist strap was attached to a force transducer which was connected to a base board by means of an adjustable length of chain for the determination of maximum force, and to a metal tube loaded with the appropriate weights for the endurance holds (Figures 1 and 2 respectively). The elbow support was adjusted to the appropriate horizontal and vertical co-ordinates to provide a comfortable arm position with the elbow directly beneath the shoulder in the antero-posterior plane and abducted approximately 5 cm. The position of the chair and the length of the chain to which the wrist strap and load cell were attached were adjusted

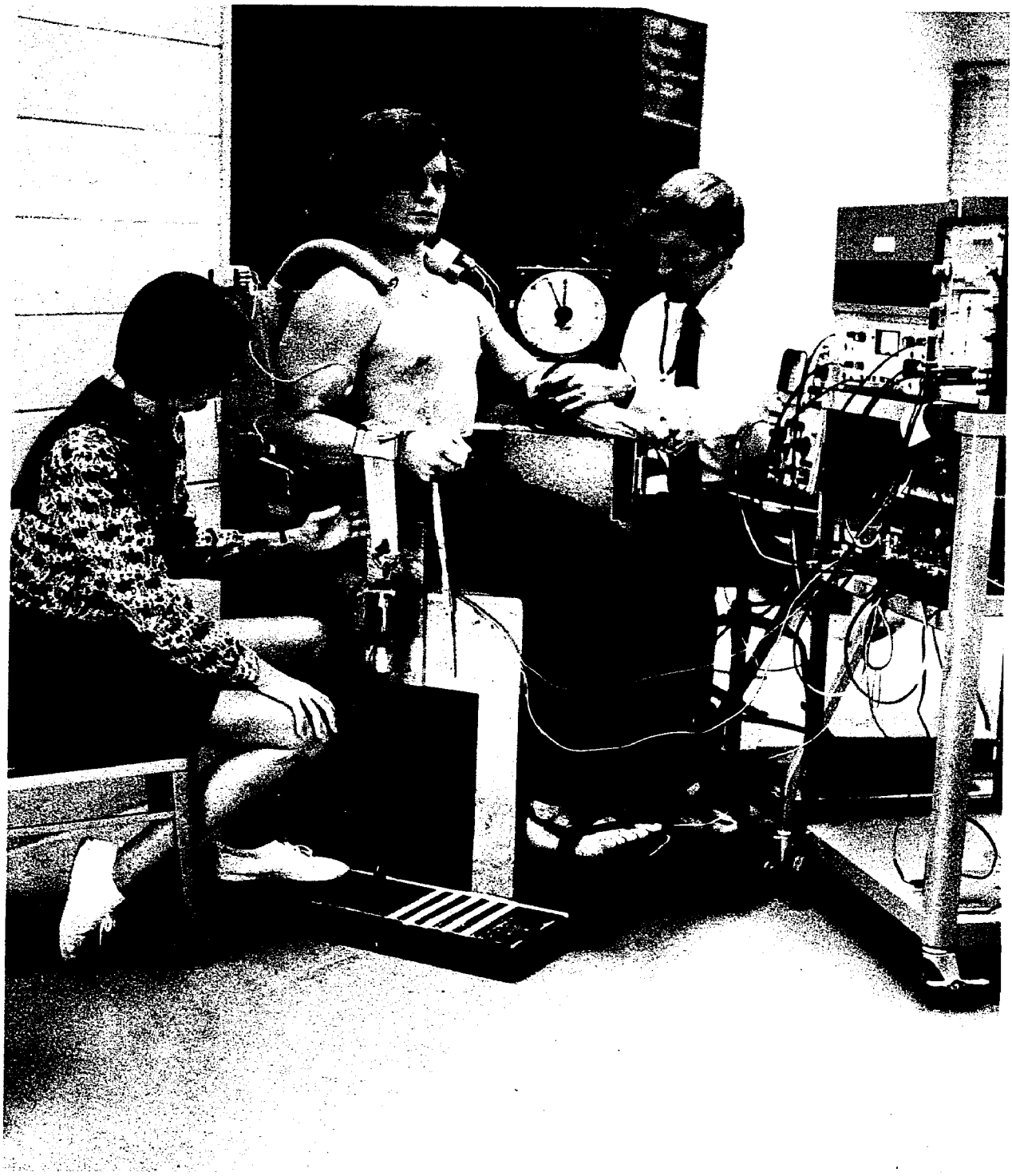


Figure 1. Arrangement of subject, investigators, and equipment during maximal voluntary contraction.

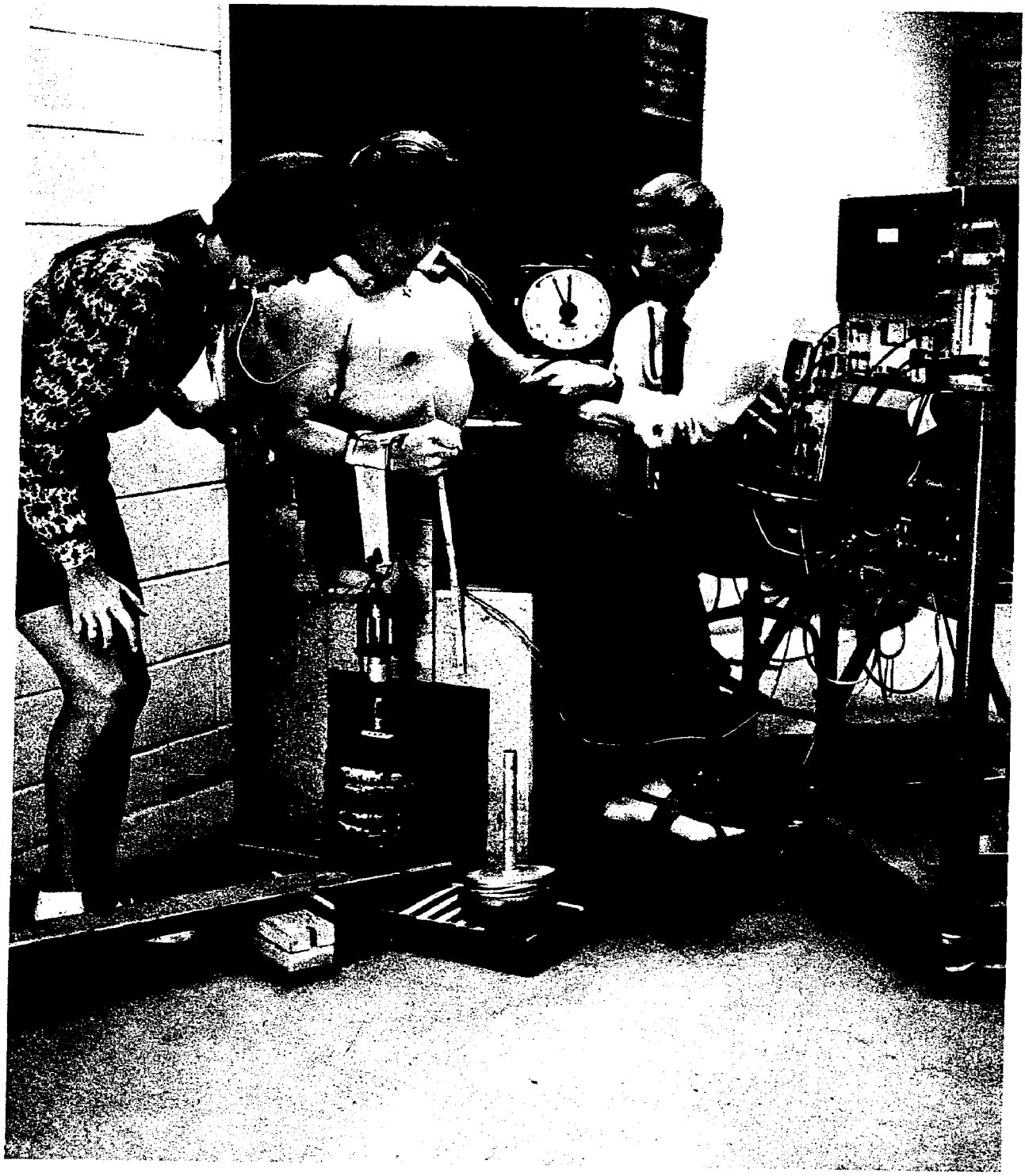


Figure 2. Arrangement of subject, investigators, and equipment during endurance hold. The small load is the 15% MVC load used for the EMG recordings during recovery.

so that the forearm was horizontal and the direction of pull vertical. After the elbow angle was verified as 90° using a goniometer, a wrist guide consisting of a stretched rubber band on an adjustable wooden frame was adjusted to touch the radial epicondyle. The appropriate co-ordinates for each subject were established and recorded on the first test day and the identical settings used for all subsequent tests.

The EMG and ECG electrodes were attached and connected to their respective amplifiers, and the signals checked on the oscilloscope and chart recorder respectively.

The blood pressure cuff was placed in position on the left arm and the brachial pulse located with the forearm resting horizontally along the arm rest. Resting heart rate and blood pressure were recorded during a 15 sec period.

The subject rested his right elbow on the elbow support and the wrist strap was placed in position. The subject was instructed to exert his maximum force without jerking for about five seconds, beginning when the time indicator (tape recorder monitor) returned to zero. It was explained that the force as recorded on the chart would be integrated for one second at its highest value to give his maximum force. Sharp peaks of less than one second duration were rejected as being the result of jerking. This method had been found in pilot tests to give good objectivity. Fifteen seconds before zero the tape recorder and chart recorder were switched on and the details of the test recorded on the voice channel. The research assistant counted down the last five seconds and checked that the lift was performed correctly. After a brief maximum contraction, the recovery clock was started by the

investigator and the blood pressure taken as soon as possible, usually between fifteen and thirty seconds into recovery. Recovery ECG was recorded continuously for 67 sec and thereafter for 15 sec at the end of each minute for five minutes (Figure 3). Blood pressures were taken and recorded on the data sheet during the same periods at the end of each minute.

On the first test day, a second similar test was given with recovery recordings made for the first minute only. If the values obtained for maximum force were within five percent, the mean was taken as the maximum force for the day. If not, a third test was given and the mean of the highest two values was used. On subsequent test days, a single test was given with five minutes recovery. If this value was within five percent of the value obtained previously, it was used as the maximum force for that day. If not, the test was repeated and, if necessary, a third test given until two values within five percent could be accepted as the maximum force for that day. To this value, the weight of the load cell and wrist strap (2.09 kg) and the force at the wrist due to the weight of the forearm (see p. 35) were added to give the maximum voluntary contraction (MVC).

The appropriate load for the maximum endurance hold was calculated as a percentage of this value. The correction for load cell, wrist strap, and forearm force were then subtracted to determine the load to be added in the form of weights. This load was made up accurately on a single beam scale and suspended from the load cell. With the amplifier gain setting increased by a factor of 10, the appropriate voltage was subtracted to balance the load at the mid-position on the chart recorder

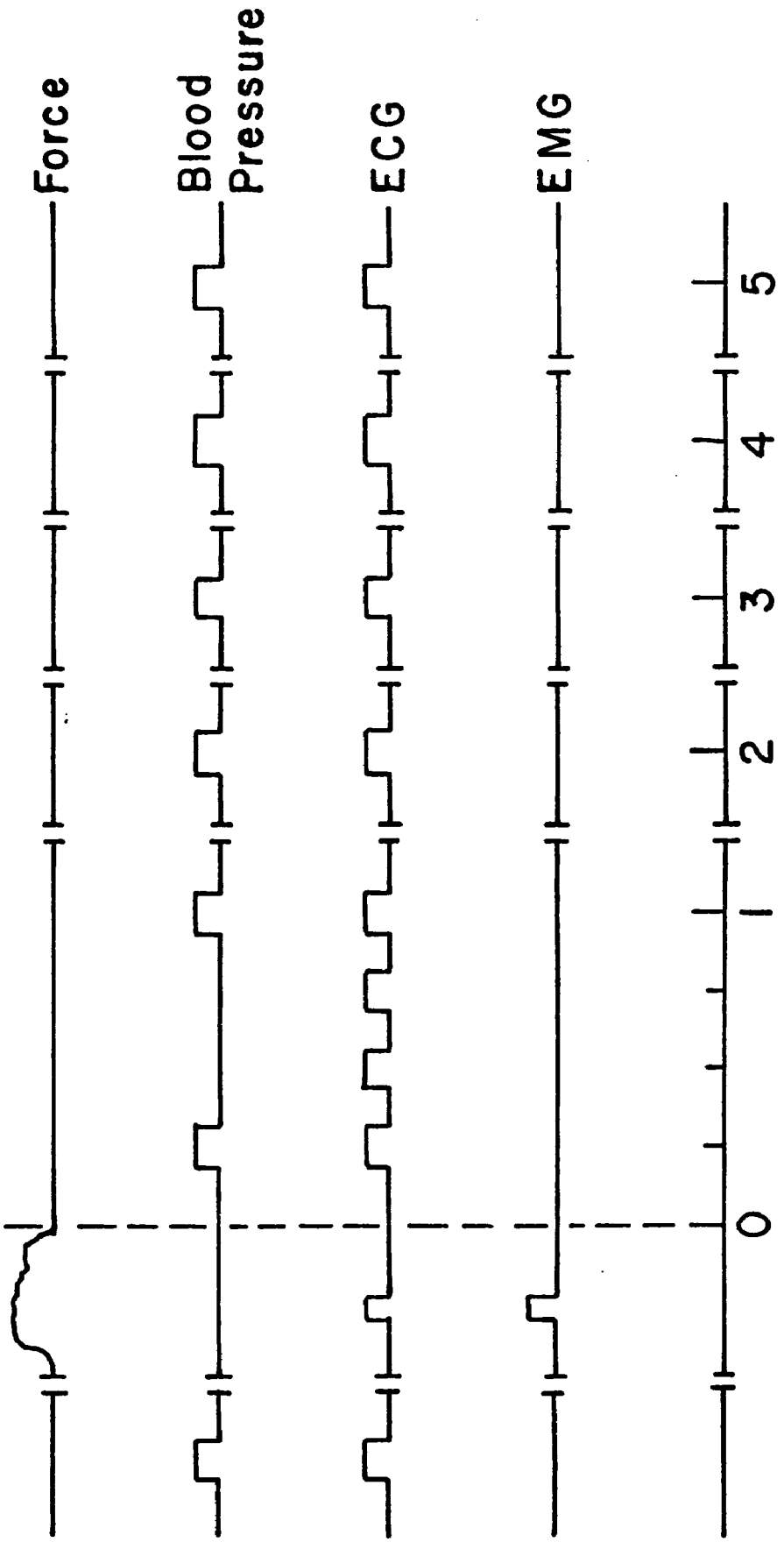


Figure 3. Sampling protocol showing times at which variables were recorded before, during, and after maximum voluntary contraction.

with sensitivity at 20 mV/div. (see p. 36). This provided a zero position around which small force variations due to tremor could be recorded during the endurance hold.

The subject was instructed to support the load suspended from the wrist strap for as long as possible and, for the longer holds, to go well beyond the threshold of pain. A clock positioned out of view of the subject was started as the hold began. Verbal motivation was provided during the later stages of the tests. The importance of maintaining the correct position was stressed. The subject was advised that the test would be considered concluded when his wrist moved out of position or dropped below the wrist guide by more than 2 cm for three consecutive seconds or on three intermittent occasions. EMG, ECG, and force were recorded continuously, and blood pressures at one minute intervals throughout the hold.

At the conclusion of the endurance hold, the endurance clock was stopped and the recovery clock started. The chart and tape recorders were allowed to run for the first 67 sec of recovery and thereafter for 15 sec every minute (Figure 4). Recovery blood pressures were taken one half minute into recovery and at one minute intervals until 4 1/2 min of recovery. From 52 to 67 sec the subject supported a load equal to 15% MVC while EMG and ECG recordings were made. This procedure was repeated every minute for five minutes of recovery. The 15% MVC recovery load was chosen so as to provide a good EMG signal while causing negligible fatigue effects during the intermittent 15 sec holds.

All tests were conducted in a closed laboratory and every attempt was made to maintain the same conditions for all tests. Room temperature

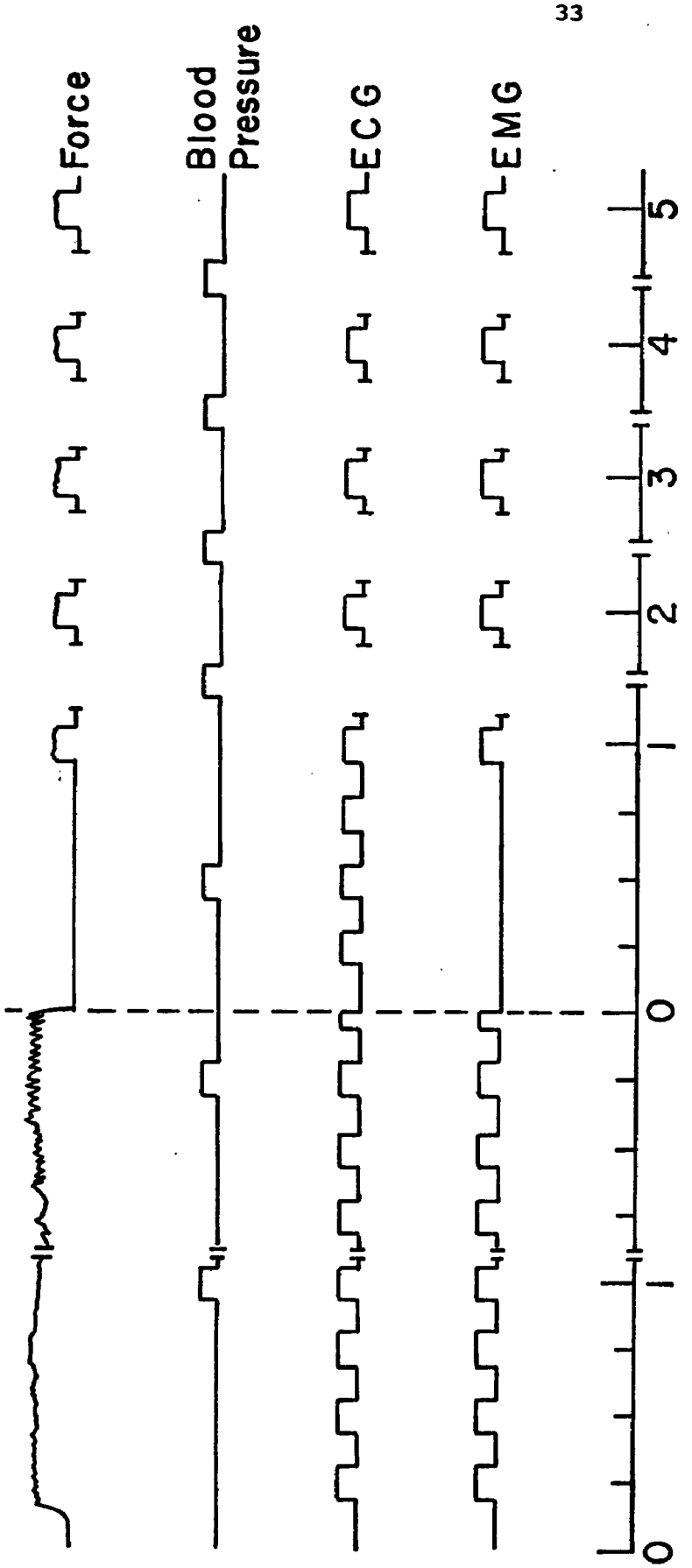


Figure 4. Sampling protocol showing times at which variables were recorded during and after endurance holds.

and relative humidity were recorded at the end of the endurance hold using a mercury thermometer calibrated in degrees Celsius and an American Standard relative humidity meter.[1] Three assistants (two male and one female) were trained to administer the tests in as nearly as possible the identical manner following a strict protocol. On each occasion all procedures were carried out by the investigator and a single assistant.

Anthropometric Measurements

Anthropometric measurements were made during the subject's first visit to the laboratory. Height was measured without shoes to the nearest millimeter using a permanently attached metric wall stadiometer. Weight was determined wearing shirt and trousers, but without shoes, using a single beam scale calibrated in pounds and ounces and tested to weigh accurately within one quarter of an ounce (.007 kg).

The subject's forearm was marked on the posterior aspect of the elbow with a line joining the most distal points of the humeral condyles. Another mark was made at the distal extremity of the radius, and the length of the forearm from this mark to the lateral condyle of the humerus was measured to the nearest half centimeter. The forearm was then immersed in water to the elbow line in a plethysmograph calibrated in divisions of .02 liters and its volume (including the hand) was determined to the nearest .01 liter. The arm was dried and re-immersed to displace half its volume. The water level was marked on the arm and

---

[1] PGS Humidity Meter Model HM101-10, accuracy = 2% at 25°C, American Standard, Special Products Department, New Brunswick, N.J.

its distance from the lateral condyle of the humerus determined as the radius of rotation of the center of gravity of the forearm about the elbow.

Using these values and an assumed value of 1.14 for the specific gravity of the forearm (83, p. 63) the force acting at the point of the center of the wrist strap due to the weight of the arm was calculated for inclusion as part of the gross load acting at that point. The formula used for the calculation was $F = 1.14V \times r/(L - 4)$, where F is the force at the wrist strap due to the weight of the arm (kg), V is the volume of the forearm (liters), r is the radius of rotation of the forearm about the elbow (cm), and $(L - 4)$ is the distance of the center of the 8 cm wide wrist strap from the elbow (cm).

Test Order

Each subject was tested on five occasions. On the first, after the anthropometric measurements were taken and MVC was determined, the subject held 25% MVC to exhaustion (Test 025). The holding time was taken as the measure of maximum relative endurance. This first test was intended to allow the subject to become familiar with the testing procedure and to minimize learning and practice effects during the other four tests designated Tests 15, 25, 50, and 75 according to the % MVC being held. It also provided, in some measure, an estimate of the reliability of the method, although this was expected to be lower than the true value, since different changes in performance were expected after the first test according to the training backgrounds and experience of the subjects. The initial test was assigned the order zero.

In order to randomize the effects of practice, the order of subsequent tests, designated one to four, was assigned using a table of random numbers, producing the test order shown in Appendix I in which each test load occurs in each order ten times. The subjects for the study were allocated numbers arbitrarily according to the order in which they reported to the laboratory for the initial test.

Data Collection

Force

Force was transduced to an electrical signal by a Statham model UC3 universal transducing cell with a model UL4 load cell accessory.[1] The signal was transmitted by shielded cable, amplified and filtered for high frequency noise by a four-channel amplifier unit, and further filtered through a low-pass filter[2] set at 10 Hz, reducing noise to a minimum. The signal was then monitored on a Clevite Brush Mark 220 chart recorder[3] and a Tektronix type 564 storage oscilloscope.[4] A four-channel FM tape recorder[5] operating at 2.06 cm (15/16 inch) per second was used to record force and also doubled as voice recorder (Figure 5).

The force system was calibrated from 0-63.6 kg (0-140 lb) and found to give a linear response throughout the range. At each test

---

[1]Statham Instruments, Inc., 12401 West Olympic Boulevard, Los Angeles, Calif 90064.

[2]Hewlett-Packard model 5489A, Hewlett-Packard Company, Palo Alto, Calif.

[3]Clevite Corporation, Brush Instruments Division, Cleveland, Ohio 44114

[4]Tektronix Inc., Portland, Oregon.

[5]Hewlett-Packard 3960 magnetic tape instrumentation recorder, Hewlett-Packard Company, Palo Alto, Calif.

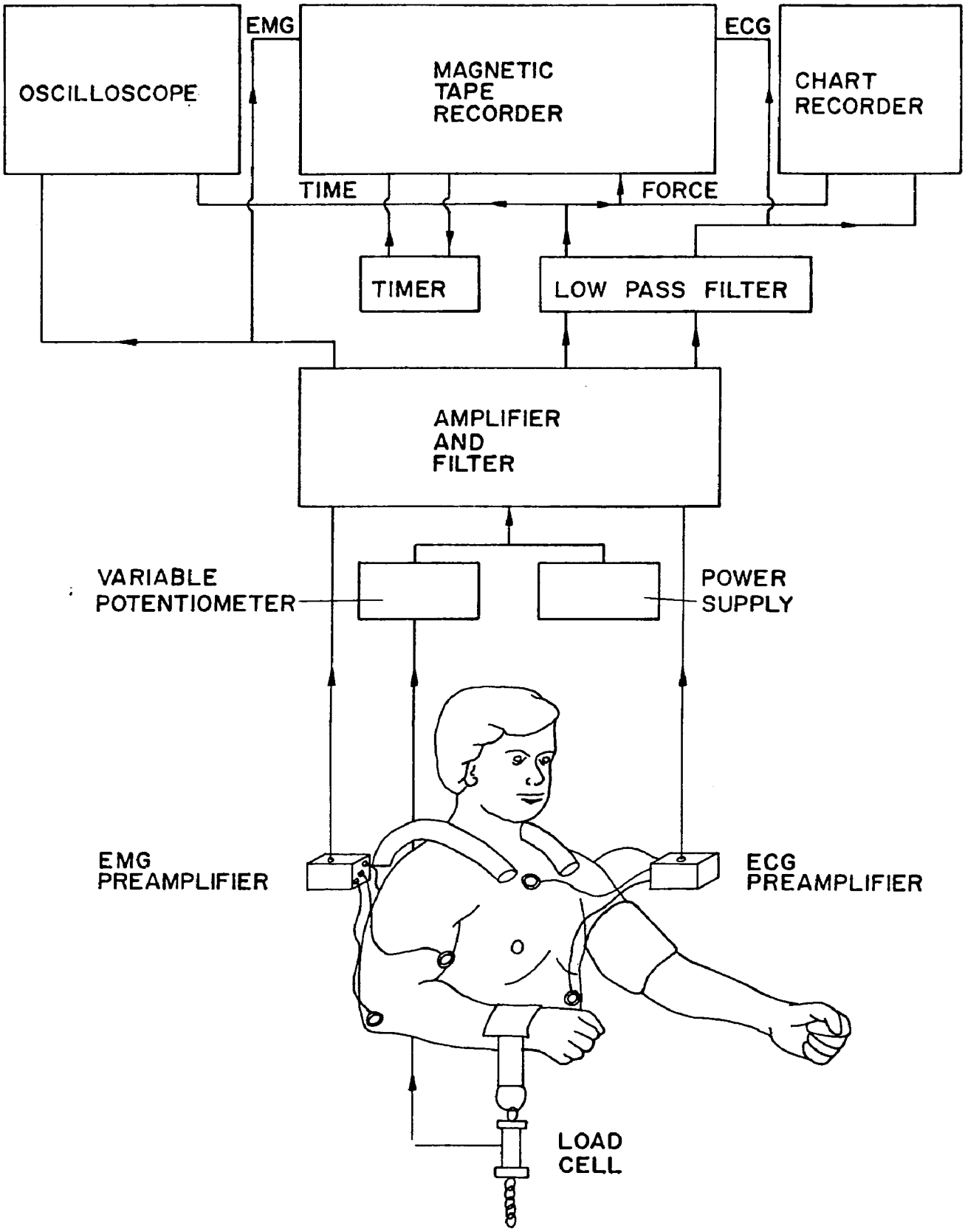


Figure 5. Flow diagram of data collection equipment.

session calibrations were carried out at zero and 45.45 kg (0 and 100 lb) with occasional checks at 9.09 kg (20 lb) intervals to verify linearity. The gain was adjusted to provide full-scale deflection on the chart recorder for 45.45 kg (100 lb) at a sensitivity of 10 mV per division. Half this gain was used for lifts over 45.45 kg (100 lb), allowing MVC to be determined with a precision of .5 kg on each test.

Time

A time reference was recorded on channel two of the tape recorder. A potentiometer driven by a small electric clock motor was used to produce a signal which increased linearly from zero to a maximum value of one volt each minute. This voltage was monitored on the monitor dial of the recorder. Endurance times were determined from the force recordings on the paper chart and verified from a Gralab Universal Timer model 165.[1] A similar timer was used to measure recovery times.

Blood Pressure

Blood pressures were determined from the first and last Korotkoff sounds by the investigator, using a standard 12 cm Baumanometer cuff[2] on the left arm and a stethoscope applied over the brachial artery in the antecubital region.

Electrocardiogram

The ECG was recorded using German silver fluid column electrodes (Hewlett-Packard 14057)[3] attached by adhesive collars over the manubrium

---

[1]Dimco-Gray Company, 207 E. Sixth, Dayton, Ohio 45431.

[2]W.A. Baum Co., 620 Oak St., Copiague, N.Y. 11726.

[3]Hewlett-Packard, 5500 Howard Street, Skokie, Illinois 60076.

of the sternum, over the sixth rib at the line of the anterior axillary fold, and the ground electrode over the seventh cervical vertebra. These positions were found to give minimal artifact during exertion and a prominent R-wave, facilitating electronic counting of the heart rate. The signal was amplified by a small DC coupled differential pre-amplifier[1] attached to the shoulder restraint, then amplified and filtered for DC bias (using channel three of the amplifier unit), and filtered through the low-pass filter set at 30 Hz to further reduce the possibility of artifact during periods of maximal exertion. The signal was then recorded on the FM tape recorder and monitored on the chart recorder.

Electromyogram

The electrode sites were prepared by rubbing the skin vigorously, first with a sponge containing isopropyl alcohol and then with a tissue pad to which Beckman Offner electrode paste[2] had been applied. This method quickly reduced resistances to below 50 kilohms, a level shown to have no significant effect on EMG power in this system (92). Electrodes were then attached using adhesive collars and Beckman Offner electrode paste to ensure good electrical contact.

The active EMG electrode was applied to the upper arm over the medial head of the biceps midway between the anterior axillary fold and the antecubital fossa. Distinguishing marks were located so as to enable relocation of the electrode in the identical position for

---

[1]Instrumentation amplifier no. 3234/15, Burr-Brown Research Corporation, Tucson, Arizona 85706.

[2]Beckman Instruments, Inc., Offner Division, Schiller Park, Ill. 60176.

subsequent tests. The reference electrode was attached over the lateral epicondyle of the humerus and the ground electrode over the medial epicondyle. When the resistances were checked and found to be below 50 kilohms, all three electrodes were then connected by short leads to a pre-amplifier (Burr-Brown 3234/15, gain = 100) mounted on the chair behind the subject's shoulder (Figure 1). The pre-amplified signal was then carried by shielded cable to channel one of the amplifier unit where it was filtered with a 1.5 Hz high pass filter to remove any possible DC bias and a 330 Hz filter to remove any high frequency noise. The characteristics of the signal in the frequency range of the EMG (4-200 Hz) were unaffected by the filters. The amplified signal was then monitored on the oscilloscope and recorded on the FM tape recorder.

Data Processing

Anthropometric variables, force, time, and blood pressure

The values of the anthropometric variables, maximum force, maximum endurance time, and blood pressures were transferred from the raw data sheets to coding sheets, punched on cards, and verified ready for computerized statistical analysis.

Electrocardiogram

The ECG signal, on magnetic tape, was replayed through a variable gain amplifier, filtered through a band-pass filter[1] set at 2-1,000 Hz, and displayed on an oscilloscope (Figure 6). The amplifier gain was

---

[1]Band-pass filter model 330N, 2 Hz-20 KHz, Kronhite, Cambridge, Mass.

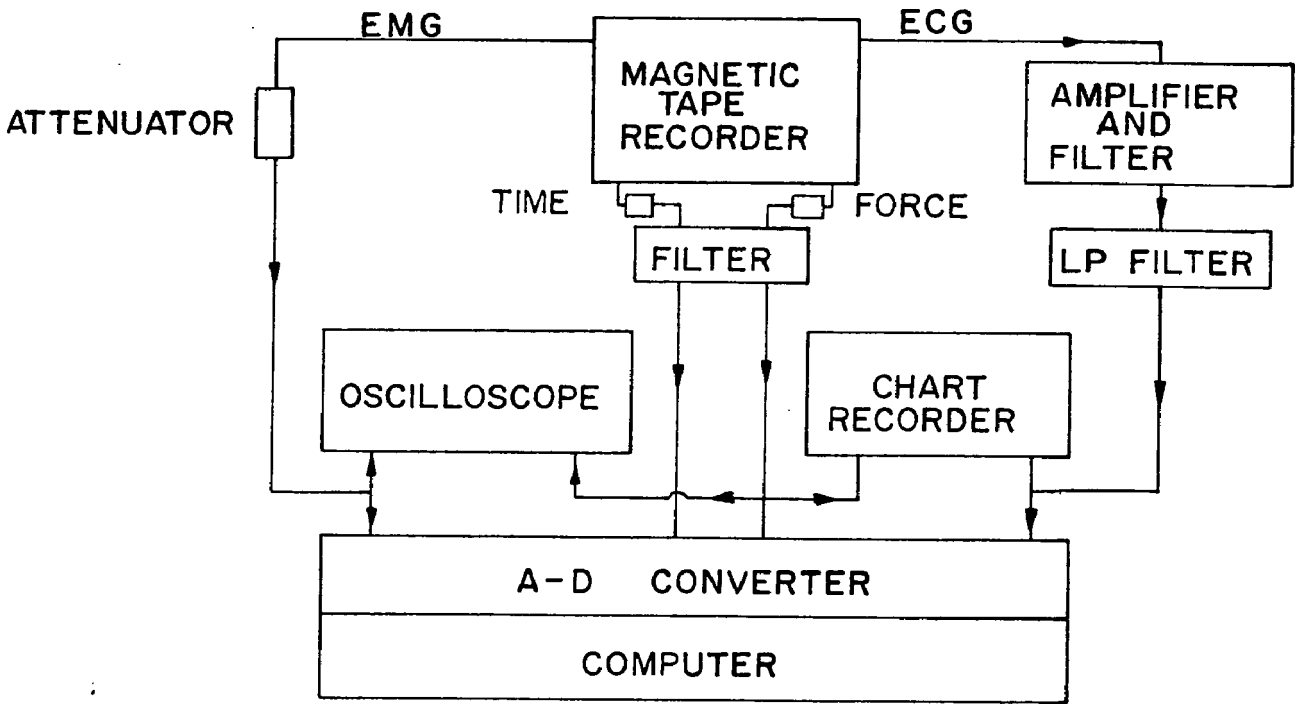


Figure 6. Flow diagram of data processing equipment.

adjusted to provide a resting R-wave peak of 1 volt, and the signal converted to digital form by a Hewlett-Packard analog-digital converter.[1] A Hewlett-Packard model 2115A computer was programmed to sample the signal according to the protocol illustrated in Figures 3 and 4. All samples were of eight seconds duration except during the maximum voluntary contraction, when a four second sample was taken. Samples were taken at rest, at 15 sec intervals throughout the endurance hold and the first minute of each recovery period, and at each minute thereafter.

Heart rates were determined by a program which calculated the mean inter-beat period between successive R-wave spikes.[2] Inter-beat periods which deviated from the mean by more than 25% were eliminated and the mean period recalculated. Heart rate was calculated from this value using the formula HR = 60 ÷ P, where HR = heart rate in beats per min, and P = mean period between R-wave spikes in sec. The paper tape computer output for each sampling period included the uncorrected and corrected heart rates and the number of spikes from which each was calculated, before and after eliminating deviant values. These values were transferred onto the University of Michigan's IBM 360/67 computer system and further screened to eliminate values for which the corrected heart rate deviated from the uncorrected value by more than ten, or for which the number of spikes sampled for the corrected value deviated

---

[1] Analog-digital converter model 5610A, Hewlett-Packard Company, Palo Alto, Calif.

[2] Time sampling and heart rate calculation programs were written by Robert Wolters, Department of Industrial and Operations Engineering, The University of Michigan.

from the number sampled for the uncorrected value by more than three.[1] This extra screening eliminated values which may have been affected by artifacts, although it did appear, if anything, too rigorous, probably screening out some good values.

At the 50 and 75% MVC levels, endurance times are sufficiently short that sampling every 15 sec may not provide a valid final heart rate. Accordingly, final heart rates for these tests (and some missing values) were calculated from the final 10 sec of the paper chart recording. The peak heart rate during each endurance hold was determined. At the 15% MVC level, peak heart rate was calculated as the mean of the highest three values.

Electromyogram

The EMG signal, on the FM magnetic tape, was converted from analog to digital form, and sampled by the computer according to the protocol shown in Figures 3 and 4. A four-second sample was taken during the maximum voluntary contraction, and eight-second samples at 15 sec intervals throughout the endurance hold and at each minute during the endurance recovery. On a second pass through the computer, a Fast Fourier Analysis was performed on the digitalized EMG samples. The output for each sample included the normalized power (percentage of total power) in each 2 Hz band from 4-200 Hz, the cumulative power in 20 Hz bands, and the total rms voltage of the signal. The values of low frequency power (4-40 Hz) and rms voltage (4-200 Hz) were selected for statistical analysis.

---

[1]The heart rate transfer and screening programs were written by Seth Feinberg, Department of Biostatistics, The University of Michigan.

Statistical analysis

Individual values of blood pressure, heart rate, and EMG parameters were plotted as a function of time for all endurance holds using an IBM 1130 computer.[1] Mean values of blood pressures and heart rate for each of the four groups at 15% MVC were plotted in similar fashion (see Figures 15, 18). All statistical analyses were performed on the University of Michigan MTS System using IBM 360/67 computers and the Michigan Interactive Data Analysis System (MIDAS) programs developed at the Statistical Research Laboratory.[2] In view of the complexity of the factors influencing the variables studied and the undesirability of committing a Type II error, the .05 level of significance was considered adequate throughout the study. In most cases, the probability associated with each statistic is given as its significance level.

---

[1]Programs were written by Mr. Seth Feinberg, Department of Biostatistics, School of Public Health, The University of Michigan, Ann Arbor, Michigan.

[2]MIDAS manual available from Statistical Research Laboratory, Rackham School of Graduate Studies, The University of Michigan, Ann Arbor, Michigan.

CHAPTER IV

RESULTS

Descriptive Data

The general characteristics and forearm measurements of individual subjects are presented in Appendices II and III. Test conditions for each of the five tests are set out in Appendices IV to VIII. Table 1 summarizes the characteristics of the subjects by groups. The wide range of strength values can be seen from the group means. The three strength groups were all significantly different from each other, since there was no overlap among them, but the swimmers were not significantly different from the high and low strength groups. The group strength differences remained significant beyond the .001 level after the means were adjusted to remove the covariance of age, height, weight, forearm length, time of day, subject order, and test order (Table 2). Multiple comparisons using the Scheffé method showed that the significant differences among the adjusted means were between the high strength group (H) and each of the other groups. The medium (M) and low (L) strength groups and swimmers (S) were not significantly different after adjustment for covariance, although the means remained in the same order. This demonstrates that there were wide absolute differences in strength among the groups, but that a large part of the differences was attributable to bodyweight and other covariates. The unusually high relationship between strength and bodyweight is shown by the

TABLE 1. SUMMARY OF PHYSICAL CHARACTERISTICS OF SUBJECTS: GROUP MEANS AND STANDARD DEVIATIONS.

Group		High Strength H	Medium Strength M	Low Strength L	Swimmers S
Age (years)	$\bar{X}$	24.4	25.4	20.8	18.8
	SD	3.8	6.2	1.5	1.3
Height (cm)[a]	$\bar{X}$	184.1	181.0	175.6	183.4
	SD	3.6	6.9	4.0	6.1
Weight (kg)[b]	$\bar{X}$	93.2	81.0	65.3	78.0
	SD	8.8	13.2	5.5	7.9
Strength (kg)[c]	$\bar{X}$	54.6	39.7	30.0	34.7
	SD	5.0	6.2	2.5	3.2

[a]ANOVA F = 5.3, significant difference among groups ($P < .01$)
[b]ANOVA F = 15.3, significant difference among groups ($P < .01$)
[c]ANOVA F = 56.4, significant difference among groups ($P < .0001$)

TABLE 2. GROUP STRENGTH MEANS SHOWING DIFFERENCES AMONG GROUPS BEFORE AND AFTER ADJUSTMENT FOR COVARIANCE.[a]

Group	High Strength H	Medium Strength M	Low Strength L	Swimmers S
Mean strength (kg)	54.56[b]	39.70	30.02	34.67
Adjusted mean (kg)	50.41[c]	38.67	34.05	35.82
Standard error	1.702	1.415	1.861	1.591

[a]Covariates were age, height, weight, forearm length, subject order, time of day and test order.

[b]ANOVA F = 56.4, $P < .0001$. Scheffé multiple comparisons showed the three strength groups to be significantly different from each other, but the swimmers to be not significantly different from the low and medium strength groups.

[c]ANOVA F = 15.6, $P < .0001$. Scheffé multiple comparisons showed the adjusted mean of the high strength group to be significantly different from each other group, but the other groups not to be significantly different from each other.

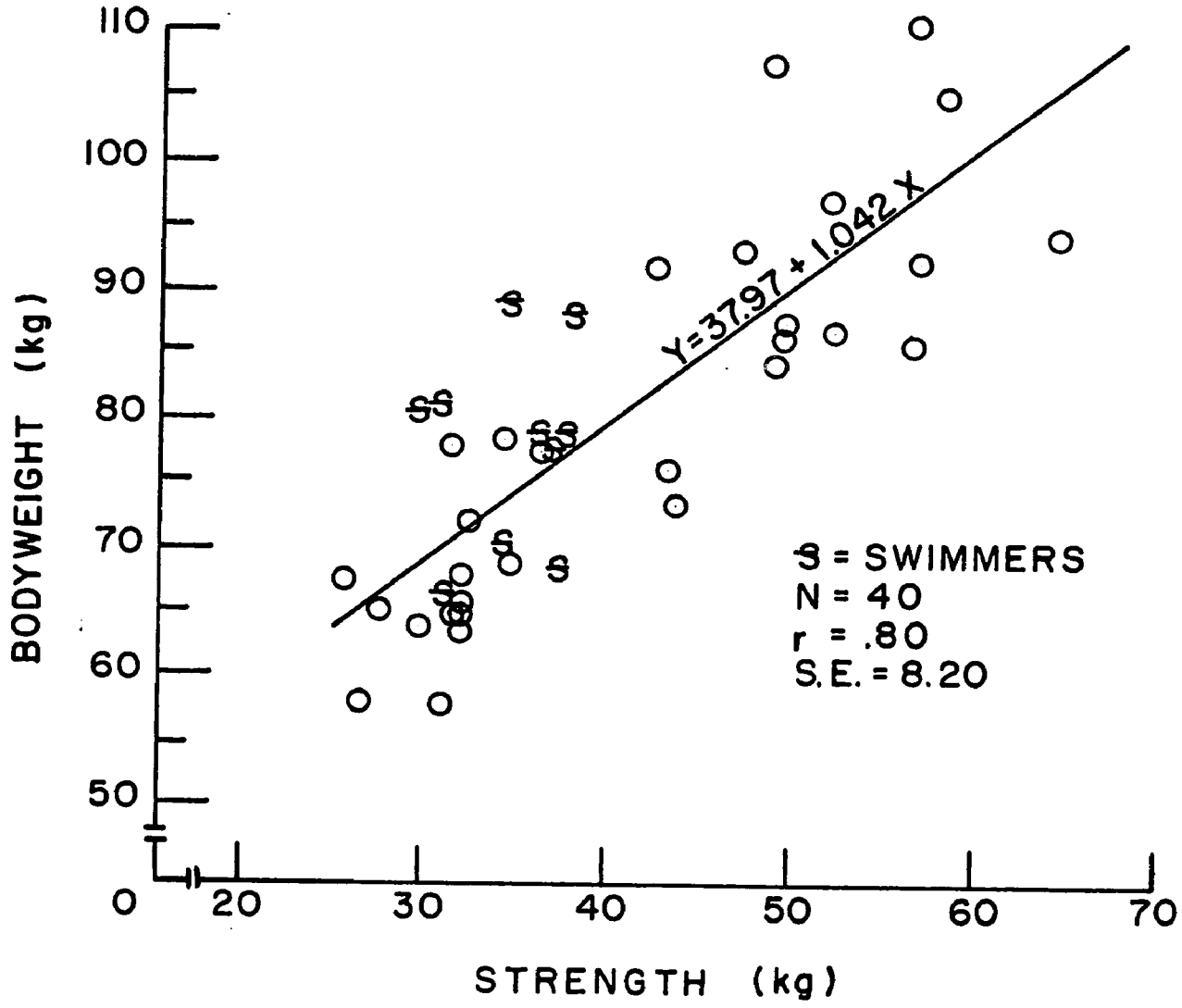


Figure 7. Regression of bodyweight on elbow flexion strength.

product-moment correlation coefficients of .86 (excluding the swimmers) and .80 (all 40 subjects). The high strength subjects were all muscular and generally large individuals. The low strength group was more ectomorphic in body type and consisted of smaller individuals. The swimmers, as a group, were highly trained for arm and cardiovascular endurance, but were no stronger than subjects of comparable size from the medium and low strength groups (Figure 7).

Repeatability of the Data

Strength measurements (MVC)

Day-to-day repeatability of maximum strength measurements was determined by product-moment correlation coefficients among all five test sessions (Table 3). Correlation coefficients were consistently around .99, or slightly less in the case of the initial test (Test 025) vs. subsequent tests. Comparison of the means using paired t-tests ($t = 3.7$ to 4.8) showed an increase in MVC, which was significant beyond the .001 level, between the first day and each of the subsequent tests.

TABLE 3. PRODUCT-MOMENT CORRELATION COEFFICIENTS SHOWING DAY-TO-DAY REPEATABILITY OF MAXIMUM STRENGTH MEASUREMENTS.

Test (% MVC)	Test (% MVC)				
	025	15	25	50	75
025	1.000	.981	.979	.976	.979
15		1.000	.991	.992	.991
25			1.000	.991	.989
50				1.000	.992
75					1.000

No significant differences were found among tests on the other four days, as may be expected, since the order was randomized. Individual variability is described by the coefficient of variation for each subject across tests (Appendix XXIII). The mean coefficient of variation for all five tests was 2.84% ± 1.60 with an individual maximum of 6.57%. Excluding the initial test, the mean coefficient of variation for the final four tests was 2.04% ± 1.21 with an individual maximum of 3.87%. These values compare favorably with those in the literature (99).

Endurance measurements

The maximum endurance times for the initial (Test 025) and later (Test 25) holds at 25% MVC were used to estimate minimum repeatability. As is characteristic after the first trial of an unfamiliar test, there was a mean increase in the endurance times for the second test (Figure 9), but the difference was found to be not significant (paired-t test). Pain, the gradually increasing inability to maintain the forearm in the horizontal position, and other largely psychological factors make the end-point much more variable and more difficult to determine at 25% MVC than at the higher tension levels. All these factors reduce the repeatability of the endurance variables as determined here for the 25% MVC holds. For this reason it is suggested that the values reported (Table 4) represent a minimal level of repeatability for all the tests. The test-retest correlation coefficient of .56 for maximum endurance time is quite comparable with values reported by Caldwell (9,15) and others (17,33) at higher proportions of MVC. The mean coefficient of variation across the two tests was 16.7%, reflecting

TABLE 4. TEST-RETEST REPEATABILITY OF ALL VARIABLES AT 25% MVC

Variable	N	Test-Retest Correlation Coefficient	Significance Level	Mean Coefficient of Variation (%)
Endurance measurements				
Maximum endurance time	40	.56	.001	16.7
Isometric work (F × T)	40	.62	.0001	15.8
Cardiovascular measurements				
Peak systolic b.p.	40	.67	.0001	5.8
Peak diastolic b.p.	40	.60	.0001	6.1
Peak mean b.p.	40	.67	.0001	5.2
Peak pulse pressure	40	.62	.0001	14.4
Peak heart rate	40	.65	.0001	7.3
Electromyographic measurements				
Initial EMG low frequency power	36	.70	.001	10.3
Initial EMG rms voltage	36	.73	.0001	9.1
Final EMG low frequency power	34	.56	.001	4.9
Final EMG rms voltage	34	.51	.01	22.2
EMG low frequency power increase	34	.45	.01	14.3
EMG rms voltage increase	34	.49	.01	28.3

the general increase after the initial test. This figure is comparable with the coefficient of 18.1% obtained by Martens and Sharkey (71) at 37.5% MVC. Bruce et al. (5) found a similar value of 20% for the first two days of testing, decreasing to 7% after two weeks of training. The present results for 25% MVC are considered acceptable for the first two tests at a low tension level.

Comparison of the isometric work (force × time) performed during the two 25% MVC tests showed a correlation coefficient of .62 and a mean coefficient of variation of 15.8%, again reflecting the variability in endurance times at this tension level and the generally improved performance after the initial test (Figure 13).

Cardiovascular measurements

Test-retest correlation coefficients at 25% MVC were all above .60 for peak blood pressures and heart rates (Table 4). Coefficients of variation were below 8%, except for pulse pressure (14.4%), indicating consistent individual cardiovascular responses. No significant differences were found between the means of the two tests except in the case of peak systolic pressure, which increased in the second test (paired $t = 2.27$, $P < .05$). In this case, the increase occurred in all but the high strength group, but did not reach significant levels in any single group (Figure 17). The cardiovascular measures appear to be more consistent than the endurance performance measures.

Electromyographic measurements

Initial values of the EMG parameters were comparatively consistent, with test-retest correlation coefficients above .70 and mean coefficients

of variation of about 10% (Table 4). Final EMG low frequency power (FLF) is more consistent than final EMG rms voltage (FV). Although test-retest correlation coefficients are both above .50, the mean coefficients of variation (4.9%, 22.2%) show that the individual FLF values are quite consistent, but FV varies considerably. The sharp increase in EMG rms voltage near the end of the test at 25% MVC (Figure 21) provides at least a partial explanation for this. A small difference in endurance time near the point of fatigue may greatly affect the FV value, but has a much smaller effect on FLF. The values of the increases in EMG low frequency power (LFI) and EMG rms voltage (VI) are subject to the variability of both initial and final values and are less consistent than either of the latter measures (Table 4). Despite the longer endurance times, the mean LFI was smaller on the second 25% MVC test, but the difference just failed to reach the .05 level of significance. The means on the two tests were not significantly different for any of the electromyographic parameters (paired-t test).

The initial EMG values and the final EMG low frequency power are as consistent as the endurance and cardiovascular measures, but the values of final EMG rms voltage and the increases of both parameters during the holds warrant a little less confidence.

Strength vs. Endurance Relationships

Maximum endurance time (MET)

Since all 15% holds were terminated at 20 min, only the 25, 50, and 75% MVC holds were used to determine the relationship between strength and endurance. However, at 15% MVC the strongest subjects had great

difficulty supporting the load for the full 20 min. The only subject who could not reach the 20 min time limit (16 min, 34 sec) was a member of the high strength group. Several others were in great pain beyond about 11 min, and completed the hold only with tremendous effort, frequently accompanied by loud screams and shouts. By contrast, many of the weaker subjects reported that boredom was a greater problem than pain, and felt that they could easily have continued.

Product-moment correlation coefficients between maximum endurance time and MVC were negative for both tests at 25% MVC ($r = -.39, -.43$) and at 50% MVC ($r = -.48$). These values are almost identical to those reported by Start and Graham (102) and Carlson and McCraw (18) at comparable relative tension levels. The correlation coefficient of $r = .03$ at 75% MVC supports the contention of these authors that at high tension levels there is no relationship between static strength and relative endurance. Since the subjects were chosen for specific strength levels rather than randomly, it was not legitimate to apply the usual tests of significance to the correlation coefficients. Tests of the regression of endurance times on strength were therefore applied (Table 5).

At 25% MVC, although there was considerable residual variability, the regression of endurance time on strength was significant beyond the .01 level with or without the inclusion of the swimmers; the weaker subjects showing greater endurance (Figure 8). Of the two most outstanding individuals, the weaker, Subject 34 (32.7 kg, 1152 sec), was the oldest subject, a 38 year old retail store salesman who had participated in no regular sport or vigorous physical training; the stronger, Subject 8 (52.3 kg, 733 sec), was a defensive back on the varsity football team

who had personally undertaken several weeks of vigorous endurance training in addition to his strength training. The swimmers were all in the low to medium strength range, but varied considerably in endurance. Analysis of variance showed no significant difference among the mean endurance times of the four groups (Table 5), but in both tests at 25% MVC the high strength group had the shortest mean endurance time and the swimmers the longest (Figure 9). In both tests, too, the regression of individual endurance times on strength was significant, indicating that grouping the strength values into four categories for the ANOVA resulted in some loss of sensitivity.

At 50% MVC, the regression of endurance time on MVC was again significant beyond the .01 level with or without inclusion of the swimmers (Figure 10). Analysis of variance revealed significant differences among group means (Table 5). Scheffé multiple comparisons showed the high strength group to have significantly less endurance than the swimmers at 50% MVC. All the means were in the order predicted by the alternative hypothesis, that there is a negative relationship between relative endurance and strength (Figure 9). At this level and at 75% MVC, the end-point of the endurance hold was well defined, being characterized by a sudden, unavoidable collapse.

At 75% MVC there was clearly no regression of endurance time on strength (Figure 11) and analysis of variance revealed no significant differences among group means (Table 5, Figure 9). Subject 8 (52.3 kg, 50 sec) was again outstanding, but Subject 34 (32.7 kg, 29 sec) was below the mean, suggesting that his MVC was valid and that his outstanding performance at 25% MVC was not merely the result of a spuriously low MVC.

TABLE 5. RELATIONSHIP OF MAXIMUM ENDURANCE TIME TO STRENGTH: INDIVIDUAL REGRESSION ANALYSIS AND ANALYSIS OF VARIANCE OF GROUP MEANS (GROUP N = 10)

Variable		Test (% MVC)							
		025		25		50		75	
Correlation coefficient (r)		-.39		-.43		-.48		.03	
Significance level of regression (P:slope = 0)		.01		.005		.002		.84	
ANOVA F ratio		.85		1.51		4.09		.31	
Significance level of ANOVA (P:$\mu_1 = \mu_2$)		.48		.23		.01		.82	
		$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Group mean endurance times (sec)	H	434.5	120.0	430.7	149.9	83.8	14.4	34.6	7.2
	M	520.4	303.9	554.0	268.6	93.2	16.5	31.4	6.2
	L	531.9	169.0	537.3	153.8	100.2	20.1	32.5	7.1
	S	597.0	274.9	607.7	164.5	108.8	14.7	33.2	9.5
Significant Scheffé multiple comparisons (P < .05)						H < S			

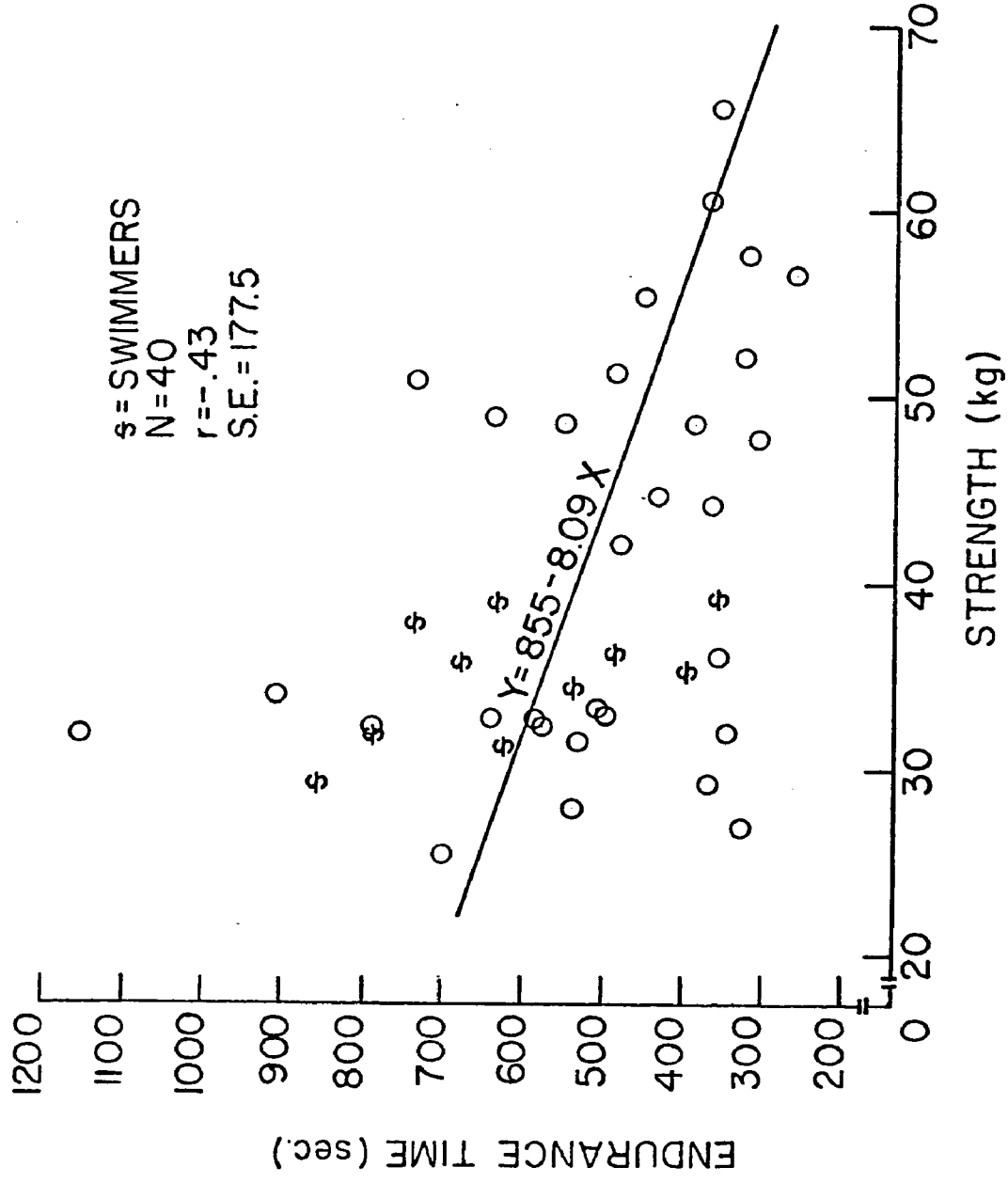


Figure 8. Regression of maximum endurance time on strength for static elbow flexion at 25% MVC.

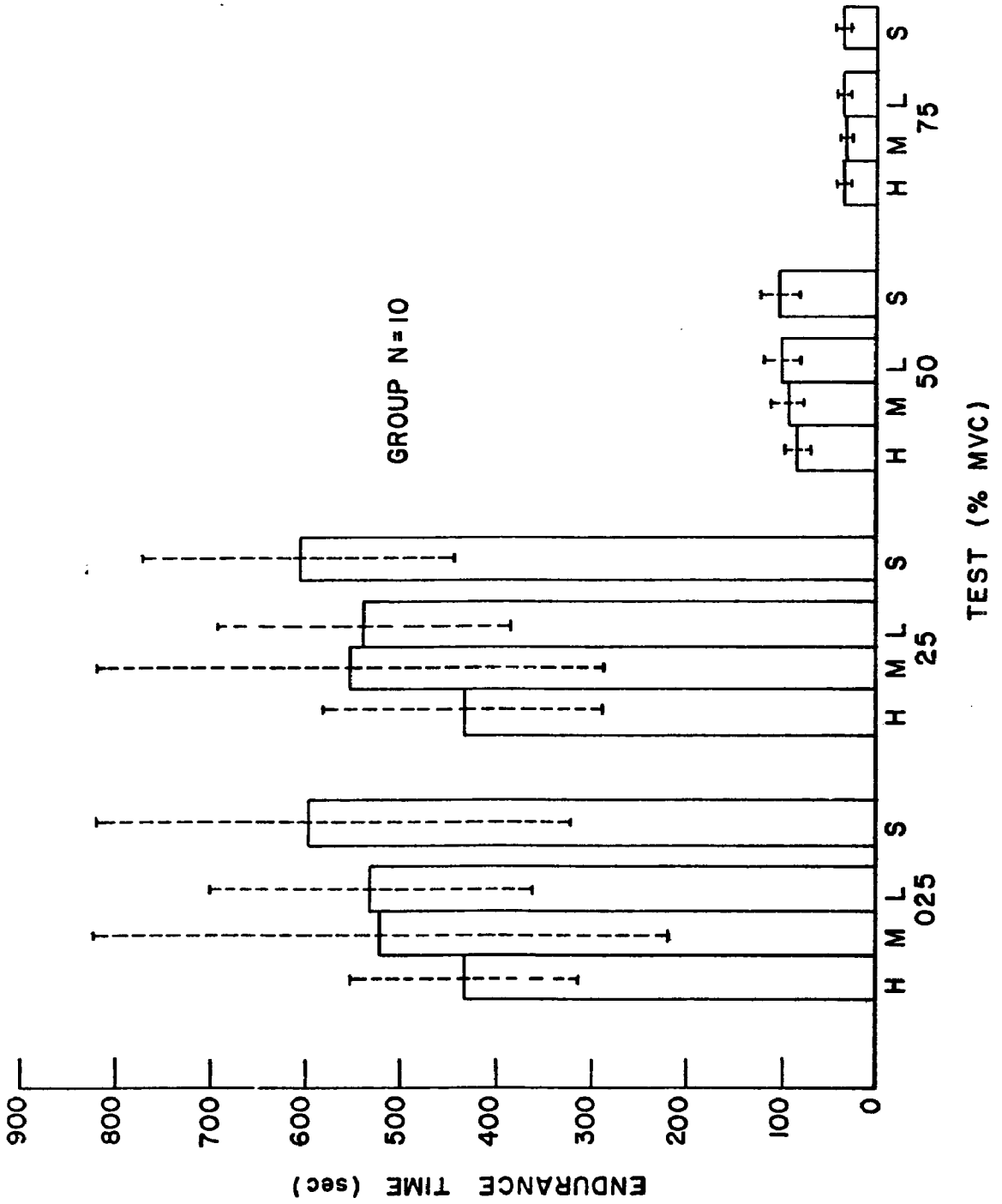


Figure 9. Relationship of maximum endurance time to strength showing group means and standard deviations for high, medium, and low strength groups and swimmers.

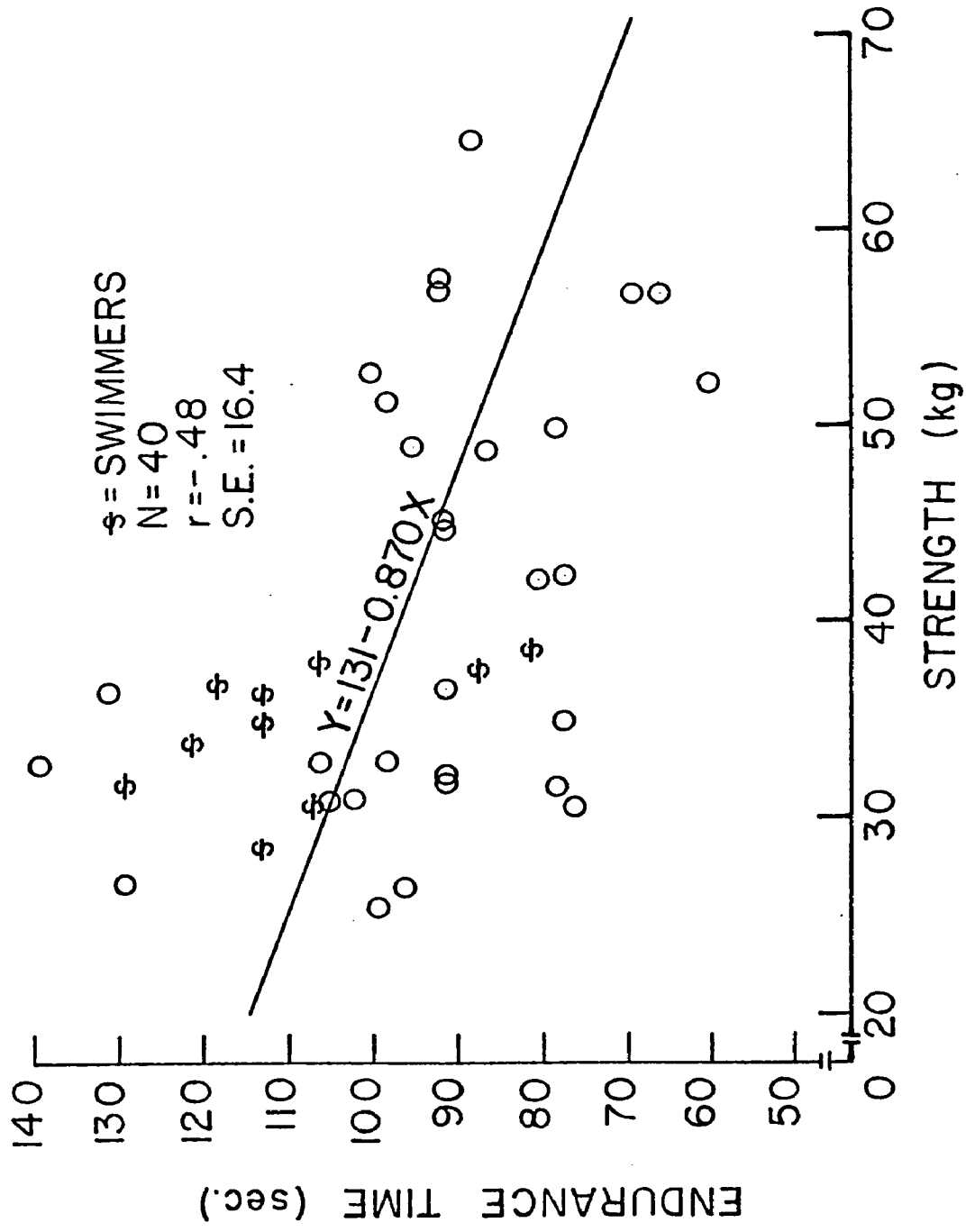


Figure 10. Regression of maximum endurance time on strength for static elbow flexion at 50% MVC.

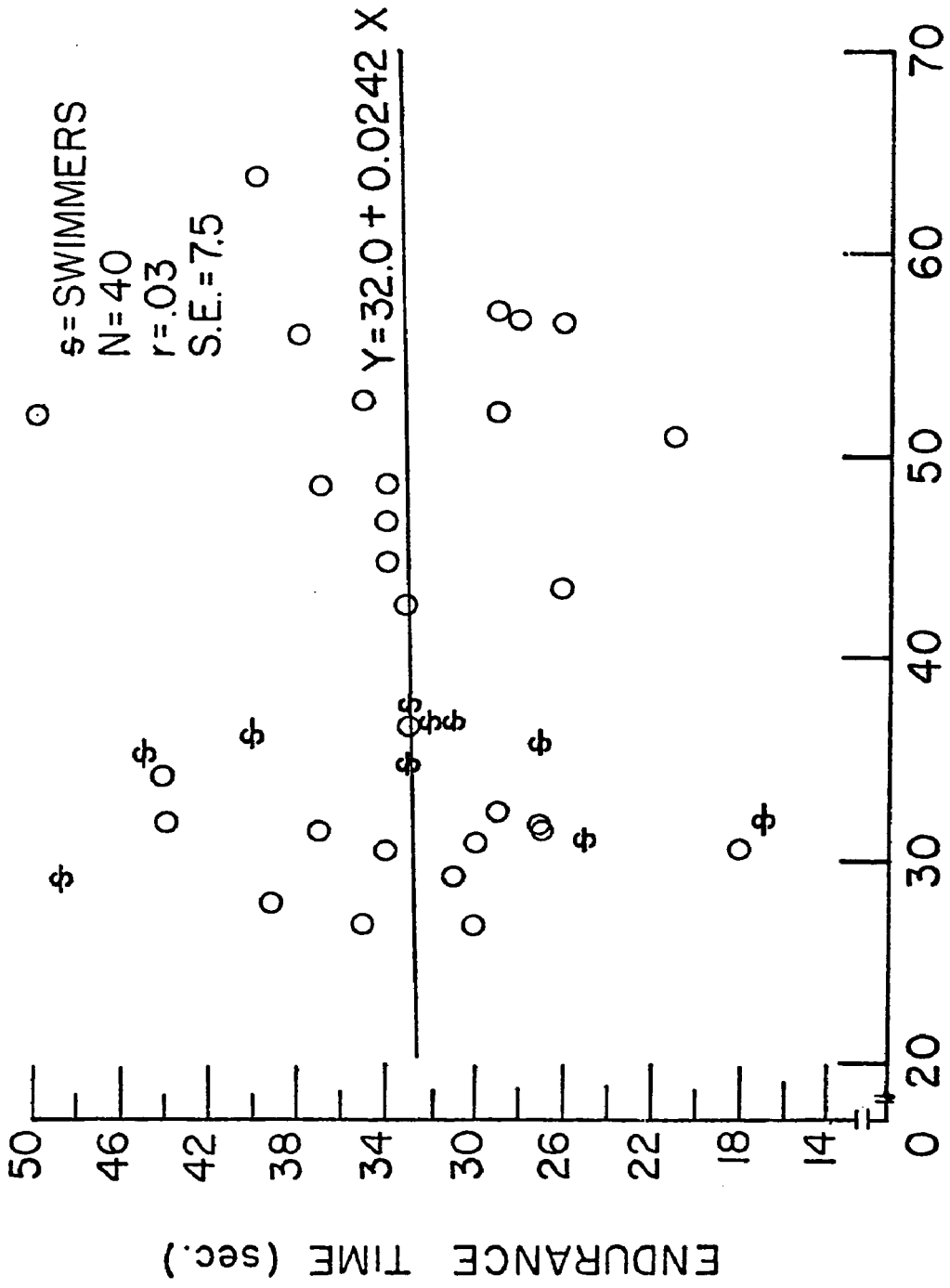


Figure 11. Regression of maximum endurance time on strength for static elbow flexion at 75% MVC.

The consistent order of the group means in the direction predicted by the alternative hypothesis, and the highly significant regression of MET on strength indicate that at 25% and 50% MVC there is a negative relationship between relative endurance and strength, even though the group differences were partly obscured by the wide variability, especially at 25% MVC, where the end-point of the hold was less definite. The relationship does not appear to exist at 75% MVC, where the group means were almost identical.

Maximum endurance time was inversely related to relative tension level with large increases at the lower tensions (Figure 12). The values obtained compare well with those of other investigators at 75% and 50% MVC, but are considerably higher than most at 25% MVC.

Isometric work (F × T)

Maximum endurance times were multiplied by the absolute value of the force sustained to give the value frequently referred to as isometric "work." Positive correlations were found between this value and strength (Table 6), even though for some of the same tests there were negative relationships between strength and relative endurance as determined by MET. Regression of isometric work on strength was highly significant for all but the 25% MVC tests, where time was the greater and more variable factor. Analysis of variance showed the mean isometric work to be significantly different among groups, except at 25% MVC. At that level, although the differences were not significant, the order of the group means was similar to that at the other tension levels, the three strength groups in order according to strength and the swimmers corresponding to

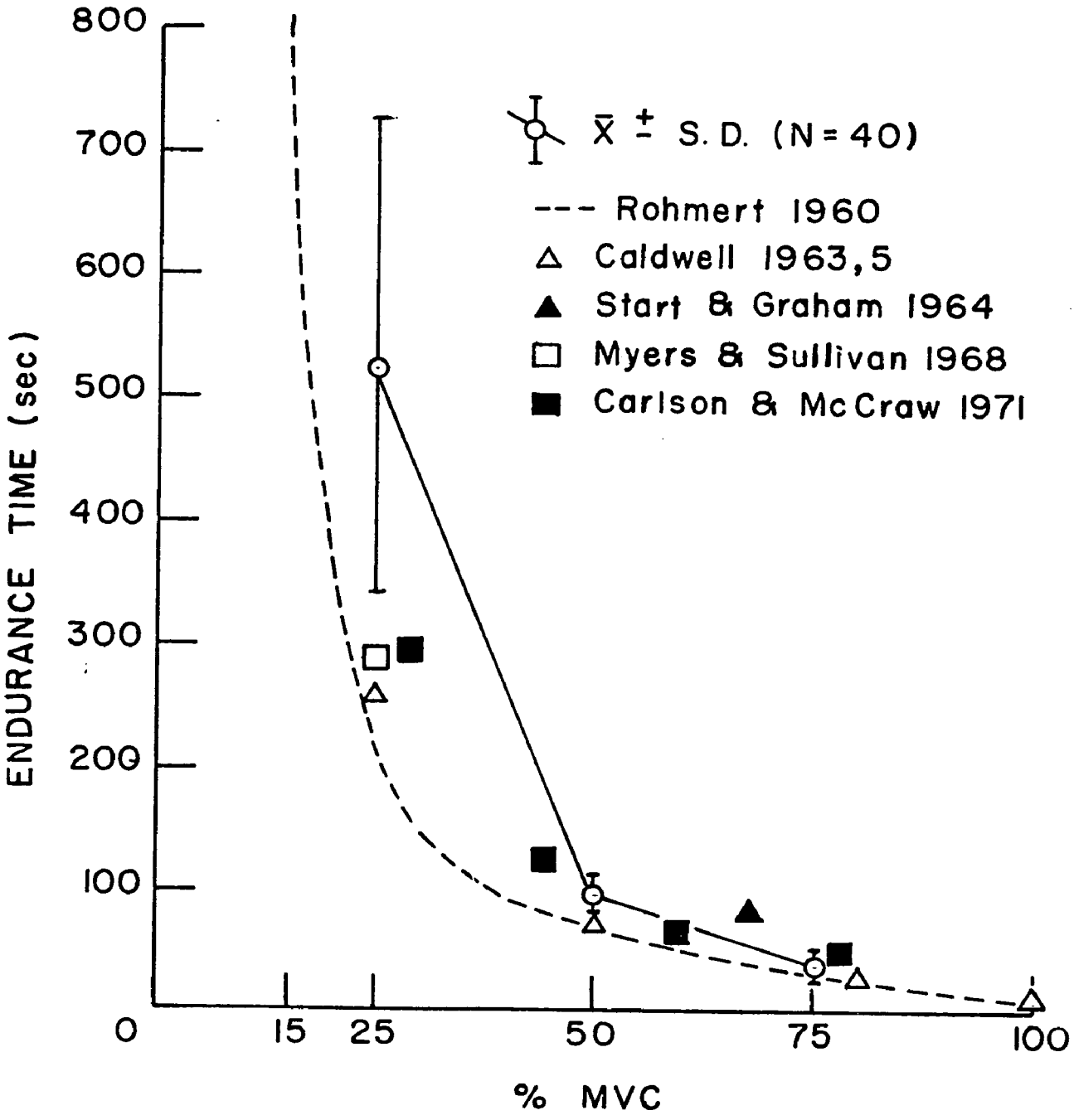


Figure 12. Relationship of maximum endurance time to relative tension for continuous static contractions.

TABLE 6. RELATIONSHIP OF ISOMETRIC WORK TO STRENGTH: INDIVIDUAL REGRESSION ANALYSIS AND ANALYSIS OF VARIANCE OF GROUP MEANS (GROUP N = 10)

Variable		Test (% MVC) 025		15[a]		25		50		75	
Correlation coefficient (r)		.18		.97		.22		.69		.77	
Significance level of regression (P:slope = 0)		.25		<.0001		.17		<.0001		<.0001	
ANOVA F ratio		1.95		37.78		2.08		9.40		16.35	
Significance level of ANOVA (P:$\mu_1 = \mu_2$)		.14		<.0001		.12		<.0001		<.0001	
		$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Group mean isometric work (kg-sec)	H	5518	1283	9906	1513	5799	1719	2289	426	1407	307
	M	4874	2280	7214	1059	5255	1968	1820	311	926	192
	L	3738	910	5407	487	4085	1288	1506	330	724	170
	S	4989	1963	6260	617	5239	1246	1868	232	858	238
Significant Scheffé multiple comparisons (P < .05)				All > S H > M,L,S M > L				H > All H > M,S		H > All H > M,L,S	

[a]20 min time limit

their strength level or better (Figure 13). Scheffé multiple comparisons showed the values of the high strength group to be significantly greater than those of each other group at 15% MVC and at 75% MVC where the endurance times were approximately equal for all four groups. The swimmers were not significantly different from the medium and low strength groups. At 50% MVC the high strength group accomplished significantly more than the medium and low strength groups, but the swimmers were not significantly different from any of the other groups.

The amount of isometric work was inversely related to the relative tension level, increasing greatly at the lower levels (Figure 14). The values obtained at 50% and 75% MVC are comparable with those reported by Caldwell (10,11), but those at 25% MVC are higher.

Cardiovascular Responses

Blood pressure

Computer plots were obtained for each individual showing the changes in systolic, diastolic, and mean blood pressures during each endurance hold. In all cases both systolic and diastolic pressures increased above resting levels, resulting in a marked increase in mean blood pressure.

At 15% MVC all subjects (with one exception) can be compared over the same 20 min time period. Subject 36 reached peak values of each variable before he stopped after 16 min, 34 sec. Group means were plotted against time for the 15% MVC hold (Figure 15) showing that the high strength group developed a higher mean blood pressure within the first minute and maintained this difference throughout the hold.

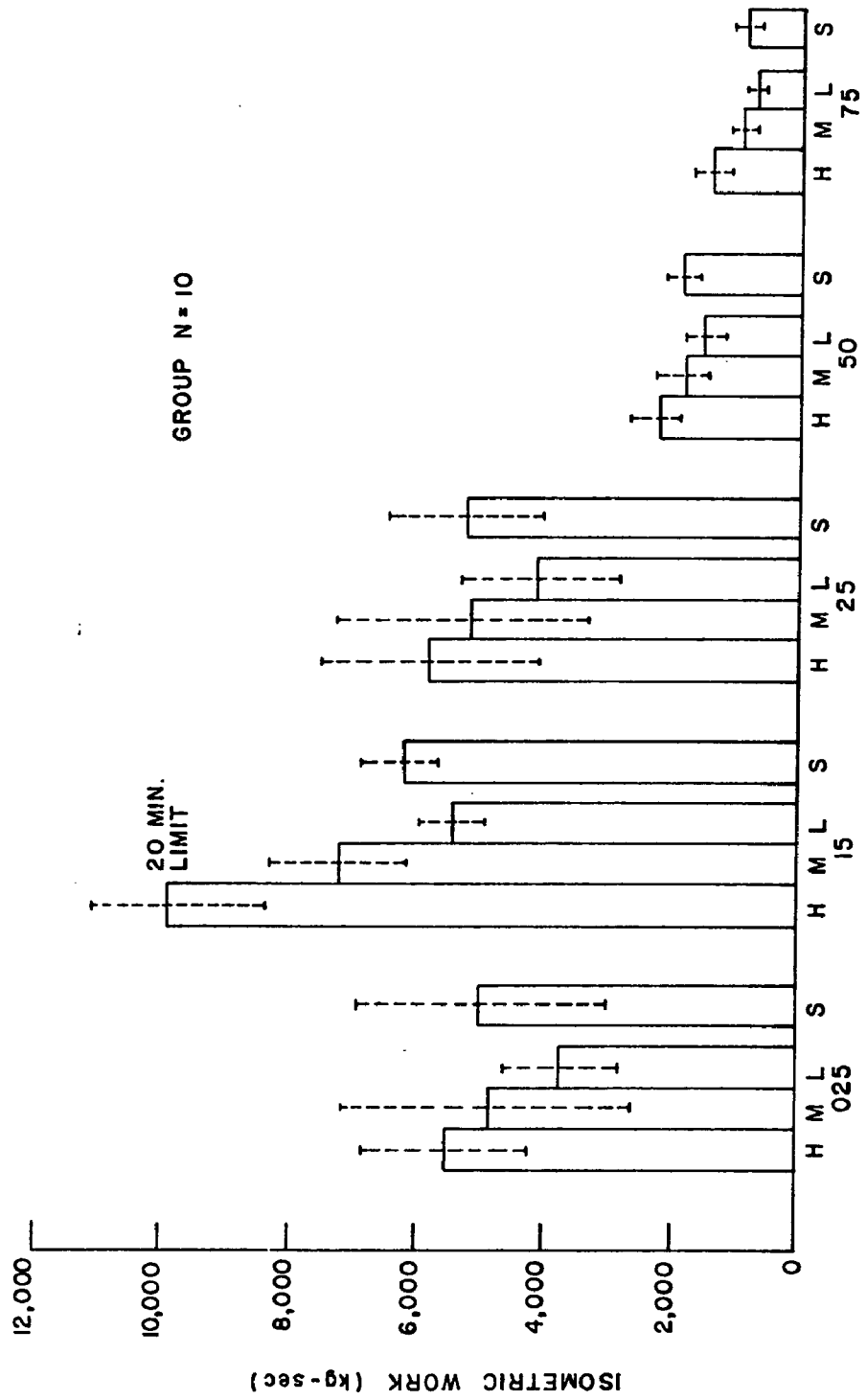


Figure 13. Relationship of isometric work (force x time) to strength showing group means and standard deviations for high, medium, and low strength groups and swimmers.

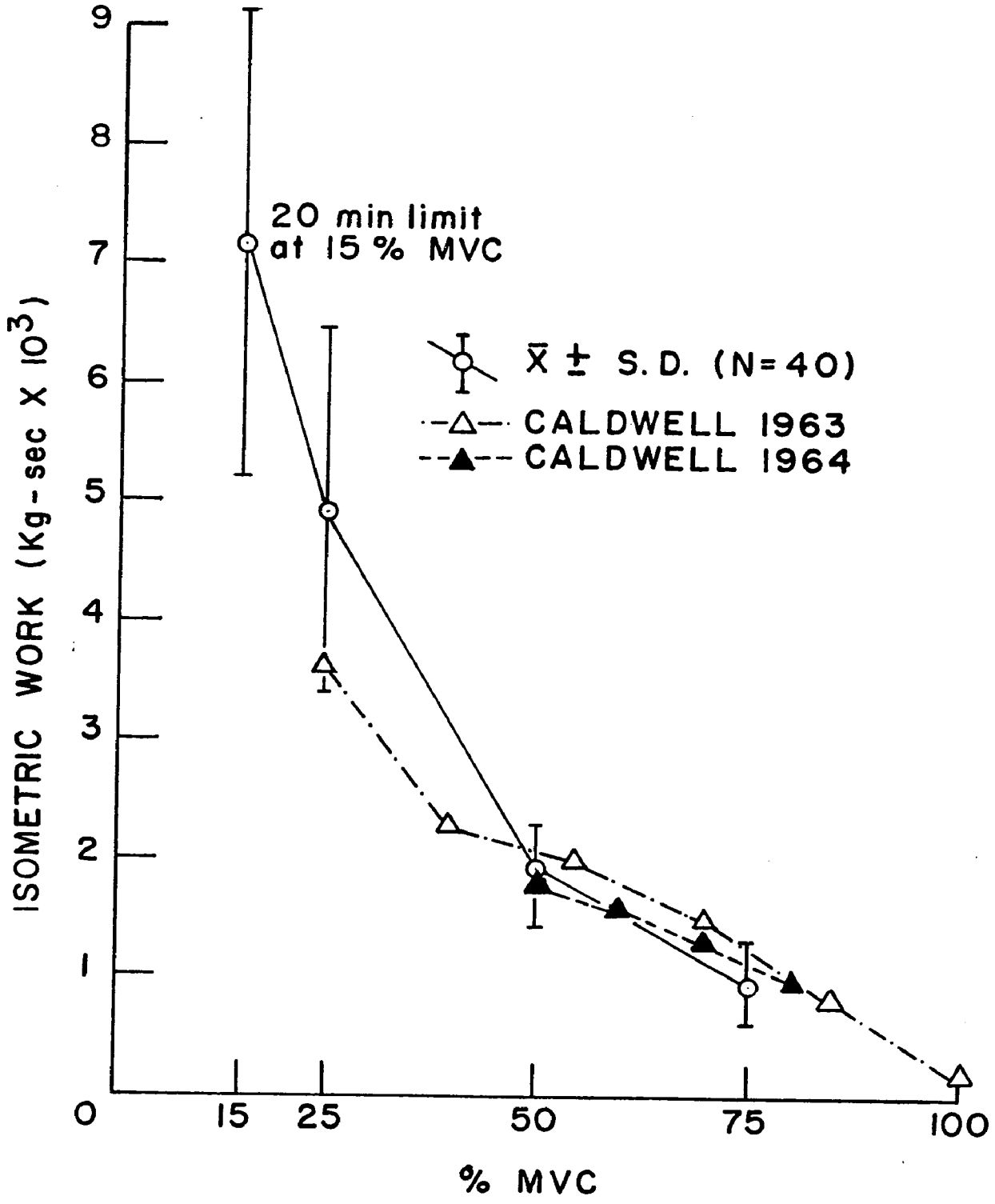


Figure 14. Relationship of isometric work (force × time) to relative tension for continuous static contractions.

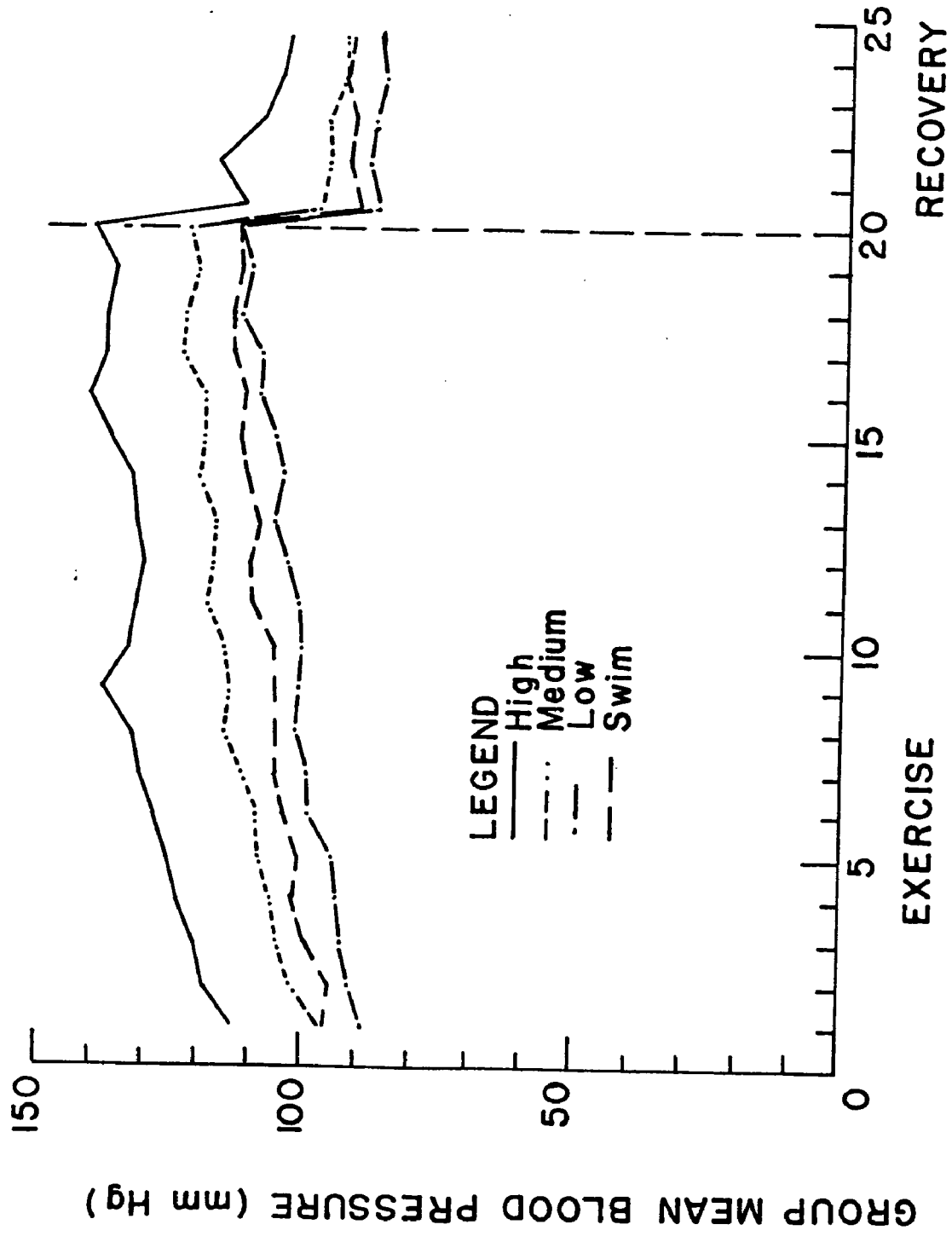


Figure 15. Group differences in mean blood pressure during a 20 min static elbow flexion at 15% MVC.

The blood pressure levels of all the groups remained in the same relative order as their strength levels throughout the 20 min hold. Systolic pressure followed a similar pattern. In the high strength group systolic pressure generally reached 150 mm Hg in the first minute or two, continued to rise during the first half of the hold, and then levelled off at about 180-200 mm Hg. In the other groups, systolic pressure continued to rise slowly throughout the test, but reached lower levels, corresponding in order to their strength levels. Among the weaker subjects systolic pressure generally remained below 150 mm Hg throughout the test, lower than the level reached by the strong subjects in the first minute. Two subjects (8 and 11) in the high strength group showed a pattern more like that of the weaker subjects, reaching a peak systolic pressure of about 150 mm Hg after a slow, fairly linear increase. In the 25% MVC hold, continued to fatigue, these two subjects had the outstanding endurance times from the high strength group (Figure 8).

Peak blood pressures, calculated as the mean of the highest three values recorded during the 15% MVC hold, showed high correlations with MVC. Correlation coefficients of .73, .73, and .76 were obtained between MVC and peak values of systolic, diastolic, and mean blood pressures respectively. Regressions of each of the three on strength were significant beyond the .0001 level (Figure 16), and analysis of variance showed the group means to be significantly different ($P < .0005$) for all three parameters (Tables 7-9). Multiple comparisons using the Scheffé method showed the peak pressures for the high strength group to be significantly greater than those of the other groups together or

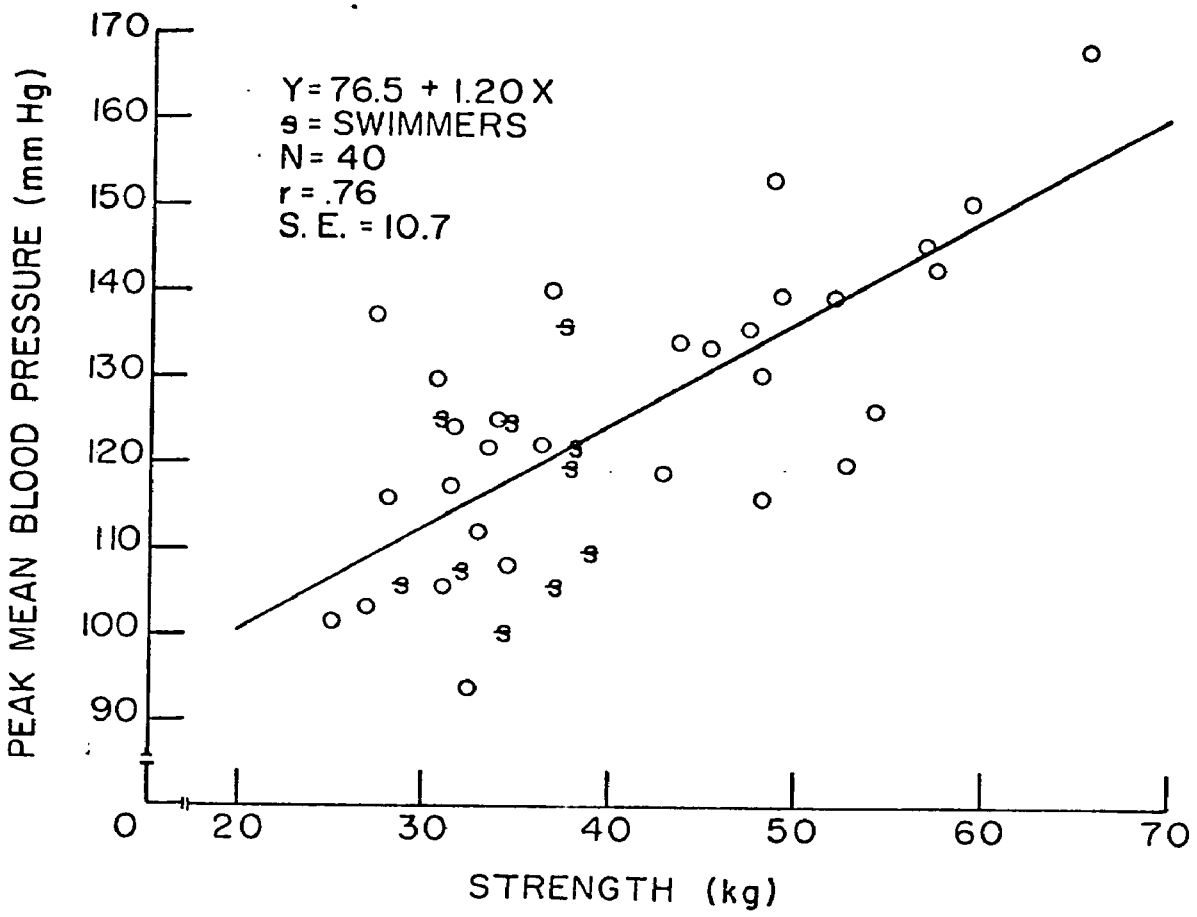


Figure 16. Regression of peak mean blood pressure on strength for static elbow flexion at 15% MVC.

separately (Figure 17). The swimmers were not significantly different from the medium and low strength groups in any of the blood pressure responses at 15% MVC.

At the other three tension levels, at which the subjects maintained the contraction to fatigue, the highest single value of each pressure was taken as the peak value, since the rate of increase was much more rapid. The peak value in these tests almost invariably occurred at the end of the hold. The results are illustrated in Figure 17 and the statistical analyses summarized in Tables 7-9.

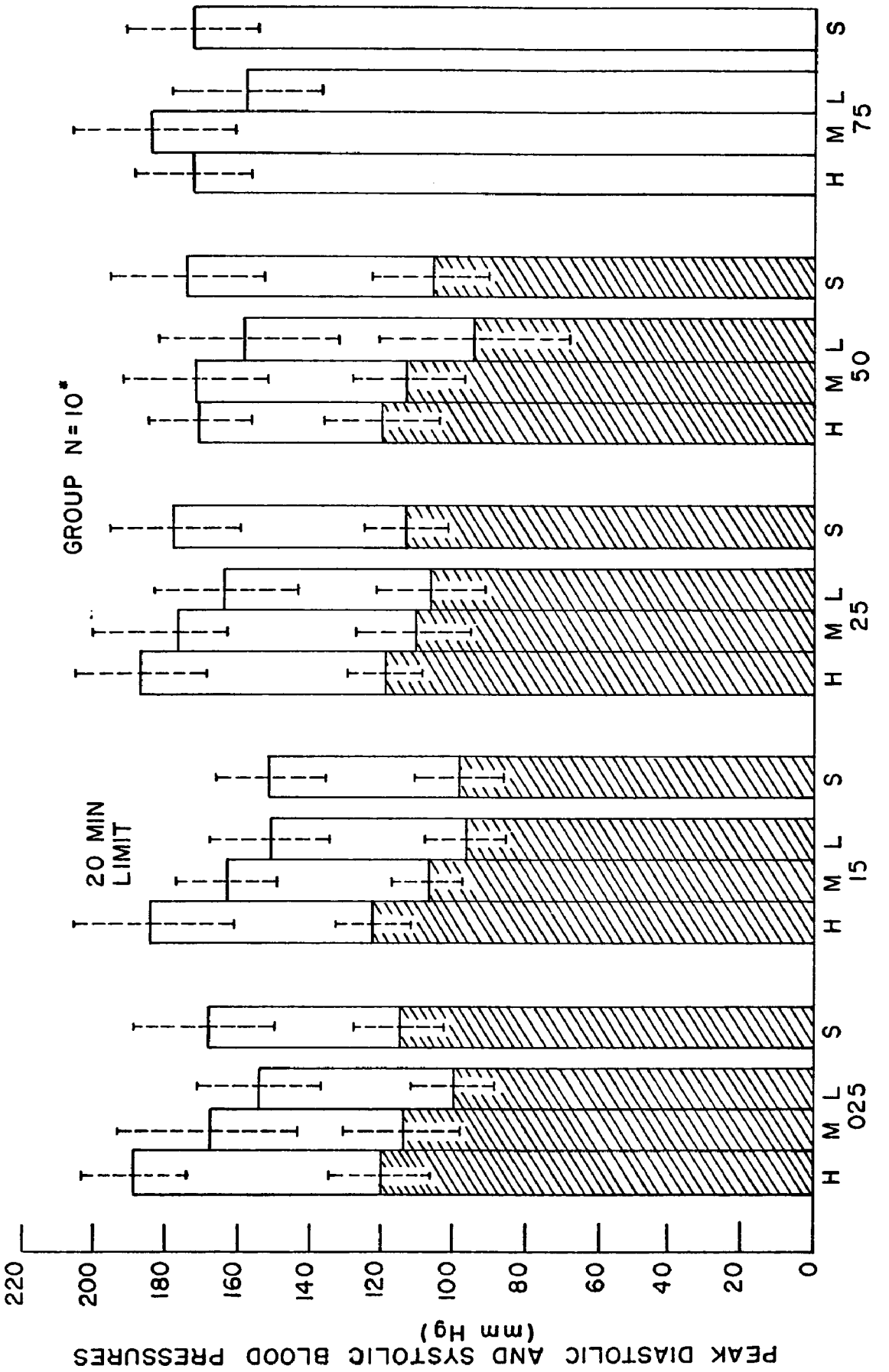


Figure 17. Relationships of peak blood pressures to strength showing group means and standard deviations for high, medium, and low strength groups and swimmers. *At 75% MVC N = 5 for strength groups, N = 6 for swimmers. Diastolic pressures are omitted because of insufficient data.

TABLE 7. RELATIONSHIP OF PEAK SYSTOLIC BLOOD PRESSURE TO STRENGTH: INDIVIDUAL REGRESSION ANALYSIS AND ANALYSIS OF VARIANCE OF GROUP MEANS (GROUP N = 10)

Variable		Test (% MVC)				
		025	15[a]	25	50	75[b]
Correlation coefficient (r)		.46	.73	.40	.03	.29
Significance level of regression (P:slope = 0)		.003	<.0001	.01	.84	.20
ANOVA F ratio		5.26	7.54	2.33	1.12	1.48
Significance level of ANOVA ($P:\mu_1 = \mu_2$)		.004	.0005	.09	.35	.26
		$\bar{X}$ SD	$\bar{X}$ SD	$\bar{X}$ SD	$\bar{X}$ SD	$\bar{X}$ SD
Group mean peak systolic blood pressure (mm Hg)	H	189.0 14.6	184.0 22.9	187.8 18.7	171.0 14.6	172.8 16.1
	M	168.2 25.3	162.7 13.8	176.8 23.8	171.7 20.2	184.0 22.7
	L	154.2 17.6	151.3 17.5	163.8 20.3	159.0 22.9	158.0 20.8
	S	169.4 19.8	152.1 14.3	178.2 18.3	173.8 21.1	172.7 18.4
Significant Scheffé multiple comparisons (P < .05)		H > All H > L	H > All H > L,S			

[a] 20 min time limit
[b] Group N = 5 for strength groups, N = 6 for swimmers

TABLE 8. RELATIONSHIP OF PEAK DIASTOLIC PRESSURE TO STRENGTH: INDIVIDUAL REGRESSION ANALYSIS AND ANALYSIS OF VARIANCE OF GROUP MEANS (GROUP N = 10)

Variable		Test (% MVC) 025		15[a]		25		50	
Correlation coefficient (r)		.55		.73		.25		.37	
Significance level of regression (P:slope = 0)		.004		<.0001		.11		.02	
ANOVA F ratio		4.19		11.5		1.50		3.36	
Significance level of ANOVA ($P:\mu_1 = \mu_2$)		.01		<.0001		.23		.03	
		$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Group mean peak diastolic blood pressure (mm Hg)	H	120.4	14.0	122.6	10.0	119.6	10.1	120.2	16.4
	M	114.2	16.5	107.2	10.0	111.2	16.4	113.6	15.1
	L	99.5	12.0	96.4	11.4	107.2	14.9	94.4	26.4
	S	115.4	12.6	98.6	12.6	114.2	11.6	106.2	16.2
Significant Scheffe multiple comparisons (P < .05)		H > L		H > All H > M,L,S				H > L	

[a]20 min time limit

TABLE 9. RELATIONSHIP OF PEAK MEAN BLOOD PRESSURE TO STRENGTH: INDIVIDUAL REGRESSION ANALYSIS AND ANALYSIS OF VARIANCE OF GROUP MEANS (GROUP N = 10)

Variable		Test (% MVC) 025		15[a]		25		50	
Correlation coefficient (r)		.46		.76		.31		.32	
Significance level of regression (P:slope = 0)		.003		<.0001		<.05		.04	
ANOVA F ratio		4.73		11.25		1.79		2.90	
Significance level of ANOVA (P:$\mu_1 = \mu_2$)		.007		<.0001		.17		<.05	
		$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Group mean peak mean blood pressure (mm Hg)	H	140.1	11.4	142.2	13.8	139.9	11.1	136.0	12.8
	M	131.2	19.2	125.0	9.6	132.2	15.5	132.0	14.0
	L	116.8	11.5	113.9	13.6	126.1	16.0	115.2	23.7
	S	132.2	12.9	115.7	11.3	134.6	10.8	125.4	14.7
Significant Scheffé multiple comparisons (P < .05)		H > L		H > All H > M,L,S					

[a]20 min time limit

At 25% MVC consistently positive correlations were found between peak blood pressures and strength on both the preliminary and subsequent tests (Tests 025 and 25 respectively). The regressions of peak systolic, diastolic, and mean pressures on strength were generally significant, with the exception of peak diastolic pressure on Test 25 ($P = .11$). Analysis of variance showed significant differences among group means on all three parameters in Test 025. Scheffé comparisons revealed that the high strength group (H) had higher peak values of all three blood pressures than the low strength group (L), and higher peak systolic pressure than all three groups combined (All). On Test 25 there were no significant differences among group means for any blood pressure parameter. Although the differences among groups were not great and the statistical significance was not consistent for the two tests at 25% MVC, the group means maintained the same relative order (H > S > M > L) for all three parameters on each test and all correlations with strength were positive. The probability of all these events occurring together is slight, suggesting a real, if slight, relationship between strength and peak blood pressures at 25% MVC. The swimmers (S) were not significantly different from the medium (M) and low (L) strength groups on any of the peak blood pressure parameters, but their group means were consistently slightly higher than both other groups, which were comparable in strength.

At 50% MVC blood pressures were determined at half-minute intervals whenever possible. The exertion of the subjects and the brief endurance times caused considerable difficulty, with the result that the timing of the recordings was imprecise. In some cases the last blood pressure reading was taken almost 30 sec before the end of the hold,

depending on the duration of the hold. Since the blood pressures may still be rising fairly rapidly in such brief holds (Figure 20), less confidence can be placed in the validity of the peak values obtained at this tension level. No relationship was found between peak systolic pressure and strength ($r = .03$), although the values obtained for the three lower strength groups corresponded fairly well with those obtained for the same groups at 25% MVC (Table 7). A positive relationship was found between peak diastolic pressure and strength ($r = .37$), with regression on strength and differences among group means being significant. Scheffé comparisons showed the high strength group to have significantly higher peak diastolic pressures than the low strength group (Table 8). As a result, a positive relationship also existed between peak mean blood pressure and strength, with significant regression and differences between group means (Table 9). No Scheffé comparisons were significant. The resulting negative relationship between peak pulse pressure and strength ($r = -.29$) did not reach significant levels on either regression or ANOVA analysis.

At 75% MVC endurance times were so short and the effort so great that blood pressures were even more difficult to obtain. Systolic readings were recorded for 21 subjects, five from each strength group and six swimmers. Insufficient diastolic readings were obtained for statistical analysis. A positive correlation was found between peak systolic pressure and strength ($r = .29$), but neither the regression nor the group differences reached significant levels (Table 7).

In spite of endurance times of little more than 30 sec at 75% MVC, systolic pressures reached levels approximating the peak values

obtained during much longer holds at the lower tension levels (Figure 17). Peak systolic, diastolic, and mean blood pressures were relatively constant for all the tension levels producing fatigue. No significant differences were found among the means for these tension levels. At 15% MVC the high strength group reached the same high level, indicating that even at that low relative tension the pressor response had reached its maximum for the elbow flexion task.

Peak pulse pressures were not significantly related to strength at any level ($r = -.29$ to $.29$) by either regression analysis or analysis of variance.

Relationships of peak blood pressures to maximum endurance times (MET) were not significant (Table 10), although at each tension level the correlation of peak systolic pressure with MET was positive ($r = .17$ to $.31$), as were the correlations of peak diastolic, mean, and pulse pressures with MET in both 25% MVC tests ($r = .14$ to $.29$). Peak blood pressures reached higher correlations with strength (Tables 7-9) than with endurance times (Table 10).

Heart Rate

Heart rates were plotted against time for each individual, revealing great individual variability. At 15% MVC mean values were calculated for each group. The high strength group maintained a greater mean heart rate than the other groups throughout most of the test (Figure 18). Surprisingly, the medium strength group maintained the lowest mean heart rate throughout, although the differences were not great. Peak heart rates showed no significant regression on strength and no significant differences among groups (Table 11).

TABLE 10. PRODUCT-MOMENT CORRELATION COEFFICIENTS SHOWING RELATIONSHIPS OF ALL VARIABLES TO MAXIMUM ENDURANCE TIMES (N = 37 to 40)

Variable	Test 025	25	50	75
Performance measurements				
Maximum voluntary contraction	-.39[a]	-.43[b]	-.48[b]	.03
Isometric work (F × T)	.81[d]	.76[d]	.29	.64[d]
Cardiovascular measurements				
Peak systolic b.p.	.31	.17	.30	.19[e]
Peak diastolic b.p.	.24	.21	-.18	--
Peak mean b.p.	.28	.24	-.07	--
Peak pulse pressure	.28	.14	.33[a]	--
Peak heart rate	-.06	.14	.11	.09
Electromyographic measurements				
Initial EMG low frequency power	-.13	.05	-.10	-.28
Initial EMG rms voltage	-.48[b]	-.30	-.13	.11
Final EMG low frequency power	.35[a]	.33[a]	.38[a]	--
Final EMG rms voltage	.25	.16	.35[a]	--
EMG low frequency power increase	.36[a]	.35[a]	.52[c]	--
EMG rms voltage increase	.34[a]	.21	.45[b]	--

[a]Significant correlation ($P < .05$)
[b]Significant correlation ($P < .01$)
[c]Significant correlation ($P < .001$)
[d]Significant correlation ($P < .0001$)
[e]N = 21
-- Insufficient data

Similarly, no significant relationships existed between peak heart rates and strength at the other tension levels, although the correlation coefficients were all positive, ranging from .13 to .35, and the high strength group had the highest mean at all tension levels, with the exception of the swimmers at 50% MVC (Figure 19). In all the fatiguing tests the peak heart rates occurred near the end of the test (Figure 20). In order to ensure accurate peak values for the shorter tests, final heart rates at 50% and 75% MVC were calculated from the last ten seconds of the paper chart record. Individual peak heart rates varied widely from 96 to 182, but were not significantly correlated with endurance time, total isometric work, or peak blood pressures for any of the fatiguing tests.

Although individual differences were great, peak heart rates in general were well below the maximum values generally associated with dynamic endurance activities such as running, and were much further below maximum values than were the corresponding blood pressures. Although they were not maximal, peak heart rates reached during fatiguing holds were approximately equal for all tests (Figure 19). No significant differences were found among mean values across tests, and inter-test correlations were all significant, the coefficients ranging from .46 to .77, indicating that individuals reached fairly constant peak heart rates during fatiguing contractions regardless of the tension level or the endurance time. In most cases the peak heart rate reached was sufficiently low and the differences among individuals were so great that heart rates did not reflect comparative levels of fatigue among individuals.

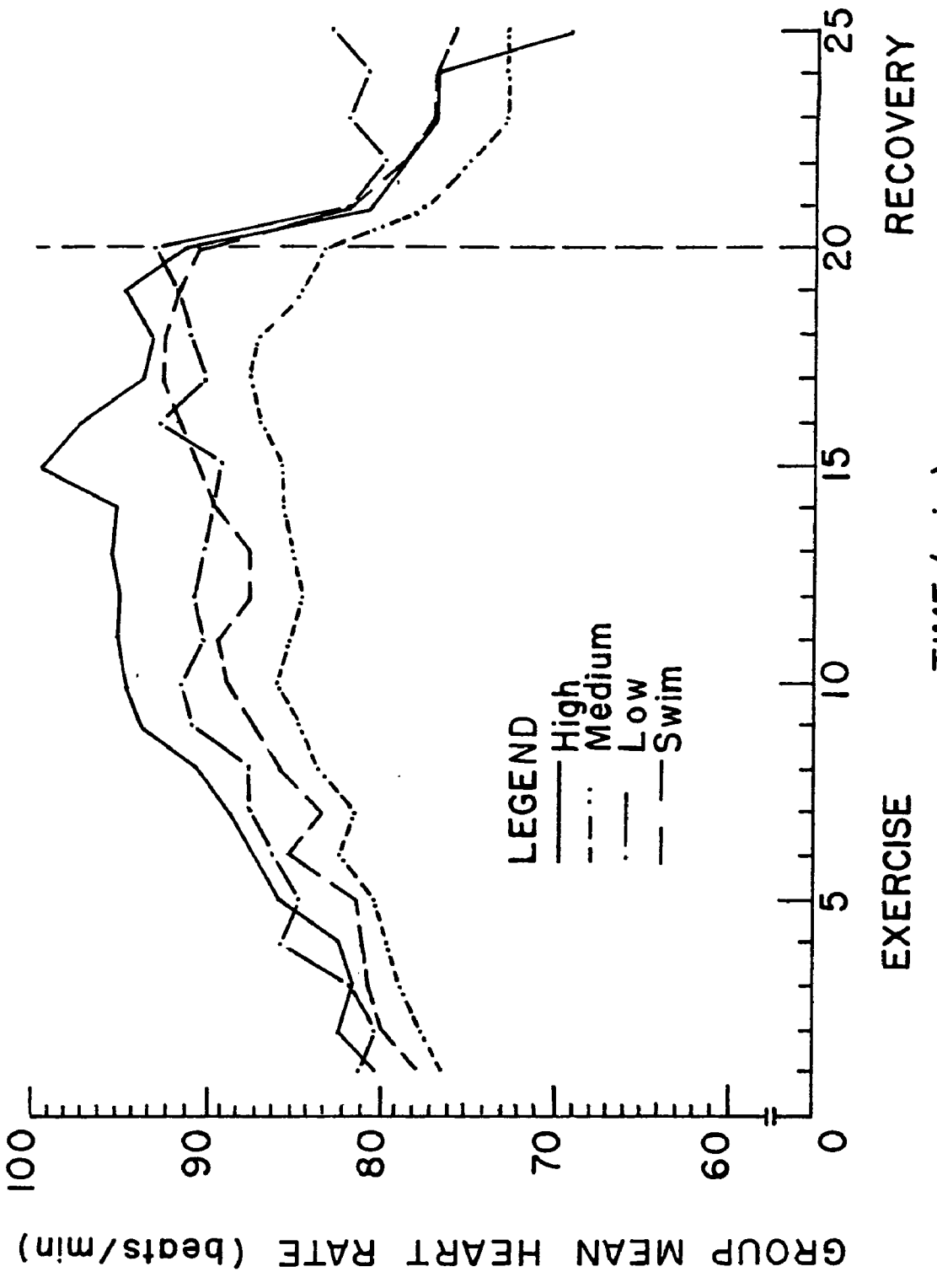


Figure 18. Group differences in mean heart rate during a 20 min static elbow flexion at 15% MVC.

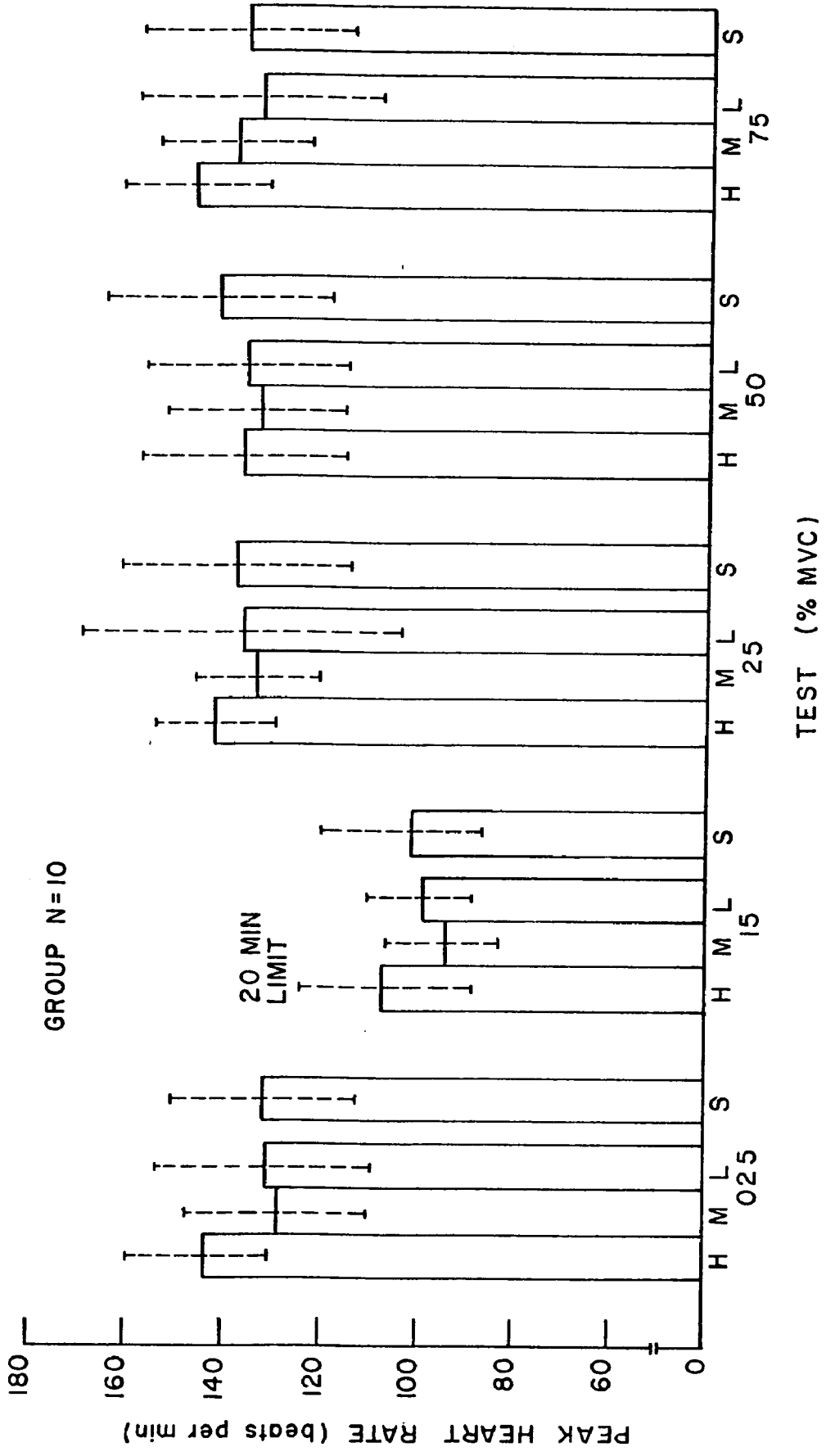
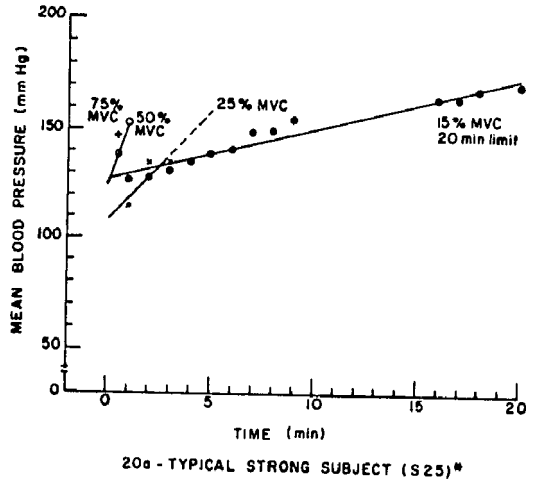


Figure 19. Relationship of peak heart rate to strength showing group means and standard deviations for high, medium, and low strength groups and swimmers.

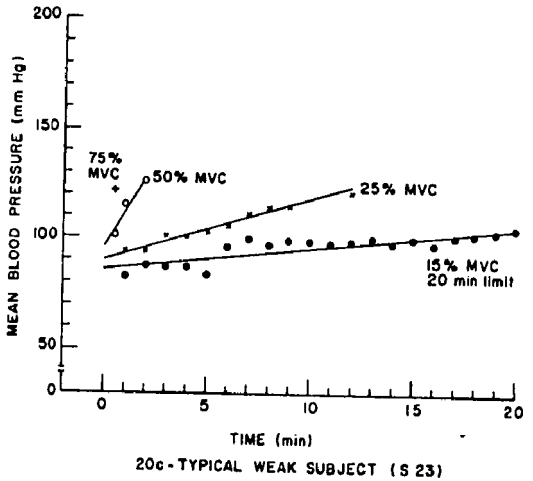
TABLE 11. RELATIONSHIP OF PEAK HEART RATE TO STRENGTH: INDIVIDUAL REGRESSION ANALYSIS AND ANALYSIS OF VARIANCE OF GROUP MEANS (GROUP N = 10)

Variable		Test (% MVC)									
		025		15[a]		25		50		75	
Correlation coefficient (r)		.36		.23		.16		.13		.31	
Significance level of regression (P:Slope = 0)		.02		.15		.34		.43		.05	
ANOVA F ratio		1.37		1.06		.26		.28		.80	
Significance level of ANOVA (P:$\mu_1 = \mu_2$)		.27		.38		.85		.84		.50	
		$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Group mean peak heart rate (beats/min)	H	144.3	14.8	106.4	17.8	141.7	12.6	136.6	21.3	146.6	15.2
	M	128.6	19.1	94.5	11.9	133.1	12.8	133.4	18.4	138.4	16.0
	L	130.9	22.7	99.5	10.7	136.0	33.0	135.8	21.2	133.4	25.4
	S	131.5	19.3	101.0	18.4	137.3	23.7	141.8	23.3	136.2	22.0

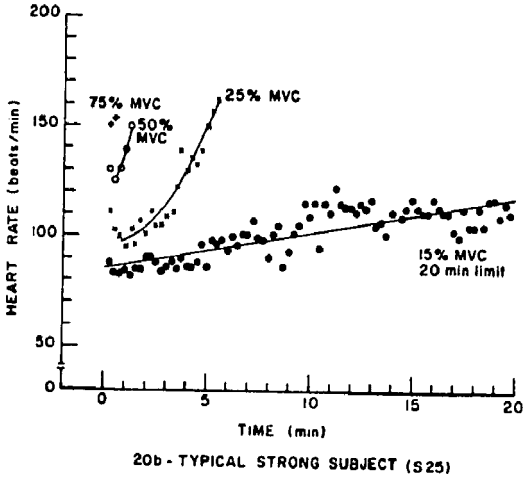
[a]20 min time limit



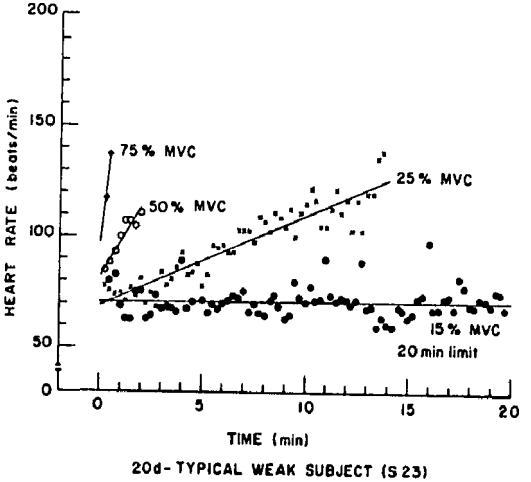
20a - TYPICAL STRONG SUBJECT (S25)*



20c - TYPICAL WEAK SUBJECT (S 23)



20b - TYPICAL STRONG SUBJECT (S25)



20d - TYPICAL WEAK SUBJECT (S 23)

Figure 20. Mean blood pressure and heart rate shown as a function of time for a typical strong subject (Subject 25) and a typical weak subject (Subject 23). *---- missing values

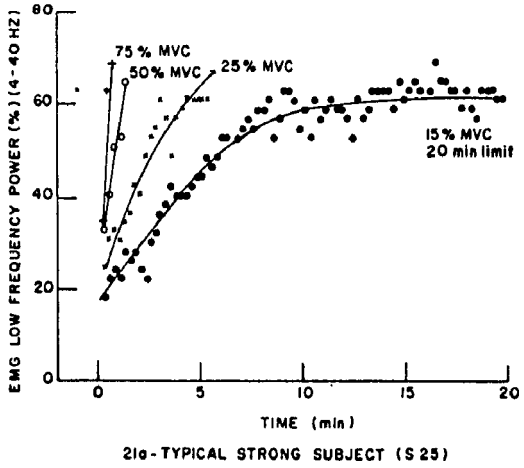
Electromyographic Responses

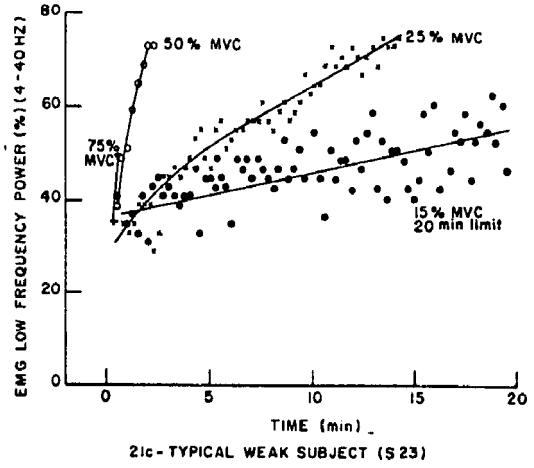
A Fast Fourier transform of the EMG amplitude provided an eight-second time-averaged estimate of the EMG rms voltage every fifteen seconds during the endurance holds. The nominal gain of the signal processing system from skin electrodes to computer output was 100, so that a computer output of 1 millivolt (mV) represented an estimate of 10 microvolts (μV) rms for the electrical output of the muscle at the site of the active electrode. The EMG rms voltages reported are the values estimated for the muscle output. The tape recorder output was calibrated at least once daily and all other gains were fixed throughout all tests, ensuring the comparability of all voltages. The EMG low frequency power was derived from a normalized power spectrum computed for each eight-second sample. The power spectrum shows the percentage of the total power of the signal estimated to occur in each 2 Hz frequency band from 4-200 Hz. The EMG low frequency power is the percentage of the total power which occurs in the 4-40 Hz band.

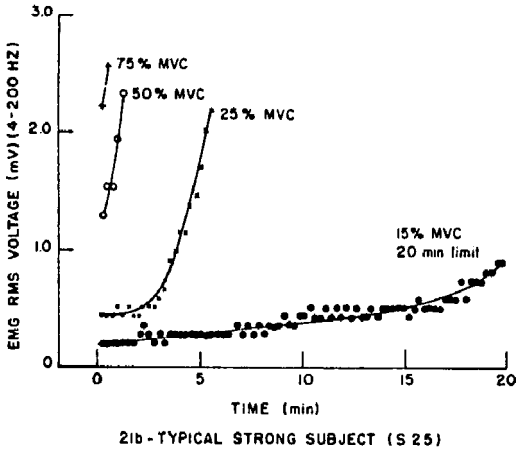
The EMG activity showed the characteristic increase in rms voltage and increase in low frequency power during all holds (Figure 21). In order to determine whether there were characteristics of these parameters which were related to strength or endurance and would provide neuro-muscular evidence for strength-endurance relationships, initial and final values and the shape of the time-related curves were evaluated in relation to strength and maximum endurance times. Group means and standard deviations for initial and final values and the increase during the hold are illustrated in Figure 22 (EMG low frequency power) and Figure 23 (EMG rms voltage). The statistical analyses are summarized

in Table 12 (EMG low frequency power) and Table 13 (EMG rms voltage). Analysis of variance revealed no significant differences among group means for any EMG parameters on any tests, suggesting that the relative loading technique had removed all EMG differences among subjects of widely different strength levels. However, there were a few significant regressions of EMG parameters on strength, and strength was consistently correlated negatively with initial low frequency power ($r = -.17$ to $-.42$) (Table 12) and positively with initial rms voltage ($r = .10$ to $.38$) (Table 13).

At 15% MVC significant regressions showed more definite relationships between EMG activity and strength. The increases in both low frequency power and rms voltage were significantly positively related to strength chiefly because of a significant negative relationship between initial low frequency power and strength (Table 12) and a significant positive relationship between final rms voltage and strength (Table 13). It appears that at this tension level, the stronger subjects started with equal rms voltage but lower low frequency power than weaker subjects. After 20 min of continuous contraction, the rms voltage was greater in the stronger subjects, but the percentage of low frequency power was equal for all. Since the absolute increase in both parameters was positively related to strength over a 20 min time period, the mean rate of increase was also positively related to strength at 15% MVC. If rate of EMG change is used as a measure of the rate of fatigue, this indicates that the fatigue rate over 20 min at 15% MVC was positively related to strength.







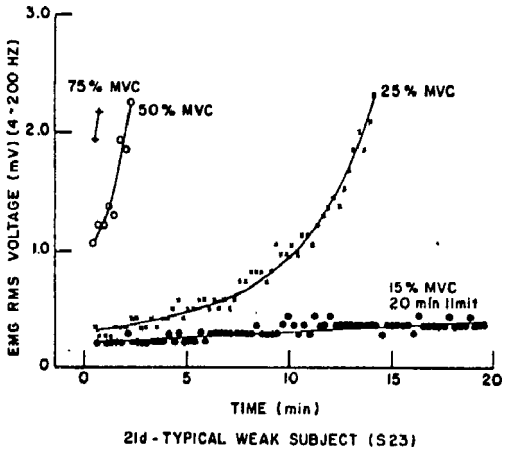


Figure 21. EMG low frequency power and EMG rms voltage shown as functions of time for a typical strong subject (Subject 25) and a typical weak subject (Subject 23).

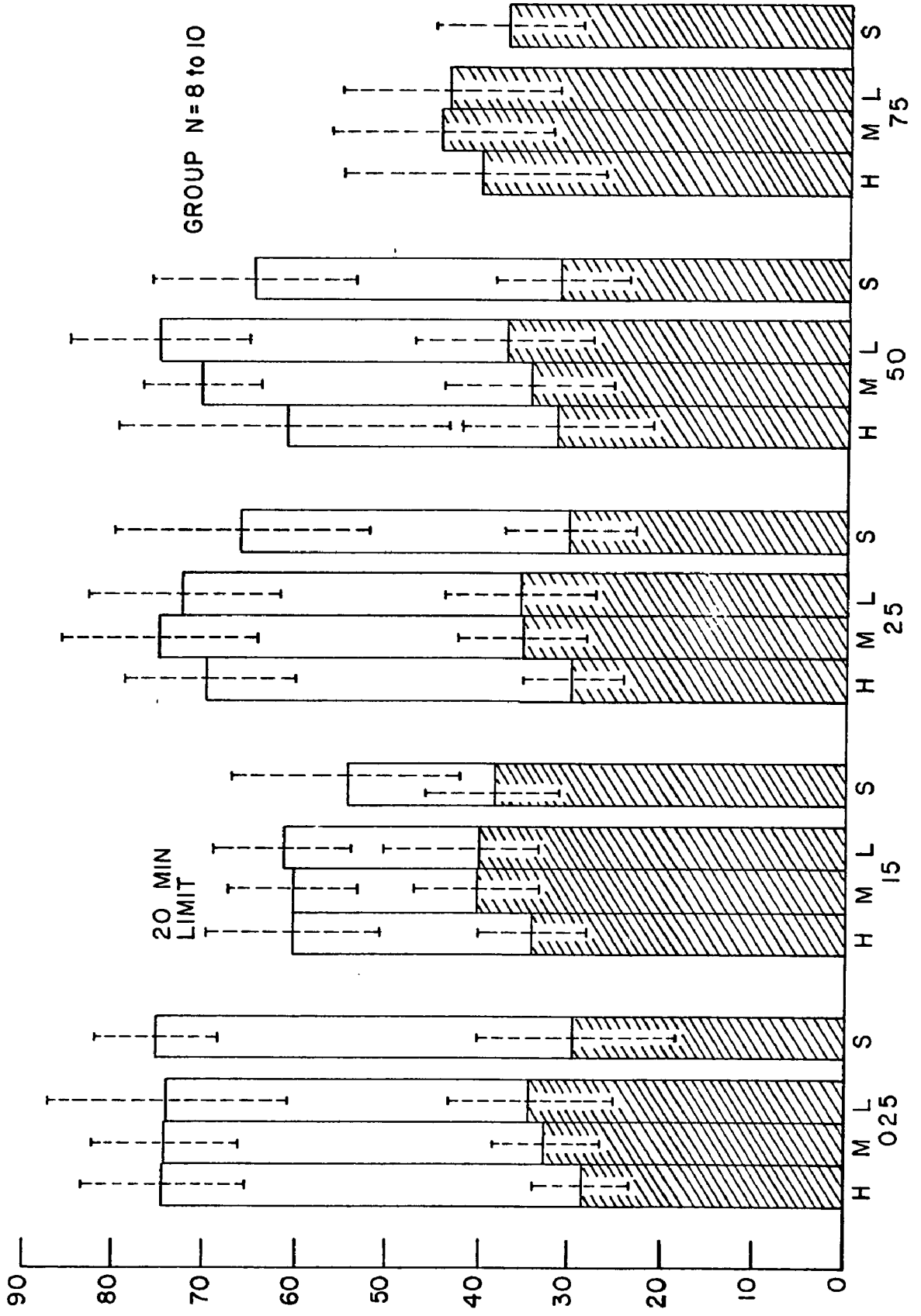


Figure 22. Relationships of EMG low frequency power to strength showing group means and standard deviations for high, medium, and low strength groups and swimmers.

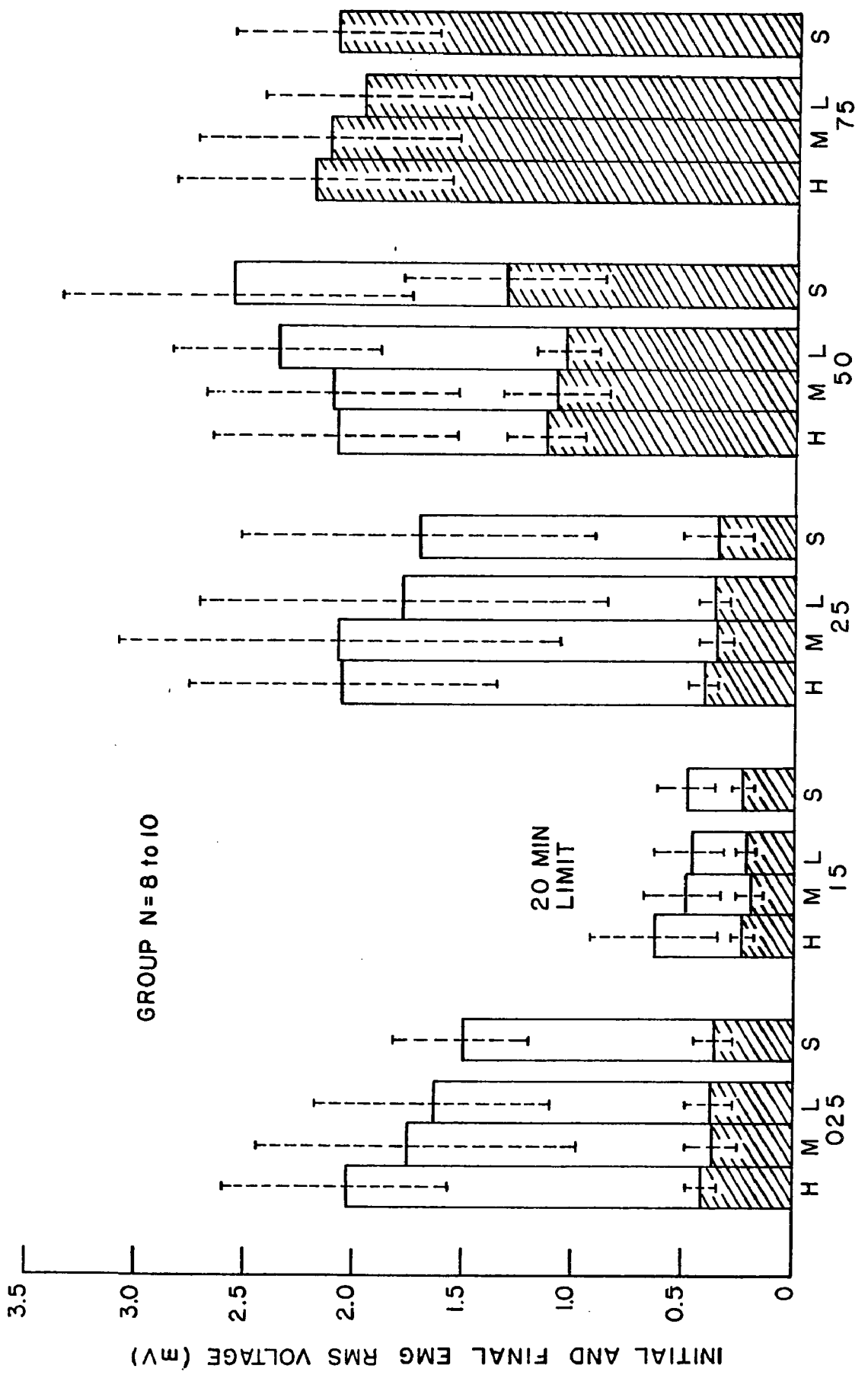


Figure 23. Relationships of EMG rms voltage to strength showing group means and standard deviations for high, medium, and low strength groups and swimmers.

TABLE 12. RELATIONSHIP OF EMG LOW FREQUENCY POWER TO STRENGTH: CORRELATION COEFFICIENTS, GROUP MEANS AND STANDARD DEVIATIONS (GROUP N = 8 to 10)

	Test (% MVC)									
	025		15[a]		25		50		75	
Variable	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Initial EMG low frequency power										
Correlation coefficient (r)	-.28		-.42[b]		-.34[b]		-.17		.03	
Group means (μV)										
H	28.6	5.3	34.3	6.1	29.9	5.6	31.9	10.5	40.8	14.4
M	32.6	5.9	40.2	6.8	35.6	7.3	34.7	9.4	44.5	12.3
L	34.5	9.2	42.0	8.7	35.7	8.4	37.5	9.9	43.8	12.2
S	29.5	10.8	38.7	7.4	30.3	7.3	31.3	7.5	37.3	8.2
Final EMG low frequency power										
Correlation coefficient (r)	.05		.07		-.04		-.26			
Group means (μV)										
H	74.6	9.2	60.5	9.6	70.0	9.4	61.8	18.2	--	
M	74.4	8.2	60.5	7.3	75.4	10.6	70.7	6.4	--	
L	74.3	13.3	61.5	7.6	72.8	10.6	75.6	10.0	--	
S	75.5	6.7	54.9	12.6	66.4	14.1	65.2	11.4	--	
EMG low frequency power increase										
Correlation coefficient (r)	.28		.41[b]		.21		-.15			
Group means (μV)										
H	46.0	8.2	26.1	10.8	40.1	5.5	29.9	13.5	--	
M	41.8	11.4	20.3	7.7	39.8	11.5	36.0	11.0	--	
L	39.8	9.4	19.5	9.1	37.1	9.5	38.1	11.0	--	
S	44.5	13.9	16.2	6.8	36.6	13.3	34.0	9.2	--	

Analysis of variance showed no significant differences among groups on any test.

[a]20 min time limit

[b]Regression on strength significant, (P:slope = 0) < .05

-- Insufficient data

TABLE 13. RELATIONSHIP OF EMG RMS VOLTAGE TO STRENGTH: CORRELATION COEFFICIENTS, GROUP MEANS AND STANDARD DEVIATIONS (GROUP N = 8 to 10)

	Test (% MVC)									
	025		15[a]		25		50		75	
Variable	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Initial EMG rms voltage										
Correlation coefficient (r)	.32		.10		.30		.12		.27	
Group means (μV)										
H	410	73	231	47	413	64	1141	182	2212	629
M	359	126	197	59	355	75	1096	244	2131	597
L	372	108	220	41	365	74	1050	143	1976	467
S	358	88	233	57	354	151	1332	462	2105	464
Final EMG rms voltage										
Correlation coefficient (r)	.29		.36[b]		.16		-.18			
Group means (μV)										
H	2038	566	632	299	2068	711	2104	560	--	
M	1705	734	494	177	2084	1018	2112	587	--	
L	1641	540	469	163	1796	937	237.3	476	--	
S	1509	308	489	134	1719	810	2570	810	--	
EMG rms voltage increase										
Correlation coefficient (r)	.24		.37[b]		.13		-.26			
Group means (μV)									--	
H	1628	557	401	275	1655	690	963	465	--	
M	1346	724	298	153	1729	989	1016	531	--	
L	1269	525	249	149	1431	896	1320	548	--	
S	1147	346	256	141	1379	734	1238	676	--	

Analysis of variance showed no significant differences among groups on any test.

[a]20 min time limit

[b]Regression on strength significant, (P:slope = 0) < .05

-- Insufficient data

Relationships with endurance

Correlation coefficients were calculated to show the relationships of the peak values of all the parameters to maximum endurance times (Table 10). At both 25% and 50% MVC final low frequency power and the low frequency power increase during the hold were significantly positively related to maximum endurance times ($r = .33$ to $.52$). Final EMG rms voltage and rms voltage increase were also consistently positively related to endurance times ($r = .16$ to $.45$), although significant only at 50% MVC. The subjects with the longer endurance times at these tension levels were able to achieve a greater increase and reach higher final values of low frequency power and to a lesser extent rms voltage.

Specific EMG responses

The time course of EMG changes varied at different tension levels. Figure 21 shows curves obtained for typical strong and weak subjects. The EMG low frequency power generally increased in approximately linear fashion, the rate of increase being directly related to the tension. The changes in rms voltage appeared to be independent of the low frequency changes. During the 25% MVC holds the rms voltage increase generally accelerated with time, with a rapid rise towards the end of the test. At 75% and 50% MVC the increase was so rapid that it was approximately linear, although in many cases some acceleration could be detected at 50% MVC. At 15% MVC the increase in rms voltage was so slow and slight that it was again approximately linear, although in some cases a slight acceleration occurred near the end of the 20 min hold. At the 15% and 25% MVC levels the rate of increase was noticeably

greater in the stronger subjects, as would be expected because of the positive correlations of the EMG increases with strength (Tables 12 and 13), coupled with equal endurance times at 15% MVC, or times negatively related to strength at 25% MVC (Table 5).

In six of the subjects from the high strength group a noticeable deviation from the usual linear pattern occurred in the EMG low frequency power curve at 15% MVC (Figure 21a). These subjects (Subjects 1, 15, 22, 25, 33, and 36) all displayed a markedly decelerating curve for the low frequency power response. After a relatively rapid increase in the first half of the 20 min hold, the curve levelled off at close to its peak value. Each of these subjects regularly lifted weights but participated in no other athletic activities. The other four members of the high strength group were football players whose weight training was only a part of their total physical conditioning program.

At 25, 50, and 75% MVC all subjects maintained the contraction to fatigue and reached relatively high levels of both EMG low frequency power and rms voltage (Figures 22 and 23). At 15% MVC the final values and increases in both parameters were significantly lower than for the other tension levels. The final value and increase in EMG rms voltage, particularly, were only a small fraction of the values for the other tests. This was the case even for the stronger subjects who had great difficulty reaching the 20 min time limit. Figure 12 illustrates the phenomenon for two individuals. Subject 25, a strong subject who was in great pain and felt extremely fatigued at 11 min, was close to his peak blood pressure (Figure 20a) and peak EMG low frequency power (Figure 21a) at that time, but at the end of the hold had still reached a final EMG rms voltage of

only 860 μV, compared to about 2 mV for each other test (Figure 21b). Subject 36, who was unable to continue beyond 16 min, 34 sec, reached a final rms voltage of only 630 μV compared to over 1680 μV for each other test. At this tension level the electrical activity in the muscle reached a much lower level than at higher tensions, even at, or close to, the point at which the subjects were unable to maintain the tension. The EMG low frequency power curve more closely resembled the blood pressure responses and subjective fatigue of the subjects at the 15% MVC level (Figures 20a and 21a).

CHAPTER V

DISCUSSION

Strength vs. Endurance Relationships

The relationship between isometric muscular strength and relative endurance was not constant at the different relative tension levels employed. At 75% MVC a correlation coefficient of .03 indicated no relationship between MVC and maximum endurance time (MET), supporting the earlier findings of Carlson and McCraw (18), Caldwell (9,10), and Rohmert (88) that at high relative tension levels there is no relationship between isometric strength and relative endurance.

The situation was quite different at 50% MVC, with a highly significant negative relationship between MVC and MET. Both regression of endurance times on strength and analysis of variance of differences among means showed a significant negative relationship, the high strength group having the shortest and the swimmers the longest endurance times. The coefficient of correlation between MVC and MET ($r = -.48$) is similar to the values ($r = -.36$ to $-.60$) reported by Start and Graham (102), Martens and Sharkey (71), and Carlson and McCraw (18) for static elbow flexion with loads of 30% to 75% MVC. At 50% MVC all the cardiovascular parameters were positively related to strength, but only peak diastolic and peak mean blood pressures at significant levels. An interesting reversal was seen in the EMG values. Although none of the relationships with strength were significant, the increases in both EMG low frequency

power and rms voltage were negatively correlated with strength (r = -.15, -.26) and the group means of the strength groups were in the opposite order to their strength levels. This may reflect a slightly lower level of fatigue, suggesting poorer motivation on the part of the weaker subjects, although this interpretation is not supported by the cardiovascular data. It is unlikely that this could account for the negative relationship of endurance time to strength which was significant beyond the .01 level on both regression analysis and analysis of variance at 50% MVC.

The 25% MVC level proved to be one at which wide variations in endurance time were possible, the range extending from four to 22 min. The regression of MET on strength was significant at the .01 level for both tests at 25% MVC. Although no significant differences were found among the group means, the high strength group again had the shortest endurance times and the swimmers the longest for both tests, suggesting that, although the relationship of relative endurance to strength was not as strong as at 50% MVC, it still existed. At 25% MVC the peak values of blood pressures and heart rate were all positively correlated with strength (r = .16 to .46), although the levels of significance were not consistent. The increases in both EMG rms voltage and EMG low frequency power were also positively correlated with strength on both tests at 25% MVC (r = .13 to .28). The fact that the values of these physiological variables are all positively correlated with strength, often at significant levels, indicates that the stronger subjects reached levels of physiological strain as great as, if not greater than, those reached by the other groups. This suggests that the negative relationship between

endurance time and strength for the 25% MVC level was not the result of motivational differences.

Since all 15% MVC tests were terminated at 20 min, any evaluation of relative endurance must be based on subjective observations, reports of the subjects, and the analysis of the physiological variables. All of the subjects who had extreme difficulty maintaining the contraction, in some cases from as early as 11 min into the hold, were members of the high strength group. Although it was difficult to gauge the pain or fatigue levels of most of the other subjects, many of the weaker subjects and swimmers complained that boredom was a greater problem than pain, and felt that they could have continued considerably longer if necessary (two even exceeded 20 min at 25% MVC). This was a subjective indication of a negative relationship between strength and relative endurance at 15% MVC. The evidence does not fully support Rohmert's (86) contention that a contraction of 15% MVC can be maintained indefinitely. In the strong subjects this certainly was not the case, as several of these subjects would have stopped before 20 min had they not received a great deal of verbal encouragement. The different findings may be due, in part, to the fact that the strength levels of Rohmert's subjects did not extend into a similar high strength range. At the low tension levels, where endurance times are long and more easily affected by motivational factors, physiological variables become more important indicators of fatigue.

In the present 15% MVC test, peak systolic, diastolic, and mean blood pressures were all significantly positively related to strength beyond the .001 level. Peak heart rates were also positively related to strength, but not at a significant level. Throughout most of the

20 min contraction period the high strength group had higher mean values of both heart rates and blood pressures (Figures 15 and 18), suggesting that these subjects were under a greater cardiac load than the other groups. The peak blood pressures of the high strength group were equal to their values at fatigue on the other tests (Figure 17, Tables 7-9), but the other groups had not yet reached the levels they attained during the fatiguing tests, suggesting that the high strength subjects were closer to fatigue at 15% MVC. No significant inter-group differences were found in EMG values, but significant regressions on strength suggested that at 15% MVC the stronger subjects began with equal voltage and less low frequency power than weaker subjects, and showed a greater increase in both, reaching higher voltages but equal percentages of low frequency power at the 20 min time limit. The positive relationships of both voltage increase and low frequency increase to strength indicate that the rate of increase was more rapid in stronger subjects. This suggests a more rapid rate of fatigue according to the criteria of EMG amplitude employed by deVries (29) and others, or low frequency shift used by Chaffin (20) and others as physiological indicators of fatigue.

Comparative endurance of swimmers

At each tension level the swimmers were compared with the medium and low strength groups, from whom they were not significantly different in size and strength. The swimmers were not significantly different from the other two groups on maximum endurance times, isometric work, peak blood pressures, peak heart rates, or EMG values at any tension level, although their mean values were consistently slightly higher on

endurance times, isometric work, and peak heart rate. The cardiovascular and dynamic muscular endurance which allowed them to swim over 4,000 meters daily was apparently little advantage in maintaining static contractions.

Evaluation of endurance performance

The maximum endurance times were comparable with values reported by Carlson and McCraw for elbow flexion with similar relative loads, but were higher than values reported by Rohmert and Caldwell for other tasks (Figure 12). In the latter case the differences were greater at the 25% MVC level. Greater endurance times could be the result of spuriously low MVC values, but this is unlikely since the subjects appeared highly motivated and apparently fatigued more rapidly at 15% MVC than did Rohmert's subjects. Furthermore, the isometric work performed at 50% and 75% MVC was comparable with that of Caldwell's subjects (Figure 14). Since isometric work is inversely related to relative tension, the present subjects should have performed more isometric work than did Caldwell's subjects at each level if their MVC values were spuriously low. Apparently this is not the case. The motivation of the subjects, which was considered very high in this study, may be a factor contributing to the high endurance times. One subject was in tears at the end of a 25% MVC hold, many were sweating profusely, and all were given vigorous verbal exhortation to continue well beyond the onset of pain. Since the 25% MVC level was clearly the most subject to the influence of motivation, this may be the reason the difference from Rohmert's and Caldwell's data was greatest at this tension level. The criteria for determining the end of the test are

also important at this relative load. Subjects were sometimes able to continue for several more minutes after the first momentary deviation from the defined position. The influence of pain is much greater at 25% MVC than in the shorter holds, suggesting the possibility that in tasks involving numerous muscle groups the broader extent of pain may lead to shorter endurance times. In this respect the present elbow flexion task with bodily restraints is considerably more localized than the horizontal manual pull task of Caldwell (9), which actively involves handgrip, elbow flexion, and shoulder extension.

Evaluation of group strength differences

The strength range of the subjects was greater than that reported in previous studies. Although the experimental conditions in the studies were not identical, the high strength group had considerably (25%) higher strength scores than groups of high strength subjects tested on similar elbow flexion tasks by other authors (17,102). The low strength group was comparable with the low strength subjects studied by other investigators. Despite the high correlation between bodyweight and strength, which was probably due to the selection of population extremes, the superior strength of the high strength group was more than that which was attributable to differences in body size. When equated for bodyweight, the other three groups were not significantly different in strength, although the means remained in the same relative order. The relationships of the performance and physiological variables to strength appeared to reflect these strength relationships among the groups. In previous studies there has been no evidence to show whether strength differences

among the subjects were any more than could be attributed to differences in bodily size. From the physiological point of view there are few reasons to expect individual differences in relative muscular performance unless there are intra-muscular differences due to heredity, training, or some factor other than body size.

Relationships between endurance times and physiological variables

What are the characteristics associated with good or bad endurance times? Correlation coefficients showing the relationships between maximum endurance time and each other variable indicated that the EMG activity was the physiological response most closely related to endurance time (Table 10). Consistently significant positive correlations of final EMG low frequency power ($r = .33$ to $.38$) and low frequency power increase ($r = .35$ to $.52$) with endurance times showed that those with the longest endurance times at 25% MVC and 50% MVC tolerated greater low frequency shifts. High final levels and increases of EMG rms voltage were also associated with longer endurance times, although not always at significant levels ($r = .16$ to $.45$). This may be a reflection of better motivation or a better physiological ability to increase the electrical output of the muscles and hence the recruitment of additional muscle fibers. Peak blood pressures were less clearly related to endurance times, but peak systolic and peak pulse pressures were consistently positively correlated with MET ($r = .14$ to $.33$), as were all peak blood pressures at 25% MVC. Peak heart rates bore little relationship to endurance time. These relationships show that subjects who had longer endurance time at tension levels of 50% MVC or below began with a low initial EMG rms voltage, were

able to continue to high levels of EMG rms voltage and low frequency power, or attained a high level of blood pressure. This could be interpreted to mean that these subjects began with few fibers recruited, were able to continue until great numbers of fibers were recruited, or were able to increase the muscle blood flow effectively by reaching a high level of blood pressure.

Physiological hypotheses

The most popular hypothesis previously advanced in explanation of a negative relationship between isometric strength and relative endurance has been the blood flow hypothesis (18,102). At high levels of tension (above about 70% MVC) the endurance time for static contractions has been found to be unaltered by mechanical occlusion of the blood flow (47,90,103), indicating intramuscular occlusion at these levels. The energy available for contraction is limited to those anaerobic and aerobic sources currently within the muscle. The proponents of the hypothesis suggest that, at a given high relative tension level, strong and weak muscles exhaust these energy supplies or build up a concentration of metabolites at the same rate, resulting in equal endurance times (18,102). The endurance time becomes increasingly longer at lower tension levels, until at some point below 15% MVC the contraction can be maintained indefinitely and the energy supply is equal to the demand. At the intermediate levels external mechanical occlusion of the blood flow shortens the endurance time, showing that the muscle relies on the circulation for aerobic energy supplies (47, 77,90,103). A negative relationship between strength and relative

endurance at these levels may be due to increased contractile protein in hypertrophied muscle without a parallel increase in the capillarization or oxidative capacity of the muscle (17,18).

The hypothesis has been extended in the present study to incorporate the findings of Lind's group (30,60,62) and others (35) concerning the blood pressure response to static contractions. Blood flow is increased by an initial increase in blood pressure which is directly related to the relative tension. At levels below 15% MVC the blood pressure remains fairly constant and appears adequate to provide sufficient blood flow to meet the energy demands. At levels above 15% MVC the blood pressure continues to increase at a rate which is directly related to the relative tension, apparently in response to the degree of inadequacy of the blood flow. The level of blood pressure at low levels and the rate of increase at high levels reflect the inadequacy of the blood flow. This may be a useful physiological index of fatigue.

The results of the present study support the blood flow hypothesis, since there was no relationship between strength and relative endurance at 75% MVC and a negative relationship at 50% and 25% MVC. The consistent positive relationships of blood pressures to strength and the negative relationships of endurance times to strength at 50% and 25% MVC suggest that the blood flow inadequacy is greater in the stronger subjects than in the weaker subjects, resulting in more rapid fatigue. This is borne out at 15% MVC by the higher blood pressures of the high strength group throughout the hold. These relationships suggest that either the rate of energy demand was greater in the stronger subjects or their supply and utilization of substrates was less effective than in the weaker

subjects. Termination of the contraction was probably due to inability of the falling phosphocreatine stores to replenish the adenosine triphosphate supply at a rate adequate to maintain the level of contraction (3,34,100). There is no research evidence to support the proposal that accumulation of a metabolite is the causal factor in fatigue.

If the blood flow hypothesis is correct, then absolute strength differences which are simply the result of differences in bodily size should not be associated with differences in relative endurance. This would explain the lack of significant differences among the three weakest groups, whose strength differences were mostly related to body size. Also, the hypothesis would predict that if the hypertrophy due to strength training were accompanied by an increase in oxidative capacity associated with endurance training, then endurance times would be unaffected by the hypertrophy. This appears to be supported by an informal comparison of the six strong weightlifters who had little or no endurance activity with Subject 8, who had equally hypertrophied muscles but had maintained a high level of endurance training.

A greater proportion of fast twitch, low oxidative, white fibers in stronger muscles would account for a more rapid fatigue rate (34), but the present EMG analysis does not show any consistent group differences in initial or final EMG values or their increases which would reflect a difference in muscle fiber types between hypertrophied and endurance-trained muscles. Buchtal and Schmalbruch (7) also found that weightlifters were no different from untrained subjects in contraction times and fiber types even though they were more than twice as strong. The rapid early rise in EMG low frequency power in six weightlifters at 15%

MVC could reflect the early fatigue of a greater proportion of white fibers, but this is purely conjecture.

Another possible explanation of a negative relationship between strength and relative endurance for the longer holds is that the heat loss from larger, hypertrophied muscles may be less effective, resulting in higher muscle temperatures with increased metabolic rate and more rapid fatigue. Increased muscle temperatures have been shown to decrease isometric contraction times (25). If this hypothesis were important, strength differences due to differences in body size alone would be expected to be accompanied by relative endurance differences. This does not appear to be the case.

It was shown earlier that the physiological data in the present study do not support the hypothesis that the negative relationship between strength and endurance at 50% MVC and below was due to motivational differences during the endurance holds. A consistent negative relationship could equally well be explained by invalid strength measurements. If the MVC values for the weaker subjects were lower than those of the stronger subjects because of poorer motivation or less experience and expertise at lifting heavy weights, then the MVC values recorded may not accurately represent their relative physiological capabilities. The expected result would be greater endurance times for the weaker subjects, since the loads would be relatively smaller than for the stronger subjects. However, if this were the case, endurance times at 75% MVC would also be expected to be longer for the weaker subjects. Since this was not the case, it is unlikely that this was the cause of the negative relationship at the lower tension levels.

Cardiovascular Responses

Within the limitations of the auscultatory method, the results of this study support many of the findings of other authors concerning the blood pressure responses to static contractions. During fatiguing contractions the blood pressure rose initially to a level which depended to some extent on the relative tension level, and then continued to rise in approximately linear fashion to a level which was reasonably constant for each individual at the point of fatigue regardless of the level of tension (Figure 20). There is a wide range of peak values among individuals. For that reason it is difficult to use absolute values of blood pressures as indices of fatigue to compare individuals. The slope of the blood pressure vs. time curve is limited as an index of fatigue by the fact that the initial value varies among individuals and is subject to anticipatory effects based on the subject's perception of the intensity of the task (35).

The heart rate response was considerably less than the blood pressure response in most subjects, confirming the view (30,60,62) that, even during contractions carried to fatigue, the blood flow demands on the heart during static contractions are minor in comparison with the pressure demands. In spite of wide individual variation, the group mean values for peak heart rate were remarkably constant for all the fatiguing tests, but were well below maximum values. Instantaneous and peak heart rate values are not comparable with those obtained during whole-body dynamic activities in evaluating the physiological load or state of fatigue, as has previously been shown by Hansen and Maggio (39), since at most tension levels the heart rate never reaches a steady level

and its peak value for static work is much less than its maximum value for dynamic work. A further problem is the variable rate of increase with time. It was linear in some cases, curvilinear in others (Figure 20). At 25% MVC there was frequently a plateau for one to four minutes, followed by a rapid increase, which was linear in many cases, indicating the influence of a delayed mechanism. During the first minute there was often even a decrease in heart rate, probably due to an excessive anticipatory heart rate. These variable factors all restrict the use of the heart rate as a physiological indicator of fatigue in static contractions. The increase of heart rate with time did not correspond with that of any other variable. At 15% MVC the mean heart rate response for all groups was considerably lower than that recorded at the higher levels of contraction (Figure 19). A similar phenomenon was seen in the EMG rms voltage response (Figure 23), although the two were not parallel (Figures 20 and 21). In this respect these two parameters differed from the blood pressure and EMG low frequency power responses, which appeared to approach maximum values at 15% MVC, especially in the stronger subjects.

Static contractions and cardiac health

The long-term effect of static contractions on the heart has received little study. The overload principle suggests that training the heart against a pressure load such as occurs during static contractions should increase the strength of the healthy heart. Since mean blood pressures reach high levels during any fatiguing static contraction regardless of the relative tension, a training effect on the

contractility of the heart should occur whenever a contraction is maintained to the point of fatigue. This could possibly account for the positive correlations between strength and peak blood pressures reached at fatigue.

The peak heart rates attained in the fatiguing tests were within the range usually accepted as being sufficient to provide a training stimulus for the heart. Since, in most cases, these levels are reached only briefly at the end of an exhausting contraction, it is not surprising that isometric training has not been found to provide a cardiovascular training effect in terms of reduction of resting heart rate or increased maximum oxygen consumption.

The cardiac risks involved in isometric contractions are clearly more closely related to elevation of blood pressure than of heart rate. Since blood pressures reached approximately the same high peak values for any fatiguing contraction, regardless of the relative tension or the size of the muscles involved, it is important for any person with a history of heart disability to be aware of the risk of holding contractions close to the point of fatigue. Although the factors of pre-selection were not controlled in this study, the evidence does not suggest that either dynamic endurance training (swimming) or weight training reduced the level of the blood pressure response to fatiguing contractions. In view of the cardiac pressure load, which is considerably greater than in dynamic activities, it is suggested that electrocardiographic and blood pressure responses to standardized static contractions may have value in cardiac evaluations, in conjunction with the present tests related to dynamic exercise.

Electromyographic Responses

Although the differences among group EMG values were almost removed using the relative loading technique, the wide range of individual differences restricts the degree to which EMG parameters can be used to provide an objective measure of fatigue. The consistent group means for final EMG low frequency power (approximately 70%) suggest this as a likely criterion for fatigue. However, individual values for fatiguing contractions ranged from 28.7 to 91.0% making it impossible to use a value such as 70% as the index of fatigue in individuals. It may be a useful normative value for the prediction of fatigue in large groups. Since EMG low frequency power as a function of time was found to increase in approximately linear fashion for most subjects at all tension levels, mean endurance times for groups could be predicted from the slope of this line during a brief contraction. In this respect the slope of the EMG rms voltage curve appears much less useful, since the shape of the curve varies at different tension levels and for different individuals. Furthermore, at 15% MVC the EMG rms voltage indicates almost no sign of fatigue (Figures 21 and 23), and yet the subjective signs, blood pressure levels, and EMG low frequency power all suggest a considerable degree of fatigue, especially in the stronger subjects. Although deVries (29) has used a logarithmic transformation of the slope of the integrated EMG curve with some success, its predictive capabilities appear less satisfactory than those of the low frequency power function, particularly at lower relative tension levels.

The time courses of the EMG low frequency power and rms voltage changes were largely independent (Figure 21), suggesting different

physiological mechanisms. The initial values were graded according to tension in the case of rms voltage, but not low frequency power, for which starting levels were approximately constant at all tension levels (Figures 22 and 23). EMG low frequency power maintained a generally linear rate of increase, while the rms voltage frequently increased rapidly near the end of the hold (Figure 21), particularly at 25% MVC. At 15% MVC the low frequency power was able to increase rapidly and then level off in six strong subjects without any corresponding change in rms voltage. In that case the low frequency power values approximated fatigue levels, but the rms voltage was less than half the value generally reached at fatigue. This phenomenon appears to negate models of the EMG changes which explain the amplitude increase totally in terms of frequency changes. Although the EMG low frequency power curve more closely approximates the corresponding blood pressure changes (Figures 20 and 21) and the EMG rms voltage changes are more similar to the heart rate changes, no two of the four functions correspond closely, as is most clearly seen at 25% MVC. It is not possible for the four functions to represent equally a single concept of fatigue.

The physiological explanations for these findings are far from clear. The EMG rms voltage has generally been taken to represent the number and size of the motor units recruited. This would account for the graded initial rms voltage values. Clarke, Hellon, and Lind (25) concluded that the sharp rise in EMG voltage near the end of a contraction was due to recruitment of extra muscle fibers. They postulated that at the point of fatigue all or almost all of the fibers in the muscle were activated. This would explain the fairly constant final

EMG rms voltage values at 25% MVC and above, but does not explain the very low voltages at 15% MVC. It is possible that the subjects who were in great pain and were struggling were not fatigued in the sense that the phosphocreatine stores were not depleted and only a small proportion of the total number of fibers was needed. In view of their struggles, the fact that they felt unable to continue in the same way that they did at 25% MVC, and their high EMG low frequency power, this seems unlikely. If it is the case, it suggests that the increases in blood pressure and EMG low frequency power are more closely related to pain than to fatigue in the sense of energy depletion, and heart rate and EMG rms voltage are associated with fatigue rather than pain.

Lloyd et al. (68,70) found that the endurance time could be predicted from pain levels and concluded that the EMG voltage enabled physiological and psychological aspects of fatigue to be differentiated, the point at which the EMG significantly increased in amplitude indicating physiological fatigue and the onset of motivational elements. The present data do not support this hypothesis. The onset of pain may be associated with certain levels of EMG activity only indirectly, since at 15% MVC pain was intense in some subjects, but was accompanied by no significant increase in EMG rms voltage. At 50% MVC and 75% MVC the EMG voltage levels were much higher, but the contraction ended before any marked level of pain was reached, indicating that the high voltage was not due to cortical recruitment in response to pain.

In view of the likelihood of pain rather than fatigue causing the termination of endurance holds, and the difficulty of gauging the level of motivation of subjects, it is suggested that the most valid and

consistent results may be obtained by providing high levels of extrinsic motivation and minimizing the influence of pain. The repeatability of the measurements was as good using this method as has been reported in studies avoiding motivational influences (9,15). Knowledge of results is one influence which was and should be avoided, at least during the tests, in order to avoid bias.

Further research on the relationships between EMG characteristics and both muscle histology and motivational influences is required before a full theoretical basis can be developed.

CHAPTER VI

CONCLUSIONS

1. The relationship between isometric muscular strength and relative endurance was not constant at different levels of relative tension.

2. At 75% MVC there was no relationship between isometric strength and relative endurance. The relative loading technique removed differences in endurance among individuals of widely different strength levels.

3. At 50% MVC and lower tension levels there was a negative relationship between isometric strength and relative endurance. Cardiovascular and electromyographic evidence indicated that this was a physiological relationship and not merely the result of motivational differences.

4. Highly trained swimmers were not significantly different from other subjects who were comparable in size and strength either on endurance performance or physiological responses.

5. The results are consistent with a blood flow hypothesis for the relationships between isometric strength and relative endurance. The hypothesis states that at levels of tension at which blood flow is occluded muscles fatigue at approximately the same rate, but at levels at which there is blood flow in the muscle relative endurance is related to the ability of the muscle to receive and utilize extrinsic substrates.

This ability may be reduced in hypertrophied muscles if there is not a parallel increase in capillarization.

6. Blood pressures, heart rate, EMG low frequency power, and EMG rms voltage increased during static contractions at rates which were largely independent. The rates were related to the level of relative tension, but since the patterns and their relationships varied at different tension levels and among individuals, no one parameter could be considered the single best index of fatigue for all circumstances.

7. Blood pressures may reach equally high levels during static contractions at any tension level which is sufficient to produce fatigue, even in persons with great strength or endurance. Any person with a history of heart disability should be aware of the risk of holding contractions close to the point of fatigue.

8. Heart rates also reached fairly consistent levels at fatigue in any individual regardless of the tension, but the levels were usually well below the maximum values attained in whole-body dynamic exercise. Since the heart rate also never reached a steady state at most tension levels, increased at variable rates, varied greatly among individuals, and was not closely related to other variables, it does not appear to be a good indicator of comparative fatigue levels in static work.

9. EMG low frequency power and EMG rms voltage were able to increase independently of each other during the course of static contractions, suggesting that two separate mechanisms are responsible for at least part of the increases. Models which explain changes in one parameter entirely in terms of the other are probably inadequate.

REFERENCES

REFERENCES

1. Barcroft, H. and Millen, J.L.E. The blood flow through muscle during sustained contraction. J. Physiol. 97:17-31, 1939.

2. Basmajian, J.V. Muscles Alive. 2nd ed. Baltimore: Williams and Wilkins Co., 1967.

3. Bergström, Jones. Local changes of ATP and phosphorylcreatine in human muscle tissue in connection with exercise. Circulation Research. Suppl. I 20:I91-I96, 1967.

4. Bigland, Brenda and Lippold, O.C.J. The relation between force, velocity, and integrated electrical activity in human muscles. J. Physiol. 123:214-224, 1954.

5. Bruce, R.A., Lind, A.R., Franklin, D., Muir, A.L., MacDonald, H.R., McNicol, G.W., and Donald, K.W. The effects of digoxin on fatiguing static and dynamic exercise in man. Clin. Sci. 34:29-42, 1968.

6. Buchthal, F. and Madsen, A. Synchronous activity in normal and atrophic muscle. Electroenceph. Clin. Neurophysiol. 2: 425-444, 1950.

7. Buchthal, F. and Schmalbruch, H. Contraction times and fiber types in intact human muscle. Acta Physiol. Scand. 79:435-452, 1970.

8. Byrd, Ronald J. and Hills, William L. Strength, endurance, and blood flow responses to isometric training. Res. Quart. 42(4):357-361, 1971.

9. Caldwell, Lee S. The load-endurance relationship for a static manual response. USAMRL Report No. 573, Fort Knox, Ky, 1963.

10. Caldwell, Lee S. Relative muscle loading and endurance. J. Eng. Psych. 2:155-161, 1963.

11. Caldwell, Lee S. The load-endurance relationship for a static manual response. Human Factors. 6:71-79, 1964.

12. Caldwell, Lee S. Body position and the strength and endurance of manual pull. Human Factors. 6:479-484, 1964.

13. Caldwell, Lee S. Measurement of static muscle endurance. J. Eng. Psych. 3:16-22, 1964.

14. Caldwell, Lee S. Recovery from the effects of isometric muscle contractions. J. Eng. Psych. 4:22-29, 1965.

15. Caldwell, Lee S. and Smith, Richard P. Pain and endurance of isometric muscle contractions. J. Eng. Psych. 5:25-32, 1966.

16. Carlson, B. Robert. Relative isometric endurance and different levels of athletic achievement. Res. Quart. 40:475-480, 1969.

17. Carlson, B. Robert. Level of maximum isometric strength and relative load isometric endurance. Ergonomics. 12(3):429-435, 1969.

18. Carlson, B. Robert and McCraw, Lynn W. Isometric strength and relative isometric endurance. Res. Quart. 42(3):244-250, 1971.

19. Carrow, R.E., Brown, R.E., and Van Huss, W.D. Fiber sizes and capillary to fiber ratios in skeletal muscle of exercised rats. Anat. Rec. 159:33-39, 1967.

20. Chaffin, D.B. Electromyography--a method of measuring local muscle fatigue. J. Methods-Time Measurement. 14(2):29-36, 1969.

21. Chaffin, D.B. Physical fatigue: what it is--how it is predicted. J. Methods-Time Measurement. 14(3):20-28, 1969.

22. Chaffin, D.B. Surface electromyography frequency analysis as a diagnostic tool. J. Occup. Med. 11(3):109-115, 1969.

23. Clarke, H.H. Relationship of strength and anthropometric measures to various arm strength criteria. Res. Quart. 25:134-143, 1954.

24. Clarke, H.H. Muscular strength and endurance in man. Englewood Cliffs, N.J.: Prentice-Hall, Inc. 1966.

25. Clarke, R.S.J., Hellon, R.F., and Lind, A.R. The duration of sustained contractions of the human forearm at different muscle temperatures. J. Physiol. 143:454-473, 1958.

26. Cobb, S. and Forbes, A. Electromyographic studies of muscular fatigue in man. Am. J. Physiol. 65:234-251, 1923.

27. Denny-Brown, D. The interpretation of the electromyogram. Arch. Neurol. Psychiat. 61:99-128, 1949.

28. Dern, H. and Walsh, J.B. Analysis of complex wave forms. In: Nastuk, W.L. (ed.), Physical Techniques in Biological Research, Vol. 6, Electrophysiological Methods, part B. New York: Academic Press, 1963, pp. 99-217.

29. deVries, Herbert A. Method for evaluation of muscle fatigue and endurance from electromyographic fatigue curves. Am. J. Phys. Med. 47:125-134, 1968.

30. Donald, K.W., Lind, A.R., McNicol, G.W., Humphreys, P.W., Taylor, S.H., and Staunton, H.P. Cardiovascular responses to sustained (static) contractions. In: Chapman, C.B. (ed.), Physiology of Muscular Exercise. American Heart Association Monograph No. 15. New York: American Heart Assoc., 1967, ppI-15-I-30. Also, Circulation Research. 20,21:Suppl. I, 1967,

31. Eason, Robert G. Electromyographic study of local and generalized muscular impairment. J. Appl. Physiol. 15(3):479-482, 1960.

32. Edwards, R.G. and Lippold, O.C.J. The relation between force and integrated electrical activity in fatigued muscle. J. Physiol. 132:677-681, 1956.

33. Elbel, E.R. Relationship between leg strength, leg endurance and other body measurements. J. Appl. Physiol. 2:197-207, 1949.

34. Faulkner, J.A. Muscle fatigue. In: Briskey, E.J., Cassens, R.G., and Marsh, B.B. (eds.), The Physiology and Biochemistry of Muscle as a Food. Vol. 2. Madison: The University of Wisconsin Press, 1970.

35. Freyschuss, U. Cardiovascular adjustment to somatomotor activation. Acta Physiol. Scand. Supp. 342, 1970.

36. Grant, R.T. Observations on the blood circulation in voluntary muscle in man. Clin. Sci. 3:157-173, 1938.

37. Gray, Sarah D., Carlsson, E., and Staub, N.C. Site of increased vascular resistance during isometric muscle contraction. Am. J. Physiol. 213(3):683-689, 1967.

38. Gray, Sarah D. and Staub, N.C. Resistance to blood flow in leg muscles of dog during tetanic isometric contraction. Am. J. Physiol. 213:677-682, 1967.

39. Hansen, O.E. and Maggio, M. Static work and heart rate. Int. Z. angew. Physiol. einschl. Arbeitsphysiol. 18:242-247, 1960.

40. Hayes, K.J. Wave analysis of tissue noise and muscle action potentials. J. Appl. Physiol. 15:749-752, 1960.

41. Henneman, E. and Olson, C.B. Relations between structure and function in the design of skeletal muscles. J. Neurophysiol. 28:581-598, 1965.

42. Henneman, E., Somjen, G., and Carpenter, D.O. Functional significance of cell size in spinal motoneurons. J. Neurophysiol. 28:560-580, 1965.

43. Henneman, E., Somjen, G., and Carpenter, D.O. Excitability and inhibitability of motor neurons of different sizes. J. Neurophysiol. 28:599-620, 1965.

44. Herberts, P., Kaiser, E., Magnusson, R., and Petersén, I. Power spectra of myoelectric signals in muscles of arm amputees and healthy normal controls. Acta Orthop. Scandinav. 39:1-31, 1969.

45. Hermansen, L. and Wachtlova, M. Capillary density of skeletal muscle in well-trained and untrained men. Acta Physiol. Scand. 79:16A, 1970.

46. Holloszy, John O. Biochemical adaptations in muscle. Effects of exercise on mitochondrial oxygen uptake and respiratory enzyme activity in skeletal muscle. J. Biol. Chem. 242(9):2278-2282, 1967.

47. Humphreys, P.W. and Lind, A.R. The blood flow through active and inactive muscles of the forearm during sustained hand-grip contractions. J. Physiol. 166:120-135, 1963.

48. Inman, V.T., Ralston, H.J., Saunders, J.B., Feinstein, B., and Wright, E.W., Jr. Relation of human electromyogram to muscular tension. Electroencephalog. Clin. Neurophysiol. 4:187-194, 1952.

49. Irish, Everett A. Optimum endurance measurement of elbow flexor muscles and the relations of strength, anthropometric and fatigue factors to arm strength criteria. Doctoral dissertation. U. of Oregon, 1958.

50. Kadefors, R., Kaiser, E., and Petersén, I. Dynamic spectrum analysis of myo-potentials and with special reference to muscle fatigue. Electromyography. 8:39-74, 1968.

51. Knowlton, G.C., Bennett, R.L., and McClure, R. Electromyography of fatigue. Arch. Phys. Med. 32:648-652, 1951.

52. Kogi, K. and Hakamada, T. Frequency analysis of the surface electromyogram in muscle fatigue. J. Sci. Labour. 38:519-528, 1962.

53. Kogi, K. and Hakamada, T. Slowing of surface electromyogram and muscle strength in muscle fatigue. Rep. Inst. Sci. Lab. 60:27-41, 1962.

54. Krogh, August. The anatomy and physiology of capillaries. New Haven: Yale University Press, 1924.

55. Kroll, Walter. Isometric fatigue curves under varied intertrial recuperation periods. Res. Quart. 39:106-115, 1968.

56. Kuroda, E., Klissouras, V., and Milsum, J.H. Electrical and metabolic activities and fatigue in human isometric contraction. J. Appl. Physiol. 29(3):358-367, 1970.

57. Lenman, J.A.R. Integration and analysis of the electromyogram. In: Walton, J.N. (ed.), Disorders of Voluntary Muscle. London: J. and A. Churchill, Ltd., 1964, pp. 556-578.

58. Lind, A.R. Muscle fatigue and recovery from fatigue induced by sustained contractions. J. Physiol. 147:162-171, 1959.

59. Lind, A.R. and McNicol, G.W. Local and central circulatory responses to sustained contractions and the effect of free or restricted arterial inflow on post-exercise hyperaemia. J. Physiol. (London) 192:575-593, 1967.

60. Lind, A.R. and McNicol, G.W. Muscular factors which determine the cardiovascular responses to sustained and rhythmic exercise. Canad. Med. Ass. J. 96:706-713, 1967.

61. Lind, A.R., McNicol, G.W., Bruce, R.A., MacDonald, H.R., and Donald, K.W. Circulatory responses to sustained contractions of a patient with syringo-myelia affecting sensory responses in one arm. Clin. Sci. 35:45-53, 1968.

62. Lind, A.R., McNicol, G.W., and Donald, K.W. Circulatory adjustments to sustained (static) muscular activity. In: Evang, K. and Andersen, K.L. (eds.), Physical Activity in Health and Disease. Baltimore: The Williams and Wilkins Company, 1966.

63. Lind, A.R., Taylor, S.H., Humphreys, P.W., Kennelly, B.M., and Donald, K.W. The circulatory effects of sustained voluntary muscle contraction. Clin. Sci. 27:229-244, 1964.

64. Lindsley, D.B. Electrical activity of human motor units during voluntary contraction. Am. J. Physiol. 114:90-99, 1935.

65. Lippold, O.C.J. The relation between integrated action potentials in a human muscle and its isometric tension. J. Physiol. 117:492-499, 1952.

66. Lippold, O.C.J., Redfearn, J.W.T., and Vuco, J. The rhythmical activity of groups of motor units in the voluntary contraction of muscle. J. Physiol. 137:473-487, 1957.

67. Lippold, O.C.J., Redfearn, J.W.T., and Vuco, J. The electromyography of fatigue. Ergonomics. 3:121-131, 1960.

68. Lloyd, A.J. Surface electromyography during sustained isometric contractions. J. Appl. Physiol. 30(5):713-719, 1971.

69. Lloyd, A.J. Auditory EMG feedback during a sustained submaximum isometric contraction. Res. Quart. 43:39-46, 1972.

70. Lloyd, A.J., Voor, J.H., and Thieman, T.J. Subjective and electromyographic assessment of isometric muscle contractions. Ergonomics. 13(6):685-691, 1970.

71. Martens, Rainer and Sharkey, B.J. Relationship of phasic and static strength and endurance. Res. Quart. 37:435-437, 1966.

72. McGlynn, George H. The relationship between maximum strength and endurance of individuals with different levels of strength. Res. Quart. 40:529-535, 1969.

73. Missiuro, W., Kirschner, H., and Kozlowski, S. Electromyographic manifestations of fatigue during work of different intensity. Acta Physiologica Polonica. 13:11-20, 1962.

74. Monod, H. Côntribution à l'étude du travail statique. Thèse Doct. Méd., Institut National de Sécurité, Paris, 1956.

75. Monod, H. and Scherrer, J. The work capacity of a synergic muscular group. Ergonomics. 8:329-338, 1965.

76. Mortimer, J.T., Kersteil, M.D., Magnusson, R., and Petersén, I. Muscle blood flow in the human biceps as a function of developed muscle force. Arch. Surg. 103:376-377, 1971.

77. Myers, S.J. and Sullivan, W.P. Effect of circulatory occlusion on time to muscular fatigue. J. Appl. Physiol. 24(1):54-59, 1968.

78. Nilsson, B. and Ingvar, D.H. Intramuscular pressure and contractile strength related to muscle blood flow in man. Scand. J. Clin. Lab. Inv. 19:Suppl. 94:31-38, 1967.

79. Norris, F.H. and Gasteiger, E.L. Action potentials of single motor units in normal muscle. Electroenceph. Clin. Neurophysiol. 7:115-126, 1955.

80. Olson, C.B., Carpenter, D.O., and Henneman, E. Orderly recruitment of muscle action potentials. Arch. Neurol. 19:591-597, 1968.

81. Person, R.S. and Libkind, M.S. Simulation of electromyograms showing interference patterns. Electroenceph. Clin. Neurophysiol. 28:625-632, 1970.

82. Person, R.S. and Mishin, L.N. Auto- and cross-correlation analysis of the electrical activity of muscles. Med. Electron. Biol. Engng. 2:155-159, 1964.

83. Ricci, Benjamin. Experiments in the Physiology of Human Performance. Philadelphia: Lea & Febiger, 1970.

84. Roberts, Joseph T., Wearn, Joseph T., and Badal, James J. The capillary-muscle ratio in normal and hypertrophied human hearts. Proc. Soc. Exper. Biol. and Med. 38:322-323, 1938.

85. Rogoff, J.R. and Reiner, S. Electrodiagnostic apparatus. In: Licht, S. (ed.), Electrodiagnosis and Electromyography. New Haven: Elizabeth Licht Co., 1961.

86. Rohmert, W. Ermittlung von Erholungspausen für statische Arbeit des Menschen. Int. Z. angew. Physiol. einschl. Arbeitsphysiol. 18:123-164, 1960.

87. Rohmert, W. Die Armkräfte des Menschen in Stehen bei verschiedener Körperstellung. Int. Z. angew. Physiol. einschl. Arbeitsphysiol. 18:175-190, 1960.

88. Rohmert, W. Die Beziehung zwischen Kraft und Ausdauer bei statischer Muskelarbeit. Schriftenreihe Arbeitsmedizin, Sozialmedizin, Arbeitshygiene. 22:118-136, 1968.

89. Rohter, F.D., Rochelle, R.H., and Hyman, C. Exercise blood flow changes in the human forearm during training. J. Appl. Physiol. 18:789-793, 1963.

90. Royce, Joseph. Isometric fatigue curves in human muscle with normal and occluded circulation. Res. Quart. 29:204-212, 1958.

91. Sato, M. A problem in the frequency analysis of the electromyogram. Electromyography. 6:21-23, 1966.

92. Schanne, F.J. and Chaffin, D.B. The effects of skin resistance and capacitance coupling on EMG amplitude and power spectra. Electromyography. 10(3):273-286, 1970.

93. Scherrer, J. and Bourguignon, A. Changes in the electromyogram produced by fatigue in man. Am. J. Phys. Med. 38:148-158, 1959.

94. Scherrer, J., Bourguignon, A., and Monod, H. La fatigue dans le travail statique. Revue de Pathologie Générale et de Physiologie Clinique. 60:357-367, 1960.

95. Shaver, Larry G. Effects of training on relative muscular endurance in ipsilateral and contralateral arms. Med. Sci. Sports. 2(3):165-171, 1970.

96. Shaver, Larry G. Maximum isometric strength and relative muscular endurance gains and their relationships. Res. Quart. 42(2): 194-202, 1971.

97. Shaver, Larry G. Maximum dynamic strength, relative dynamic endurance, and their relationships. Res. Quart. 42(4):460-467, 1971.

98. Shaver, Larry G. Relation of maximum isometric strength and relative isotonic endurance of the elbow flexors of athletes. Res. Quart. 43(1):82-88, 1972.

99. Simonson, E. and Lind, A.R. Fatigue in static work. In: Simonson, E. (ed.), Physiology of Work Capacity and Fatigue. Springfield, Ill.: C.C. Thomas, 1971.

100. Spande, J.I. and Schottelius, B.A. Chemical basis of fatigue in isolated mouse soleus muscle. Am. J. Physiol. 219(3):1490-1495, 1970.

101. Start, K.B. Load and local isometric endurance with occluded blood supply. J. Appl. Physiol. 19:1135-1138, 1964.

102. Start, K.B. and Graham, J.S. Relationship between the relative and absolute isometric endurance of an isolated muscle group. Res. Quart. 35:193-204, 1964.

103. Start, K.B. and Holmes, Rosemary. Local muscle endurance with open and occluded circulation. J. Appl. Physiol. 18:804-807, 1963.

104. Stern, Michael. A model that relates low frequency EMG power to fluctuations in the number of active motor units: application to local muscular fatigue. Doctoral dissertation. The University of Michigan, 1971.

105. Surwillo, W.W. Psychological factors in muscle-action potentials: EMG gradients. J. Exper. Psych. 52:263-272, 1956.

106. Tuttle, W.W., Janney, C.D., and Salzano, J.V. Relation of maximum back and leg strength to back and leg strength endurance. Res. Quart. 26:96-106, 1955.

107. Tuttle, W.W., Janney, C.D., and Thompson, C.W. Relation of maximum grip strength to grip strength endurance. J. Appl. Physiol. 2:663-670, 1950.

108. Wearn, Joseph T. The extent of the capillary bed of the heart. J. Exper. Med. 47:273-292, 1928.

109. Wilcott, R.C. and Beenken, H.G. Relation of integrated surface electromyography and muscle tension. Percept. Motor Skills. 7:295-298, 1957.

APPENDICES

APPENDIX I. RANDOMIZED ORDER OF TESTS

Group	Subject	Test (% MVC)			
		15	25	50	75
High strength	1	1	2	3	4
	8	3	1	2	4
	9	4	3	2	1
	11	4	2	3	1
	12	1	4	3	2
	15	4	1	2	3
	22	2	1	4	3
	25	4	3	2	1
	33	1	2	3	4
	36	2	3	1	4
Medium strength	5	3	2	1	4
	6	3	4	2	1
	7	2	1	4	3
	10	1	4	2	3
	17	3	1	4	2
	18	3	2	4	1
	21	3	4	1	2
	28	3	1	4	2
	34	3	4	1	2
	40	2	1	3	4
Low strength	2	3	2	4	1
	3	4	2	1	3
	4	2	3	1	4
	16	1	4	2	3
	19	3	2	4	1
	20	2	3	4	1
	23	1	4	3	2
	24	1	4	2	3
	29	2	3	4	1
	32	4	1	3	2
Swimmers	13	4	3	1	2
	14	2	4	1	3
	26	4	1	3	2
	27	1	4	2	3
	30	4	3	1	2
	31	4	2	1	3
	35	2	1	3	4
	37	1	3	2	4
	38	1	2	3	4
	39	2	3	4	1

APPENDIX II. CHARACTERISTICS OF SUBJECTS

Group	Subject	Age (years)	Height (cm)	Weight (kg)	Strength* (kg)
High strength	1	28	183.5	92.3	57.1
	8	21	183.0	86.9	52.3
	9	21	186.5	105.4	58.2
	11	21	180.0	84.6	49.0
	12	21	183.5	86.8	49.2
	15	25	183.5	87.6	49.7
	22	31	190.5	110.3	56.8
	25	29	182.5	94.6	64.7
	33	25	189.0	97.2	52.0
	36	22	179.5	86.2	56.6
Medium strength	5	20	177.0	68.0	32.2
	6	22	177.5	76.0	43.3
	7	23	175.0	73.7	44.8
	10	20	189.0	108.8	48.8
	17	19	177.0	77.6	36.4
	18	27	183.0	93.7	47.0
	21	30	183.0	78.8	34.6
	28	32	176.0	69.0	34.8
	34	38	176.5	71.9	32.7
	40	23	196.0	92.9	42.4
Low strength	2	20	173.0	58.3	31.2
	3	22	176.5	66.0	32.2
	4	20	176.5	67.9	25.6
	16	23	177.0	78.1	31.4
	19	22	179.0	65.1	32.1
	20	21	172.5	64.8	31.6
	23	18	179.0	58.5	26.8
	24	20	182.0	65.5	27.4
	29	22	169.5	64.6	32.0
	32	20	170.5	64.1	29.9
Swimmers	13	17	177.5	79.2	37.8
	14	19	181.0	68.6	37.4
	26	17	189.5	79.1	36.0
	27	18	189.5	78.0	36.9
	30	19	185.0	89.1	34.9
	31	20	181.5	81.0	30.8
	35	18	193.5	88.3	38.0
	37	19	176.0	80.7	28.9
	38	20	184.0	70.5	34.2
	39	21	176.0	65.2	31.8

*mean of four test days

APPENDIX III. FOREARM MEASUREMENTS OF SUBJECTS

Group	Subject	Length (cm)	Radius of Rotation (cm)	Volume (liters)	Force at Wrist (kg)
High strength	1	27.0	15.0	1.84	2.2
	8	28.5	15.0	2.00	1.1
	9	29.0	16.0	2.36	1.3
	11	29.0	15.5	1.78	1.0
	12	26.5	15.5	1.91	1.0
	15	27.0	15.5	1.78	1.0
	22	29.0	15.0	2.09	1.1
	25	27.5	16.0	2.06	1.1
	33	28.5	16.5	1.80	1.0
	36	26.5	15.0	1.74	.9
Medium strength	5	27.0	14.0	1.36	.7
	6	27.5	16.0	1.52	.8
	7	25.5	14.0	1.50	.8
	10	28.5	14.0	2.14	1.2
	17	27.0	16.5	1.48	.8
	18	49.8	16.0	1.78	1.0
	21	27.5	17.0	1.50	.8
	28	27.0	14.5	1.28	.7
	34	27.5	16.0	1.46	.8
	40	30.6	18.0	1.93	1.1
Low strength	2	28.0	15.3	1.30	.7
	3	26.0	15.0	1.17	.6
	4	28.0	14.0	1.30	.7
	16	27.0	16.0	1.58	.9
	19	26.0	15.0	1.24	.7
	20	26.3	15.0	1.24	.7
	23	27.5	16.5	1.14	.6
	24	27.5	16.0	1.29	.7
	29	28.0	16.5	1.32	.7
	32	29.0	16.5	1.43	.8
Swimmers	13	26.0	16.0	1.42	.8
	14	28.0	16.0	1.34	.7
	26	29.0	16.5	1.64	.9
	27	29.0	17.0	1.62	.9
	30	26.0	15.5	1.67	.9
	31	27.0	15.5	1.58	.9
	35	28.5	17.5	1.64	.9
	37	28.0	16.0	1.58	.9
	38	27.5	15.5	1.40	.8
	39	28.5	17.0	1.28	.7

APPENDIX IV. TEST CONDITIONS: TEST 025

Group	Subject	Month	Day	Hour	Temperature (°C)*	Relative Humidity (%)*
High strength	1	6	2	20	--	--
	8	6	8	11	22.0	37
	9	6	8	21	22.0	30
	11	6	15	21	24.8	30
	12	6	16	20	23.0	31
	15	6	30	9	22.8	39
	22	7	7	9	20.2	42
	25	7	9	20	22.0	44
	33	7	28	9	20.0	41
	36	8	13	10	22.1	40
Medium strength	5	6	4	22	25.3	44
	6	6	7	11	23.5	45
	7	6	8	10	21.9	38
	10	6	14	20	24.7	40
	17	6	30	11	23.5	45
	18	6	30	21	24.0	44
	21	7	1	11	22.5	43
	28	7	13	20	21.0	38
	34	7	28	19	21.8	45
	40	9	22	12	23.7	27
Low strength	2	6	4	9	23.6	42
	3	6	4	11	23.6	42
	4	6	4	20	24.1	44
	16	6	30	11	23.0	42
	19	7	1	8	22.2	46
	20	7	1	10	22.4	44
	23	7	8	21	22.5	46
	24	7	9	9	21.1	47
	29	7	13	22	21.0	38
	32	7	22	10	21.6	41
Swimmers	13	6	24	21	26.4	44
	14	6	25	10	24.2	41
	26	7	12	21	23.4	42
	27	7	12	21	23.8	44
	30	7	14	11	21.4	38
	31	7	14	9	23.5	36
	35	9	17	14	21.2	37
	37	9	17	16	21.8	35
	38	9	17	17	22.4	36
	39	9	17	18	22.1	36

*--missing data

APPENDIX V. TEST CONDITIONS: TEST 15

Group	Subject	Month	Day	Hour	Temperature (°C)	Relative Humidity (%)
High strength	1	6	6	20	25.0	45
	8	6	24	10	24.0	40
	9	6	24	22	25.4	48
	11	7	14	9	20.3	42
	12	6	21	22	25.0	36
	15	7	10	22	20.0	40
	22	7	13	10	22.3	47
	25	7	27	19	22.0	39
	33	7	30	9	20.2	44
	36	8	18	12	22.7	41
Medium strength	5	6	16	23	22.5	31
	6	6	22	11	22.5	36
	7	6	18	11	20.3	39
	10	6	17	20	21.0	40
	17	7	8	11	21.4	51
	18	7	21	21	23.0	42
	21	7	13	11	20.8	37
	28	8	16	20	23.5	39
	34	8	5	21	23.0	37
	40	9	29	13	25.2	39
Low strength	2	6	17	11	21.0	37
	3	6	22	9	24.2	36
	4	6	15	9	22.3	39
	16	7	2	10	20.8	43
	19	7	12	8	20.0	47
	20	7	8	10	20.6	48
	23	7	15	21	23.0	44
	24	7	13	9	21.9	44
	29	7	22	10	23.5	44
	32	8	4	9	20.8	38
Swimmers	13	7	10	20	20.0	40
	14	7	1	21	21.8	38
	26	7	27	21	21.0	38
	27	7	14	20	23.2	35
	30	7	27	10	18.1	45
	31	8	4	10	21.2	37
	35	9	27	10	24.9	42
	37	9	20	15	20.4	42
	38	9	20	16	20.8	41
	39	9	24	14	23.2	22

APPENDIX VI. TEST CONDITIONS: TEST 25

Group	Subject	Month	Day	Hour	Temperature (°C)	Relative Humidity (%)
High strength	1	6	8	19	22.0	37
	8	6	17	11	20.4	39
	9	6	23	21	24.5	44
	11	6	28	21	24.7	44
	12	7	5	22	21.1	53
	15	7	2	9	20.0	46
	22	7	9	10	21.8	46
	25	7	22	20	23.0	43
	33	8	2	9	19.8	46
	36	8	20	11	20.8	48
Medium strength	5	6	9	9	20.0	29
	6	6	24	11	24.6	37
	7	6	15	20	24.8	32
	10	6	30	20	23.9	45
	17	7	2	11	21.1	42
	18	7	7	21	21.7	42
	21	7	15	11	23.0	45
	28	7	15	20	22.7	45
	34	8	10	20	22.8	43
	40	9	24	12	21.8	25
Low strength	2	6	15	11	24.8	30
	3	6	8	22	22.0	30
	4	6	16	9	23.0	31
	16	8	16	13	22.1	40
	19	7	8	9	20.4	47
	20	7	12	10	21.4	42
	23	7	28	12	21.2	40
	24	7	22	9	23.5	44
	29	7	27	9	17.9	46
	32	7	28	10	20.5	40
Swimmers	13	7	8	19	22.0	48
	14	7	7	19	21.5	42
	26	7	14	19	22.8	37
	27	7	27	20	20.6	42
	30	7	22	11	23.8	47
	31	7	28	21	21.8	45
	35	9	22	22	24.4	35
	37	9	29	15	25.5	37
	38	9	24	15	23.2	21
	39	9	27	14	24.9	52

APPENDIX VII. TEST CONDITIONS: TEST 50

Group	Subject	Month	Day	Hour	Temperature (°C)	Relative Humidity (%)
High strength	1	6	17	22	21.0	38
	8	6	20	20	22.2	47
	9	6	18	21	20.7	40
	11	7	7	22	21.8	44
	12	7	1	20	21.7	39
	15	7	6	21	21.5	44
	22	7	20	10	21.8	40
	25	7	20	20	23.2	38
	33	8	4	9	20.4	40
	36	8	16	11	21.4	41
Medium strength	5	6	7	9	22.7	40
	6	6	16	11	23.5	32
	7	6	25	9	24.6	39
	10	6	21	20	23.0	39
	17	7	12	11	22.8	48
	18	7	28	21	21.0	40
	21	7	6	10	21.0	40
	28	8	18	19	21.5	39
	34	7	30	10	20.7	44
	40	10	1	13	25.2	29
Low strength	2	6	22	20	23.7	33
	3	6	6	22	25.0	45
	4	6	7	10	23.1	43
	16	8	10	20	22.7	43
	19	7	15	9	21.8	38
	20	7	14	10	20.8	40
	23	7	23	9	21.0	42
	24	7	15	12	22.5	41
	29	8	3	9	19.5	43
	32	8	2	10	20.5	44
Swimmers	13	6	29	20	23.5	47
	14	6	29	21	24.0	46
	26	7	21	21	23.9	37
	27	7	21	21	24.0	37
	30	7	16	11	21.5	42
	31	7	20	21	23.8	39
	35	9	29	10	24.9	49
	37	9	27	16	24.6	54
	38	9	27	13	24.9	44
	39	10	1	11	24.6	36

APPENDIX VIII. TEST CONDITIONS: TEST 75

Group	Subject	Month	Day	Hour	Temperature (°C)	Relative Humidity (%)
High strength	1	6	21	21	23.2	37
	8	6	22	10	22.5	36
	9	6	16	22	23.0	31
	11	6	24	9	23.7	42
	12	6	23	20	24.3	44
	15	7	8	20	23.2	47
	22	7	15	10	22.2	39
	25	7	13	20	21.0	40
	33	8	5	9	20.4	39
	36	8	23	11	21.4	37
Medium strength	5	6	18	9	19.8	42
	6	6	9	11	20.5	27
	7	6	22	9	21.7	37
	10	6	28	20	24.3	47
	17	7	6	12	20.0	45
	18	7	5	21	21.1	54
	21	7	9	12	22.0	46
	28	7	22	22	23.0	41
	34	8	2	19	20.1	42
	40	10	4	13	22.8	38
Low strength	2	6	8	9	21.7	38
	3	6	16	10	20.0	39
	4	6	18	10	20.2	43
	16	8	13	12	22.8	40
	19	7	6	9	19.8	49
	20	7	6	10	21.0	40
	23	7	21	19	23.7	37
	24	7	20	9	21.5	41
	29	7	15	11	22.4	39
	32	7	30	10	20.5	45
Swimmers	13	7	6	20	21.5	44
	14	7	5	20	21.1	55
	26	7	20	21	23.7	37
	27	7	27	22	21.2	38
	30	7	20	11	22.2	42
	31	8	2	11	21.0	43
	35	10	4	10	22.4	41
	37	10	4	15	23.2	36
	38	9	29	16	25.8	35
	39	9	22	16	24.2	26

APPENDIX IX. MAXIMUM VOLUNTARY CONTRACTION (MVC)*

Group	Subject	Test (% MVC)				
		025	15	25	50	75
High strength	1	57.6	57.1	57.6	56.7	57.1
	8	50.9	54.0	50.9	52.7	51.8
	9	50.6	58.3	60.6	57.4	56.5
	11	47.5	47.5	48.9	51.2	48.5
	12	45.4	47.2	51.3	49.9	48.5
	15	44.4	48.9	48.5	48.9	52.6
	22	51.8	59.1	55.5	56.8	55.9
	25	62.7	65.4	65.4	64.5	63.6
	33	49.4	51.7	52.1	52.1	52.1
	36	56.6	56.6	56.6	56.6	56.6
Medium strength	5	31.0	33.2	33.2	31.0	31.6
	6	42.9	43.3	44.7	42.0	43.3
	7	42.9	45.1	44.2	45.1	44.7
	10	45.0	47.8	47.8	48.7	50.9
	17	36.0	36.5	36.0	36.5	36.5
	18	50.7	48.0	48.5	44.8	46.7
	21	33.8	36.0	32.9	34.9	34.7
	28	34.1	34.6	34.1	36.4	34.1
	34	31.5	33.7	31.9	32.8	32.4
	40	41.3	42.6	42.2	42.2	42.6
Low strength	2	30.9	30.9	31.8	31.8	30.5
	3	31.4	32.2	32.7	32.2	31.8
	4	24.6	24.6	25.5	25.5	26.8
	16	29.3	31.1	31.5	31.5	31.5
	19	31.8	32.7	32.3	32.7	30.9
	20	30.5	31.4	32.7	30.9	31.4
	23	24.5	26.8	26.8	26.8	26.8
	24	27.3	27.8	27.8	26.4	27.8
	29	30.9	32.3	32.3	32.8	30.5
	32	26.0	30.6	29.2	30.6	29.2
Swimmers	13	34.2	37.8	39.2	38.3	36.0
	14	36.4	37.3	37.8	37.8	36.9
	26	35.2	36.6	35.7	36.1	35.7
	27	36.6	37.5	36.1	37.5	36.6
	30	34.3	34.3	35.2	34.8	35.2
	31	28.4	30.6	31.1	30.6	31.1
	35	37.0	38.9	38.9	36.6	37.5
	37	30.6	28.8	29.3	28.4	29.3
	38	34.6	34.2	34.2	33.7	34.6
	39	32.3	31.8	31.8	31.8	31.8

*in kilograms

APPENDIX X. MAXIMUM ENDURANCE TIME (MET)*

Group	Subject	Test (% MVC)			
		025	25	50	75
High strength	1	294	316	69	29
	8	520	733	100	50
	9	541	369	92	26
	11	572	634	98	37
	12	544	484	78	34
	15	410	387	95	35
	22	526	450	92	38
	25	339	353	88	40
	33	353	322	60	29
	36	246	259	66	28
Medium strength	5	498	505	102	27
	6	412	431	80	26
	7	448	364	91	34
	10	255	305	86	21
	17	380	352	91	33
	18	446	548	91	34
	21	257	494	77	33
	28	621	909	131	44
	34	1318	1152	106	29
	40	569	480	77	33
Low strength	2	315	342	91	18
	3	376	638	91	44
	4	766	695	99	30
	16	674	528	78	27
	19	427	788	139	30
	20	464	581	105	37
	23	828	325	129	35
	24	468	533	96	39
	29	525	574	98	34
	32	476	369	76	31
Swimmers	13	363	356	81	40
	14	596	735	106	32
	26	903	679	113	27
	27	462	485	87	31
	30	486	394	113	45
	31	1254	621	107	25
	35	544	630	118	33
	37	402	854	113	49
	38	454	537	121	33
	39	506	786	129	17

*in seconds

APPENDIX XI. ISOMETRIC WORK (FORCE × TIME)*

Group	Subject	Test (% MVC) 025	15	25	50	75
High strength	1	4234	12847	4550	1956	1242
	8	6617	9720	9327	2635	1942
	9	6844	10494	5590	2640	1102
	11	6792	8550	7751	2509	1346
	12	6174	8496	6207	1946	1237
	15	4551	8802	4692	2323	1381
	22	6812	10638	6244	2613	1593
	25	5314	11772	5772	2838	1908
	33	4360	9306	4194	1563	1133
	36	3481	8439	3665	1868	1189
Medium strength	5	3860	5976	4192	1581	640
	6	4419	7794	4816	1680	844
	7	4805	8118	4022	2052	1140
	10	2869	8604	3645	2094	802
	17	3420	6570	3168	1661	903
	18	5653	8640	6644	2038	1191
	21	2172	6480	4063	1344	859
	28	5294	6228	7749	2384	1125
	34	10379	6066	9187	1738	705
	40	5875	7668	5064	1625	1054
Low strength	2	2433	5562	2719	1447	412
	3	2952	5796	5216	1465	1049
	4	4711	4428	4431	1262	603
	16	4937	5598	4158	1228	638
	19	3395	5886	6363	2273	695
	20	3538	5652	4750	1622	871
	23	5072	4824	2178	1729	704
	24	3194	5004	3704	1267	813
	29	4056	5814	4635	1607	778
	32	3094	5508	2694	1163	679
Swimmers	13	3104	6804	3489	1551	1080
	14	5424	6714	6946	2003	886
	26	7946	6588	6060	2040	723
	27	4227	6750	4377	1631	851
	30	4167	6174	3467	1966	1188
	31	8903	5508	4828	1637	583
	35	5032	7002	6127	2159	928
	37	3075	5184	6256	1605	1077
	38	3927	6156	4591	2039	856
	39	4086	5724	6249	2051	405

*in kilogram-seconds

APPENDIX XII. PEAK SYSTOLIC BLOOD PRESSURE*

Group	Subject	Test (% MVC) 025	15	25	50	75**
High strength	1	190	195	190	142	174
	8	220	150	192	166	174
	9	196	202	202	180	--
	11	178	143	174	162	146
	12	184	173	212	176	--
	15	184	185	196	194	--
	22	204	197	204	184	188
	25	168	216	188	178	182
	33	184	184	172	168	--
	36	182	193	148	160	--
Medium strength	5	150	153	150	170	176
	6	194	170	194	168	--
	7	176	173	176	158	--
	10	144	177	186	152	--
	17	132	179	132	166	--
	18	206	156	204	210	202
	21	146	149	164	139	--
	28	158	141	166	184	156
	34	190	152	192	182	174
	40	186	176	204	188	212
Low strength	2	138	138	142	134	130
	3	156	184	192	190	--
	4	174	132	158	190	--
	16	140	166	176	144	172
	19	156	150	166	164	--
	20	152	158	172	158	--
	23	178	141	148	170	150
	24	162	146	196	172	184
	29	120	129	136	120	--
	32	166	168	152	148	154
Swimmers	13	154	170	166	160	144
	14	176	177	184	178	188
	26	174	129	164	144	--
	27	132	143	144	142	--
	30	170	156	172	168	160
	31	206	160	208	208	--
	35	178	144	182	176	178
	37	174	144	174	178	194
	38	152	144	192	190	172
	39	178	152	196	194	--

*in mm Hg
**-- missing data

APPENDIX XIII. PEAK DIASTOLIC BLOOD PRESSURE*

Group	Subject	Test (% MVC) 025	15	25	50	75**
High strength	1	140	119	126	112	--
	8	132	114	138	132	--
	9	130	132	124	140	--
	11	128	109	124	120	110
	12	116	119	120	88	--
	15	126	119	122	102	--
	22	114	128	108	126	--
	25	122	144	120	140	--
	33	96	118	112	118	--
	36	100	122	102	124	--
Medium strength	5	100	106	90	120	--
	6	136	118	132	134	--
	7	124	114	92	86	--
	10	110	109	100	96	--
	17	86	120	116	118	--
	18	132	98	106	120	--
	21	100	110	118	98	--
	28	108	92	98	120	104
	34	132	112	136	126	136
	40	114	92	124	118	--
Low strength	2	96	89	94	80	--
	3	124	114	128	110	--
	4	95	86	98	124	--
	18	94	103	126	86	--
	19	100	94	96	88	--
	20	96	99	122	46	--
	23	92	86	90	104	--
	24	94	101	116	132	122
	29	86	79	92	66	--
	32	118	112	110	108	--
Swimmers	13	104	100	102	118	88
	14	128	118	134	114	144
	26	116	95	112	92	--
	27	108	110	116	98	--
	30	114	109	122	126	108
	31	140	108	126	122	--
	35	124	92	118	120	--
	37	112	88	112	100	--
	38	96	79	96	96	--
	39	112	86	104	76	--

*in mm Hg
**-- missing data

APPENDIX XIV. PEAK MEAN BLOOD PRESSURE*

Group	Subject	Test (% MVC)				
		025	15	25	50	75**
High strength	1	157	143	141	122	--
	8	148	126	156	143	--
	9	149	153	150	153	--
	11	145	120	138	134	122
	12	139	136	151	117	--
	15	145	140	139	122	--
	22	139	150	135	145	--
	25	135	168	140	153	--
	33	125	140	132	135	--
	36	119	146	117	136	--
Medium strength	5	113	121	110	137	--
	6	155	134	149	145	--
	7	141	134	120	110	--
	10	121	130	129	115	--
	17	101	140	121	134	--
	18	157	116	136	140	--
	21	115	122	133	112	--
	28	125	108	118	141	121
	34	149	125	155	145	149
	40	135	119	151	141	--
Low strength	2	109	106	110	94	--
	3	134	137	149	137	--
	4	121	102	118	146	--
	16	108	124	143	103	--
	19	115	112	119	113	--
	20	112	117	139	83	--
	23	121	103	109	126	--
	24	117	116	143	145	143
	29	97	94	107	84	--
	32	134	130	124	121	--
Swimmers	13	119	122	119	132	107
	14	114	136	150	134	159
	26	134	106	129	109	--
	27	116	119	125	113	--
	30	131	125	139	140	125
	31	155	125	153	143	--
	35	142	110	139	139	--
	37	133	106	131	116	--
	38	115	101	128	127	--
	39	133	107	133	101	--

*in mm Hg
**-- missing data

APPENDIX XV. PEAK PULSE PRESSURE*

Group	Subject	Test (% MVC) 025	15	25	50	75**
High strength	1	52	80	48	30	--
	8	54	42	54	34	--
	9	74	88	82	44	--
	11	64	44	54	42	36
	12	72	68	92	88	--
	15	62	72	52	60	--
	22	100	75	80	68	--
	25	50	72	64	38	--
	33	88	67	66	50	--
	36	56	71	46	36	--
Medium strength	5	62	52	60	64	--
	6	60	57	52	34	--
	7	82	62	106	72	--
	10	60	80	88	56	--
	17	46	59	16	48	--
	18	90	60	110	66	--
	21	46	52	56	41	--
	28	50	49	72	64	52
	34	56	42	56	56	38
	40	78	89	80	104	--
Low strength	2	66	54	48	42	--
	3	68	88	80	80	--
	4	91	48	72	66	--
	16	54	68	66	52	--
	19	54	72	78	76	--
	20	64	98	64	112	--
	23	88	60	72	66	--
	24	68	52	80	44	62
	29	50	63	54	54	--
	32	66	59	44	40	--
Swimmers	13	56	78	74	58	56
	14	64	63	64	60	44
	26	64	44	58	52	--
	27	24	44	36	44	--
	30	60	54	64	44	52
	31	94	54	88	72	--
	35	64	54	68	56	--
	37	74	60	64	52	--
	38	64	64	96	96	--
	39	84	74	110	76	--

*in mm Hg

**-- missing data

APPENDIX XVI. PEAK HEART RATE*

Group	Subject	Test (% MVC)				
		025	15	25	50	75
High strength	1	130	116	153	153	152
	8	127	86	136	109	139
	9	157	106	146	154	149
	11	163	77	162	141	155
	12	162	101	150	163	173
	15	133	107	139	148	151
	22	136	93	127	105	127
	25	162	119	139	150	153
	33	137	125	119	110	119
	36	136	135	146	133	148
Medium strength	5	127	94	122	111	121
	6	136	73	115	115	143
	7	142	104	153	169	176
	10	157	100	150	157	150
	17	122	104	127	133	142
	18	127	76	142	138	131
	21	96	105	130	127	138
	28	109	96	139	128	128
	34	117	89	120	117	125
	40	153	104	133	139	130
Low strength	2	115	104	115	118	115
	3	162	117	182	166	176
	4	142	99	171	148	164
	16	166	79	139	146	117
	19	142	113	176	168	162
	20	103	93	113	115	105
	23	139	92	109	112	137
	24	122	97	157	139	131
	29	115	99	100	133	111
	32	103	102	98	113	116
Swimmers	13	120	84	111	132	153
	14	153	111	171	169	133
	26	133	97	142	135	128
	27	118	106	139	135	109
	30	166	88	162	142	162
	31	113	79	113	139	114
	35	133	130	142	162	157
	37	103	86	101	90	102
	38	130	98	130	143	154
	39	146	131	162	171	150

*in beats per minute

APPENDIX XVII. INITIAL EMG LOW FREQUENCY POWER*

Group	Subject	Test (% MVC) 025**	15**	25**	50**	75**
High strength	1	37.0	37.5	37.3	--	50.9
	8	26.2	45.2	32.1	24.8	29.4
	9	26.6	33.2	28.4	40.1	34.9
	11	25.6	35.9	25.7	21.1	25.6
	12	22.9	33.8	24.2	20.1	26.5
	15	34.5	40.3	38.9	49.9	68.9
	22	31.3	32.1	26.2	30.6	37.3
	25	21.7	22.8	25.6	33.7	34.8
	33	25.7	29.4	24.9	24.1	41.0
	36	34.4	33.0	35.4	43.1	59.1
Medium strength	5	34.0	37.6	35.3	32.9	40.4
	6	28.4	35.8	--	30.9	44.2
	7	31.6	34.3	--	30.2	49.8
	10	26.4	39.2	32.7	33.9	62.5
	17	41.1	49.0	30.8	32.8	44.7
	18	27.0	39.0	27.2	42.3	36.9
	21	43.9	54.1	49.5	54.7	56.5
	28	27.4	34.4	29.3	17.6	20.3
	34	32.8	38.6	39.5	34.1	55.2
	40	33.2	--	40.2	37.7	34.7
Low strength	2	27.9	30.7	28.2	39.6	46.6
	3	19.8	28.3	21.0	24.4	18.7
	4	41.6	--	41.0	45.1	46.2
	16	27.8	44.0	24.7	20.8	33.8
	19	35.0	52.4	36.3	26.7	42.3
	20	39.8	51.5	46.6	41.1	52.1
	23	30.4	36.6	39.6	38.3	34.3
	24	52.3	49.4	44.0	47.6	60.3
	29	39.5	40.5	38.4	44.8	47.8
	32	31.0	44.8	37.4	46.5	55.5
Swimmers	13	--	41.2	24.0	22.0	31.2
	14	38.6	48.2	20.6	25.7	54.6
	26	19.2	24.3	25.7	28.7	30.1
	27	--	--	43.1	35.9	38.1
	30	11.5	30.0	25.5	28.5	38.8
	31	25.1	36.6	27.0	21.8	37.7
	35	29.0	42.5	28.2	--	--
	37	32.9	43.6	34.5	39.4	38.8
	38	34.8	38.9	40.0	39.2	--
	39	45.2	43.1	34.3	40.1	28.8

*in percent
**-- missing data

APPENDIX XVIII. INITIAL EMG rms VOLTAGE*

Group	Subject	Test (% MVC) 025**	15**	25**	50**	75**
High strength	1	400	240	270	--	1320
	8	420	240	420	1380	2320
	9	330	170	330	960	3240
	11	410	200	370	1030	2200
	12	340	210	340	950	1070
	15	390	270	460	1300	2750
	22	310	170	330	1050	2120
	25	480	220	470	1360	2310
	33	530	270	450	970	2310
	36	490	320	490	1270	2480
Medium strength	5	290	200	370	880	2160
	6	640	290	--	1410	2980
	7	280	140	--	1350	2810
	10	460	220	440	1220	2060
	17	380	260	360	840	2320
	18	450	230	480	1310	1790
	21	290	170	330	1010	2040
	28	240	110	270	690	950
	34	250	150	270	1010	1620
	40	310	--	320	1240	2580
Low strength	2	440	240	380	910	1900
	3	340	230	400	1020	2220
	4	350	--	370	1190	1360
	16	240	150	220	980	1200
	19	470	270	400	960	2650
	20	340	210	480	960	2100
	23	300	190	280	1000	1930
	24	610	270	400	1050	2630
	29	280	180	320	1070	1870
	32	350	240	400	1390	1900
Swimmers	13	--	240	340	1470	2300
	14	300	170	170	710	2170
	26	330	300	320	1800	2480
	27	--	--	710	1910	2560
	30	340	210	300	940	2200
	31	280	180	320	810	1430
	35	450	260	400	--	--
	37	530	260	480	1460	2360
	38	350	320	270	1820	--
	39	280	160	230	1070	1340

*in μV

**-- missing data

APPENDIX XIX. FINAL EMG LOW FREQUENCY POWER*

Group	Subject	Test (% MVC)				
		025**	15**	25**	50**	75**
High strength	1	79.7	77.3	80.0	--	--
	8	75.7	54.2	69.7	72.8	48.5
	9	81.1	53.6	62.8	58.9	--
	11	76.6	52.5	61.4	60.6	42.6
	12	49.4	47.6	57.5	32.2	28.7
	15	81.7	73.6	86.2	83.3	--
	22	77.3	57.8	76.1	72.4	53.3
	25	75.6	62.2	67.5	64.4	63.6
	33	73.7	58.9	62.2	33.5	--
	36	74.8	66.9	76.5	78.2	--
Medium strength	5	76.1	67.4	75.6	57.7	--
	6	74.2	57.5	--	76.6	--
	7	80.3	66.3	--	73.4	--
	10	71.2	64.5	73.4	73.3	--
	17	71.0	63.3	55.5	68.5	--
	18	82.8	49.6	86.2	72.6	58.1
	21	63.1	67.2	76.9	72.3	--
	28	62.3	48.2	70.1	68.8	38.8
	34	88.4	60.3	91.0	80.0	--
	40	74.1	--	74.3	63.5	68.8
Low strength	2	53.4	60.2	60.0	74.9	--
	3	54.7	54.6	64.2	60.3	33.0
	4	86.9	--	86.2	67.4	57.8
	16	86.2	65.0	75.5	67.0	--
	19	79.1	55.6	76.9	85.4	--
	20	72.6	58.8	86.0	84.6	77.0
	23	75.5	56.1	58.2	72.9	48.4
	24	89.1	78.9	81.0	85.8	77.4
	29	83.0	59.0	77.0	89.2	76.2
	32	62.4	65.5	63.4	68.4	--
Swimmers	13	--	49.0	44.5	44.3	36.7
	14	86.1	76.0	82.6	79.5	--
	26	--	35.4	46.5	61.2	--
	27	--	--	77.8	61.4	--
	30	80.4	43.8	67.2	67.0	50.9
	31	77.6	50.9	55.9	54.5	--
	35	75.3	64.4	74.8	--	--
	37	66.9	55.4	--	71.3	57.3
	38	68.5	51.4	71.0	68.8	--
	39	73.5	67.6	77.4	79.2	--

*in percent
**-- missing data

APPENDIX XX. FINAL EMG rms VOLTAGE*

Group	Subject	Test (% MVC) 025**	15**	25**	50**	75**
High strength	1	1940	770	2290	--	--
	8	1350	400	2340	2200	2550
	9	2440	390	1550	1940	--
	11	2980	340	3100	1910	2280
	12	1150	290	770	1470	1170
	15	2010	1030	3080	3440	--
	22	2110	490	1860	1750	2010
	25	2030	860	2220	2350	2570
	33	2690	1120	1520	1860	--
	36	1680	630	1950	2020	--
Medium strength	5	2090	650	2890	2740	--
	6	2210	730	--	2800	--
	7	1530	600	--	2940	--
	10	1080	700	1320	1380	--
	17	1450	420	1470	1540	--
	18	2090	390	3680	1940	2090
	21	550	360	1120	1450	--
	28	810	240	1050	1780	1360
	34	2580	360	2010	2110	--
	40	2660	--	3130	2440	2860
Low strength	2	1140	260	1180	1970	--
	3	1370	480	1590	2860	3080
	4	1750	--	3140	2600	2500
	16	1780	460	1070	2000	--
	19	2650	460	2740	3050	--
	20	1450	420	2660	3010	3110
	23	2330	390	630	2320	2230
	24	1840	790	2830	2060	2790
	29	1030	310	1100	2140	2080
	32	1070	650	1020	1720	--
Swimmers	13	--	630	1830	2260	2370
	14	1810	550	2020	1870	--
	26	--	330	890	2380	--
	27	--	--	3340	3190	--
	30	1240	350	790	2990	3050
	31	1600	270	940	1630	--
	35	1860	580	1760	--	--
	37	1070	520	--	1870	2460
	38	1690	580	1590	4200	--
	39	1290	590	2310	2740	--

*in μV

**-- missing data

APPENDIX XXI. EMG LOW FREQUENCY POWER INCREASE*

Group	Subject	Test (% MVC)				
		025**	15**	25**	50**	75**
High strength	1	42.7	39.8	42.7	--	--
	8	49.5	9.0	37.6	48.0	19.1
	9	54.5	20.4	34.4	18.8	--
	11	51.0	16.6	35.7	39.5	17.0
	12	26.5	13.8	33.3	12.1	2.2
	15	47.2	33.3	47.3	33.4	--
	22	46.0	25.7	49.9	41.8	16.0
	25	53.9	39.4	41.9	30.7	28.8
	33	48.0	29.5	37.3	9.4	--
	36	40.4	33.9	41.1	35.1	--
Medium strength	5	42.1	29.8	40.3	24.8	--
	6	45.8	21.7	--	45.7	--
	7	48.7	32.0	--	43.2	--
	10	44.8	25.3	40.7	39.4	--
	17	29.9	14.3	24.7	35.7	--
	18	55.8	10.6	59.0	30.3	21.2
	21	19.2	13.1	27.4	17.6	--
	28	34.9	13.8	40.8	51.2	18.5
	34	55.6	21.7	51.5	45.9	--
	40	40.9	--	34.1	25.8	34.1
Low strength	2	25.5	29.5	31.8	35.3	--
	3	34.9	26.3	43.2	35.9	14.3
	4	45.3	--	45.2	22.3	11.6
	16	58.4	21.0	50.8	46.2	--
	19	44.1	3.2	40.6	58.7	--
	20	32.8	7.3	39.4	43.5	24.9
	23	45.1	19.5	18.6	34.6	14.1
	24	36.8	29.5	37.0	38.2	17.1
	29	43.5	18.5	38.6	44.4	28.4
	32	31.4	20.7	26.0	21.9	--
Swimmers	13	--	7.8	20.5	22.3	5.5
	14	47.5	27.8	62.0	53.8	--
	26	--	11.1	20.8	32.5	--
	27	--	--	34.7	25.5	--
	30	68.9	13.8	41.7	38.5	12.1
	31	52.5	14.3	28.9	32.7	--
	35	46.3	21.9	46.6	--	--
	37	34.0	11.8	--	31.9	18.5
	38	33.7	12.5	31.0	29.6	--
	39	28.3	24.5	43.1	39.1	--

*in percent
**-- missing data

APPENDIX XXII. EMG rms VOLTAGE INCREASE*

Group	Subject	Test (% MVC) 025**	15**	25**	50**	75**
High strength	1	1540	530	1820	--	--
	8	930	160	1920	820	230
	9	2110	220	1220	980	--
	11	2570	140	2730	880	80
	12	810	80	430	520	100
	15	1620	760	2620	2140	--
	22	1800	320	1530	700	-110
	25	1550	640	1750	990	260
	33	2160	850	1070	890	--
	36	1190	310	1460	750	--
Medium strength	5	1800	450	2520	1860	--
	6	1570	440	--	1390	--
	7	1250	460	--	1590	--
	10	620	480	880	160	--
	17	1070	160	1110	700	--
	18	1640	160	3200	630	300
	21	260	190	790	440	--
	28	570	130	780	1090	410
	34	2330	210	1740	1100	--
	40	2350	--	2810	1200	280
Low strength	2	700	20	800	1060	--
	3	1030	250	1190	1840	860
	4	1400	--	2770	1410	1140
	16	1540	310	850	1020	--
	19	2180	190	2340	2090	--
	20	1110	210	2180	2050	1010
	23	2030	200	350	1320	300
	24	1230	520	2430	1010	160
	29	750	130	780	1070	210
	32	720	410	620	330	--
Swimmers	13	--	390	1490	790	70
	14	1510	380	1850	1160	--
	26	--	30	570	580	--
	27	--	--	2630	1280	--
	30	900	140	490	2050	850
	31	1320	90	620	820	--
	35	1410	320	1360	--	--
	37	540	260	--	410	100
	38	1340	260	1320	2380	--
	39	1010	430	2080	1670	--

*in μV
**-- missing data

APPENDIX XXIII. INDIVIDUAL COEFFICIENTS OF VARIATION FOR DAILY DETERMINATIONS OF MVC

Group	Subject	Coefficient of Variation (%)	
		All Five Tests	Four Randomized Tests
High strength	1	.67	.64
	8	2.52	2.52
	9	6.57	3.05
	11	3.11	3.19
	12	4.73	3.59
	15	5.97	3.87
	22	4.73	2.83
	25	1.82	1.33
	33	2.28	.38
	36	.00	.00
Medium strength	5	3.50	3.48
	6	2.25	2.54
	7	2.06	.95
	10	4.41	2.99
	17	.75	.68
	18	4.58	3.51
	21	3.40	3.70
	28	2.87	3.13
	34	2.61	2.32
	40	1.25	.54
Low strength	2	1.88	2.09
	3	1.52	1.14
	4	3.55	3.53
	16	3.08	.63
	19	2.35	2.65
	20	2.64	2.43
	23	3.90	.00
	24	2.22	2.55
	29	3.14	3.16
	32	6.45	2.70
Swimmers	13	5.38	3.56
	14	1.61	1.16
	26	1.45	1.18
	27	1.67	1.88
	30	1.29	.93
	31	3.70	1.22
	35	2.83	2.97
	37	2.83	1.50
	38	1.08	1.07
	39	.70	.00