A COMPARISON OF THE FORCE PLATFORM OUTPUT AND THE ELECTROMYOGRAM AS MEASURES OF MUSCULAR FATIGUE

by

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TABLE OF CONTENTS

LIST OF FIGURES

Figure | Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

Throughout time, man has attempted to perform essential tasks with minimal effort. This does not necessarily indicate that man is basically lazy, but rather that he is insuring his health and comfort while simultaneously maximizing productivity. Optimum design of work stations requires some method for measuring and quantifying the deleterious effects of the task on the performer. Measuring the effects of the task is the problem to which this thesis is directed.

Man becomes physically tired when his muscles are in tension regardless of whether work (force X distance) is actually done. The increment of muscle fatigue associated with a given task seems to be an important index of the physiological cost of that task.

What is needed is a method of measuring a set of parameters which would describe the fatiguing of a muscle. The rate of fatigue is a function of the degree and duration of muscular tension along with the amount of rest a muscle obtains between contractions.

Many experiments have been concerned with obtaining the physiological cost of task performance. A number of experimental techniques have been devised for measuring indicators of physiological cost. Important techniques are: measuring the heart rate and the rate of change of the heart rate [19]; measuring the amount of air consumed and CO_2 content in exhausted air [10]; and observing the change in the electromyogram (EMG) of a muscle or group of muscles undergoing muscular activity [7].

Using the rate of heart beat or O_2 content is not a suitable method of analysis for this research. The time lag between the beginning of the task and the first notice of change in the heartbeat or O_2 content is too long for satisfactory use in this study. Changes in heartbeat and O_2 content correspond to whole body processes and are not selective for individual portions of the body.

Electromyography:

The electromyogram is the measurement of the electrical signal generated when a muscle contracts, and has been used as an indicator of muscular fatigue. The chief advantage of using the EMG is that there is less of a time lag with this method compared to the heart beat or O_2 method. The EMG can also be used to measure the behavior of a selected portion of the body.

The two most widely used electrodes for obtaining the EMG are surface and needle point electrodes. Surface electrodes are generally small plates made of silver or stainless steel which may be placed in pairs over a muscle so that the potential difference between them may be recorded. One electrode can be at ground potential. It is frequently more satisfactory to connect each electrode to one side of a balanced amplifier, a third lead connecting the subject to ground. It is important to minimize electrical resistance between the muscle and the electrode. This resistance is reduced by removing dead skin and oils from the skin surface. An electrode paste can be applied to the skin to increase conduction.

Surface electrodes can be used only with superficial muscles and their pick-up may be from many muscles. Ease of use, subject comfort and the averaging characteristics of the surface electrodes make them well suited for this research.

Edwards and Lippold [6] discovered that during the course of a continuous contraction, of a given strength, the number of spikes per unit time of the muscle's electrical signal progressively increased. They concluded that this is due to an increase in the number of motor units activated in the muscle as the muscle fatigues.

Figure 1 shows a plot of the number of spikes per unit time versus force. There is an increase in slope with fatigue. From the change in slope, it may be possible to derive an index of fatigue.

The Force Platform

A force platform is a device capable of measuring the three components of force and torque exerted by a test subject on the platform. These forces are uncoupled into three independent, perpendicular planes (frontal, lateral, and vertical) and then recorded. Torques are measured about the three independent perpendicular axes.

Physically, the platform consists of eight cantilever beams that rest on an aluminum plate. The steel cantilever beams are used to limit the movement of the upper frame and subsequent movement of the linear variable differential transformers (LVDT). There are nine LVDT's attached to the beams. One measures linear translational forces along each of the three orthogonal axes while two additional transformers measure the rotation about each of the same orthogonal axes. As a force is exerted on the platform, the cantilever beams deflect causing the cores of the LVDT's to be displaced. This displacement causes a signal to flow from the LVDT. This signal is directly proportional to the force applied and after amplification can be recorded. A more complete description of the force platform used is given by Hearn and Konz [11].

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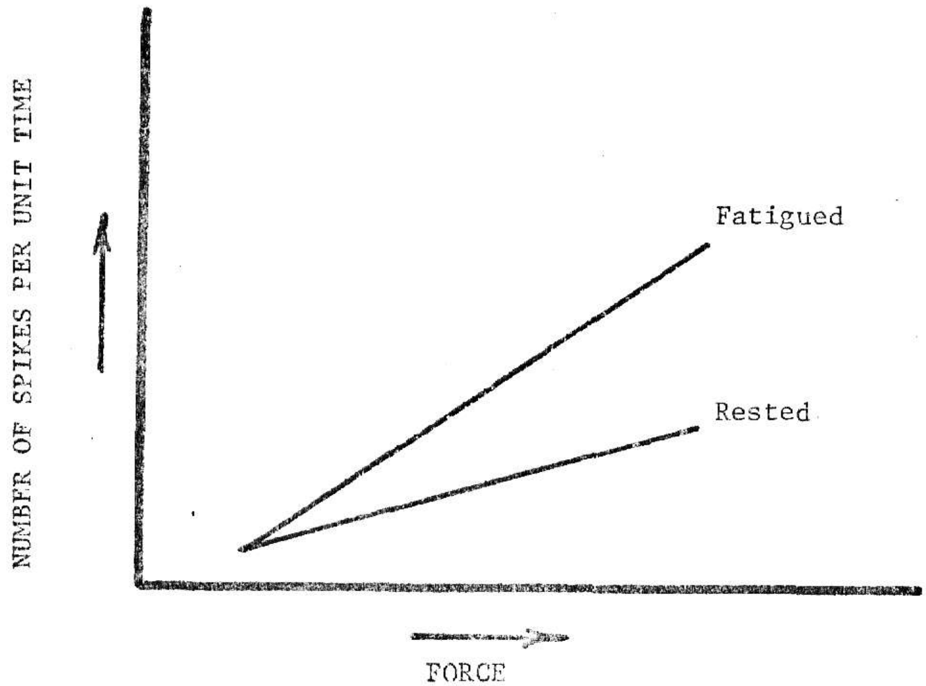

Figure 1: Representative Plots of the Number of Spikes Per Unit Time for a Given Muscle Before and After a Fatiguing Exercise.

CHAPTER II

LITERATURE SURVEY

Measuring the effects of the task on the performer is the problem toward which this thesis is directed.

Electromyography

Numerous techniques have been developed for analyzing the electrical activity of the muscle. The most basic approach is through an "examination" of the "raw" EMG. Larson [16] used this method to compare the nature of pre-exercise and post-exercise waveforms. This is a very tedious method for treating large amounts of data.

Probably the simplest way to quantify the EMG is to obtain the average amplitude. This method was used by Allphin [1]. He integrated the EMG over a time interval of one second. To analyze the data, he used a moving average. Each point plotted on a curve was the average of the three nearest readings, x-1, x, and x+1. A line was then drawn through these points. Gatev [8] used a graphic method for quantifying raw EMG traces. This involves repeated measures of the approximate absolute amplitude of the waveforms. Then a line is drawn through these amplitudes as an approximation to the average amplitude.

The most widely used method of quantification is integration of the absolute value of the EMG. Integration can be accomplished by using a mechanical planimeter [18] or electronically [2, 12]. The integrator provides a measure of the area under the EMG-time curve over the integration period. Thus the integrated electromyogram (IEMG) reflects changes in average properties of the EMG with time.

Close [4] argued that a better approach to quantifying the EMG would be counting the number of action potentials or spikes. He based this assumption on the fact that, for a given muscle, each motor unit contributes the same amount of tension each time it fires. He showed that there is a linear relationship between muscular tension in an isometric contraction and the total number of action potentials. The degree of linearity is similar to that for the relationship between the integrated EMG and muscular tension.

Another method of EMG quantification is frequency analysis. Sato [21] noticed that the energy regions of a subject's EMG, as seen in the power spectral density, shift to lower frequencies with fatigue. However, the frequency spectrum of the EMG is also affected by inter-electrode distance, position of the electrodes with respect to the direction of the muscle fiber and the length of the muscle [21].

For frequency analysis, the EMG signal is fed into a device equipped with band pass filters. Kaiser and Petersén [13] divided the EMG signal into four frequency bands. Sato [21] divides the EMG into seven bands. However, Kogi and Hakamada [14] analyzed the data in terms of only two frequency bands. Those portions of the EMG between 8 Hz and 40 Hz were compared with the portions of the EMG between 40 Hz and 120 Hz. The actual measure used by Kogi and Hakamada was the number obtained when the EMG below 40 Hz is divided by the EMG above 40 Hz. This is referred to as the "slow wave ratio".

For this study, an integration technique was used to quantify the EMG. There has not been any evidence indicating that action potential counts offer any practical advantages over the integration techniques. Since the instrumentation involved with separation of the EMG according to frequency is quite complex, this method was not used. It was felt that integration would give adequate quantification of the EMG without the necessity for complex instrumentation or complex data analysis.

The Force Platform

Lauru [17] developed the first modern force platform. He first used piezoelectric force sensors and later replaced them by LVDT's. He used the force platform to analyze bricklaying, working a cutting and stamping press and studying clerical work along with other activities.

Lauru [17] interpreted the force platform output by assuming a one-to-one relation between the amplitude of the force exerted and the amount of energy expended. The optimum force trace, he said, would consist of a pattern in the general form of a sine-wave with a low amplitude, thereby representing relatively small alternating contractions and relaxations of a muscle group, which would tend to minimize fatigue.

Greene [9] conducted an experiment to investigate the relationship between the output data from the force platform and other measures of physiological cost. The output was reduced to two factors: the force frequency product (FFP = force X cycles/time); and the force-time integral, which was obtained by integrating the force-time curve. The results indicated a high correspondence between the two platform factors and the energy expenditures as indicated by oxygen consumption measurements. However, the correspondence was considerably lower than the one-to-one correspondence assumed by Lauru between the amplitude of the force exerted and the amount of energy expended.

Greene indicated that, if the force platform data are highly correlated with oxygen consumption, the force platform could be used for designing work methods that would minimize fatigue.

Konz and Day [15] used the force platform to study the effect of varying the height and handle orientation of a push-pull task. They used the maximum height of the three force traces exerted by the operator when performing the task as measures of the force exerted by the operator. They found that the force exerted by the subject was minimized when the handle was at chest height. Changing the height of the handle caused each subject to exert a greater force to maintain body position.

Dey [5] used a force platform to study the behavior of a lifting task in terms of three parameters, distance, weight and angle of turn.

Payne, Slater and Telford [20] used the force platform to investigate the mechanics of several different kinds of athletic activities.

Tichauer [22], through the use of a one-axis force platform, kinesometer and surface myogram, produced an array of readouts which constitute a biomechanical profile of a lifting task.

The three force components of the force platform are F_x, F_y and F_z.

For this study, the absolute values of the three force components will be summed algebraically. The area under this force-time curve will be taken. This will be called the scalar impulse ($\int \Sigma F dt$). In addition, the area under the resultant force, R ($R = \sqrt{F_x^2 + F_y^2 + F_z^2}$)-time curve, will be taken. This will be called the vector impulse ($\int R dt$).

These two areas will be compared one to the other and with IEMG data to determine the relative usefulness as measures of cost.

Torques were not used because it was felt that they would not be significant indicators of cost.

CHAPTER III

METHOD AND PROCEDURE

The purpose of this thesis is to develop and evaluate methods for measurement and quantification of task cost to the performer. The objective is to study and compare the surface electromyogram and the force platform data as measures of fatigue. Proposed force platform measures are the time integral of the force R and the time integral of the algebraic sum of the absolute value of the x, y, and z components of the force R. These will be analyzed and compared with the IEMG.

General Procedure

Figure 6 shows that three surface electrodes were attached to the upper right arm over the biceps brachii muscle. The subject was then strapped into a chair on the force platform. The dynamic (isotonic) exercise consisted of having the subject rotate his elbow around a fixed point against a constant torque. The static (isometric) exercise required the subject to try to lift his right forearm while constrained in a horizontal position by a fixed load cell.

Subject Selection

Six male subjects were used. They were between the ages of nineteen and twenty-three years, between 70 and 73 in. in height, between 150 and 185 pounds in weight, had a right arm maximum strength between 35 and 70 pounds, had a right hand maximum grip strength between 70 and 120 pounds, were non-smokers and right handed. These conditions were used to select subjects that were neither "too strong" nor "too weak".

The maximum strength is the maximum force, as measured by the split ring force transducer, exerted by the individual against a fixed loading fixture with his right forearm in the horizontal position. Figure 3 shows the forearm in the horizontal position; this is also the position taken for the static exercise.

Grip strength is the maximum closing force generated by the hand, while having the right forearm in the horizontal position, as measured with a hand grip tester.

Apparatus and Arrangement

Figures 2 and 3 show the arrangement of the apparatus. The force platform was designed and built by Hearn and is located in the Human Engineering Laboratory of the Industrial Engineering Department at Kansas State University. It is capable of measuring forces along three perpendicular axes and torques about three perpendicular axes. The outputs are voltages calibrated in terms of forces and torques.

These voltages are amplified and recorded on three two-channel strip chart recorders manufactured by Texas Instruments, Incorporated. Auxiliary voltage outlets on the strip chart recorders were used to drive the ADI-PB-24 analog computer.

Figure 4 shows the chair and pulley mechanism, designed and built by Dillion [5] as modified for use in this research.

The analog computer was model ADI-PB-24 manufactured by Applied Dynamics.

The electrodes used for the EMG pickup were Beckman Ag-AgCl surface electrodes.

A Grass P16 microelectrode amplifier was chosen for EMG signal amplifi-

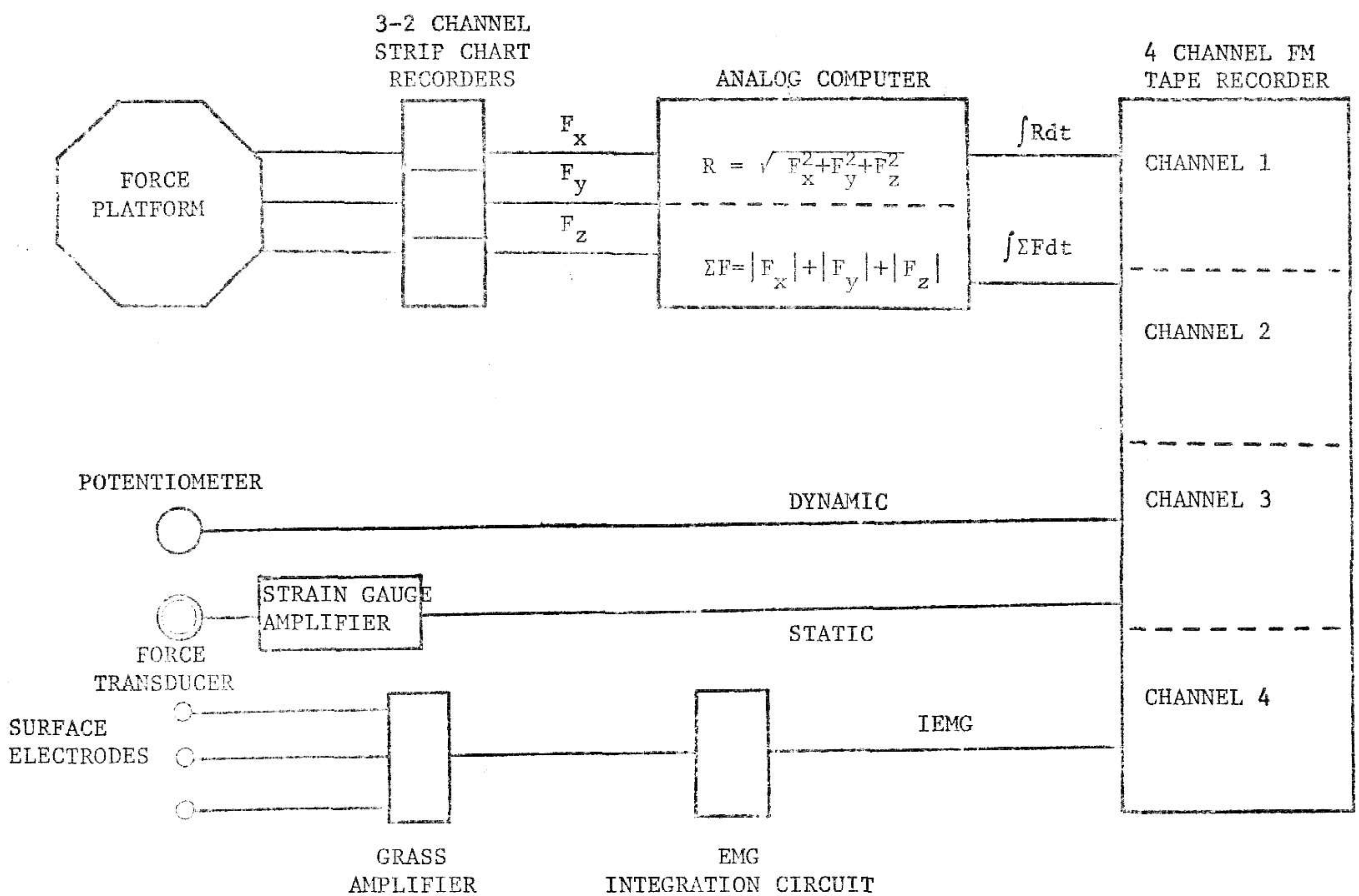

Figure 2: The Arrangement of the Components Used.

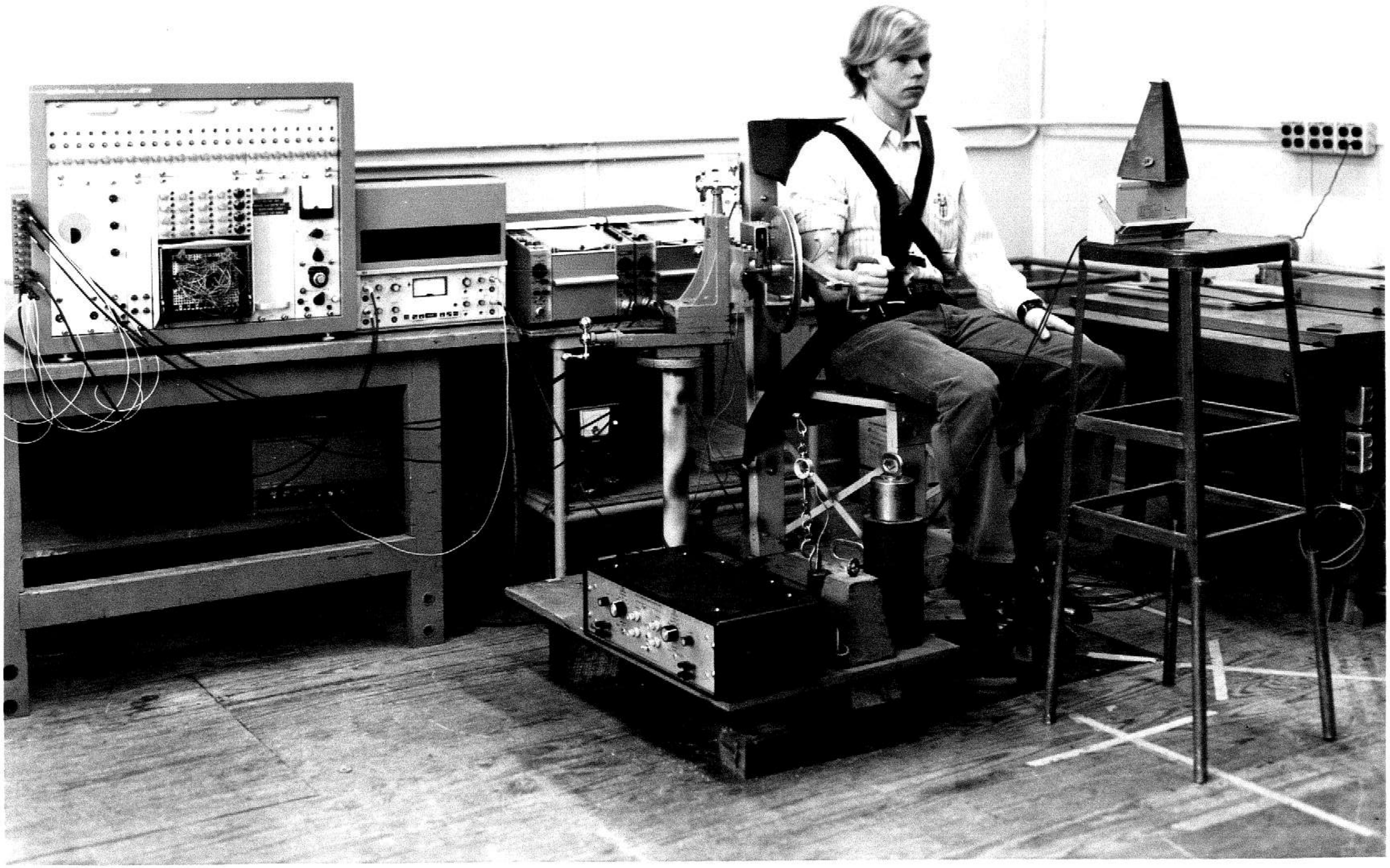

Figure 3: Arrangement of the Experimental Apparatus.

Figure 4: The Test Chair and Force Platform.

cation. It has high input impedance, sufficient amplification, low noise and a variable bandwidth which makes it suitable for this kind of work.

The EMG integration circuit removes any offset in the amplified EMG signal. It rectifies the EMG signal and then integrates over a moving time interval. It was designed and built by Dillion. The resulting output is an approximation to the following signal

$$IEMG = \int_{t-\tau}^{t} |EMG| \, dt$$

where $\tau = 0.5$ seconds.

If τ is too small, the IEMG will correspond to the instantaneous EMG. If it is too long, significant trends in the average characteristics of the EMG may be obscured.

The tape recorder is a four channel FM recorder manufactured by Hewlett Packard.

Force and displacement transducers were made to meet the needs of the experiment. The force transducer consisted of a bonded strain gauge force transducer and the displacement transducer was a rotary potentiometer with a voltage source.

The analog computer is used to sum the absolute values of the voltages corresponding to the three force components. It then integrates this sum. The analog computer also calculates the resultant of the three voltages and integrates this voltage.

Figure 5 is the analog model used. Table I shows the potentiometer settings on the computer. Potentiometer 6, 10 and 11 were varied for each subject to null out tare loads. Thus the voltages integrated by the computer are only those due to exercise loading on the platform, that is, net loads.

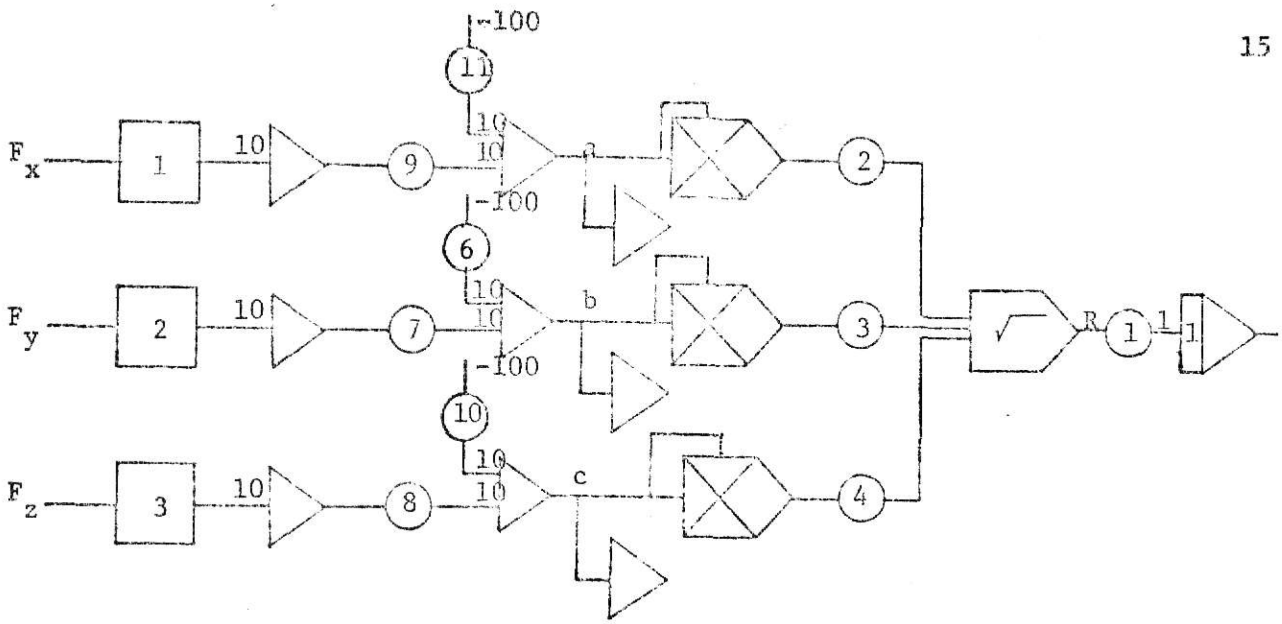

Figure 5a: Analog Model for Vector Impulse.

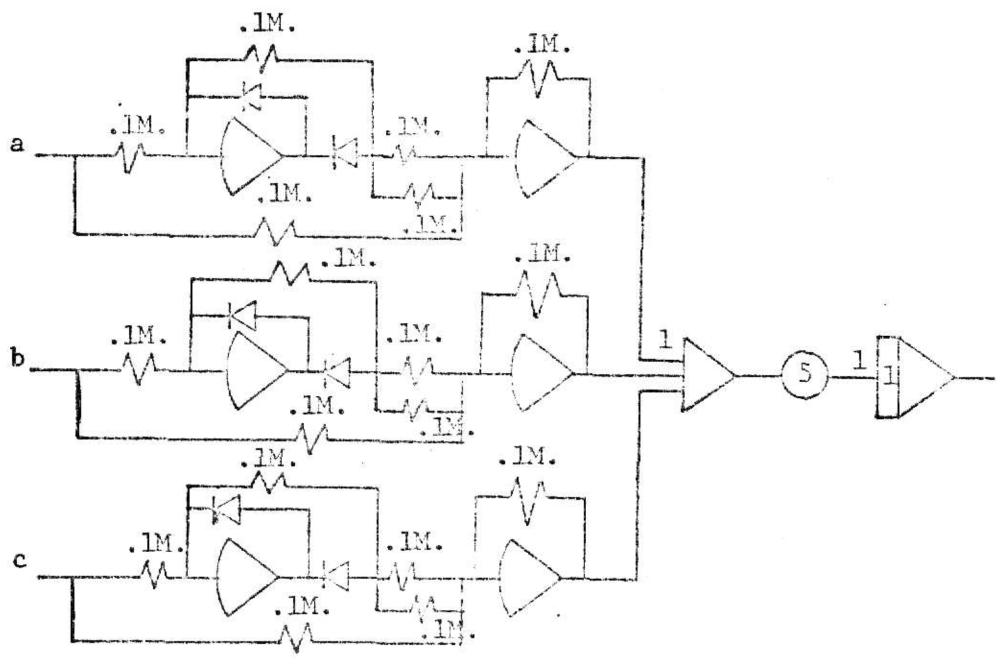

Figure 5b: Analog Model for Scalar Impulse.

Table I

Potentiometer Settings for the Analog Computer

Potentiometer Number	Potentiometer Setting
1	0.0022
2,3,4	0.272
5	0.0025
6*	0.0856
7,8,9	0.300
10*	0.0379
11*	0.0218

* Potentiometers 6, 10, and 11 varied from subject to subject.

Procedure

One electrode was placed at one end of the muscle (near the elbow) and another was placed at the other end of the muscle (towards the shoulder). A third electrode, placed on the muscle belly, serves as a common ground. Figure 6 shows the positioning of the electrodes. Beckman Electrode Paste was used to increase the conductivity between the skin and the electrodes.

The electrodes were connected to the Grass Amplifier. The signal from the amplifier was operated on by the EMG integration circuit to give the moving time integral of the EMG. Then this integral of the EMG was recorded.

After the electrodes were attached to the subject, he was seated on the test chair on the force platform. Belts were connected around the subject. One belt extended over one shoulder to over the opposite. The third crossed over the lap. Both ends of all the belts were secured to the chair. The purpose of the belts was to limit extraneous body movement.

After the subject was secured in the chair, his right arm was placed in the lever assembly as shown in Figures 3, 6 and 7.

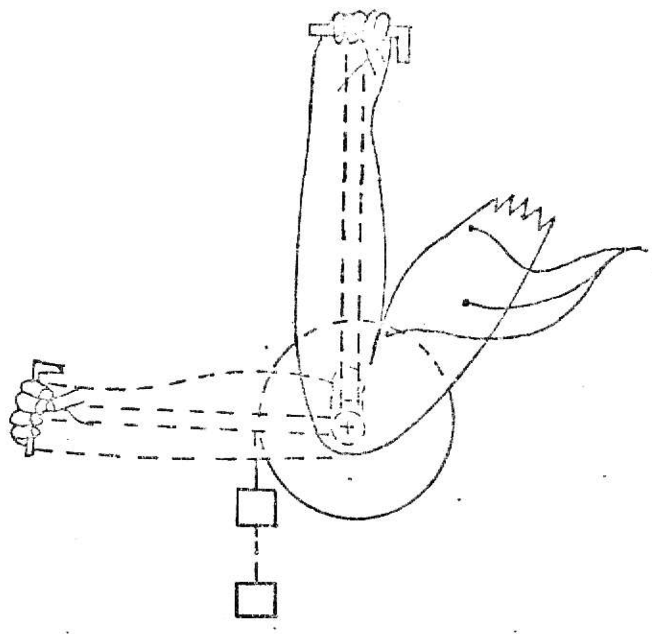

Figure 6: The Forearm in the Vertical and Horizontal Positions for the Dynamic Exercise.

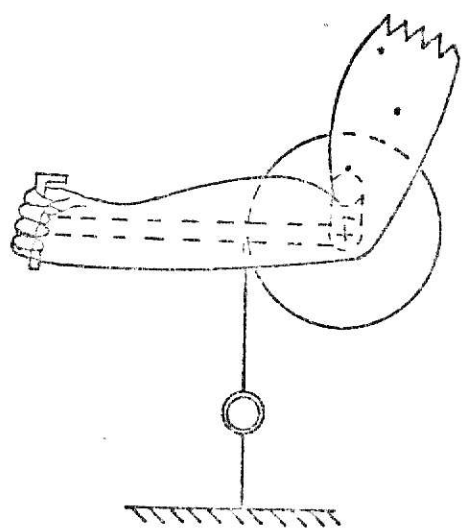

Figure 7: The Forearm in the Horizontal Position for the Static Exercise.

In the dynamic exercise, the subject raises his right arm from the horizontal position to the vertical position. This causes the pulley to rotate. Attached to the edge of the pulley is one end of a cable. On the other end of the cable is attached a weight. As the arm is lifted, the weight rises. Therefore, the subject is exerting a near constant force while rotating his arm. The subject was instructed not to use body movement to help lift his arm. He was to use only his arm muscles.

Figure 8 shows a force diagram of the pulley and arm lever assembly. F_3 is the force exerted by the hand. F_1 and F_2 are the external load and the weight of the hand and forearm, respectively. R_1 and R_2 are the corresponding moment arms.

Figure 7 shows the arrangement for the static exercise. The weight was removed and a force transducer was attached to the cable and to a fixed object. This constrained the subject's arm in the horizontal position.

The force exerted by the arm muscle is the force required to lift the weight plus the weight of the hand and forearm. This force is related to the EMG of the biceps brachii muscle and to the force exerted on the force platform. In Table II are listed the external loads and the corresponding forces on the arm muscle.

Table II

External Loads and Corresponding Muscle Loads for the Static Exercise.

External Load (lbs.)	Muscle Load (lbs.)
0.5	2.0
5.0	4.0
15.0	8.5
40% of maximum strength	11.6 (Avg.)

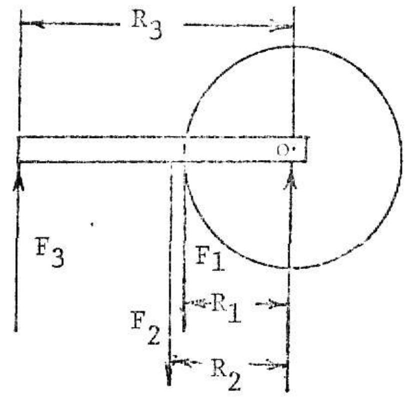

Figure 8a: Force Diagram for the Forearm in the Horizontal Position.

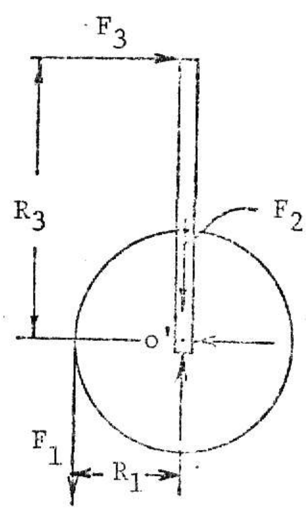

Figure 8b: Force Diagram for the Forearm in the Vertical Position.

Dynamic Exercise

First the dynamic exercise was performed by all of the subjects. Each subject was required to lift each of three different weights twenty-five times. It was presumed that the sequence of the weights lifted might have a bearing on the results. Table III shows the sequence of weights lifted for each subject.

Table III

Sequence of weights lifted for the dynamic exercise.

Subject	First trial	Second trial	Third trial
1	0.5 lbs.	5.0 lbs.	15.0 lbs.
2	0.5	15.0	5.0
3	5.0	0.5	15.0
4	5.0	15.0	0.5
5	15.0	0.5	5.0
6	15.0	5.0	0.5

Each cycle consisted of raising the forearm to the vertical within two seconds, hold for one second, drop in one second and then rest for three seconds before starting the cycle again. A metronome was used to pace the exercise. The person running the experiment counted the cycles until the required number was completed.

After lifting each weight twenty-five times, the subject was allowed to rest for five minutes. During the five minute rest period, the subject remained seated without exerting any forces on his arm other than those necessary to position the arm so as to have it feel comfortable.

Static Exercise

At least one day passed between the dynamic and static exercises. Four runs were made by each subject at respective force levels of 0.5, 5.0, 15.0 pounds and 40% of the subject's maximum strength.

As in the dynamic exercise, the sequence of the forces differed for all of the subjects. Table IV shows the sequence of the forces on the force transducer.

Table IV

Sequence of Forces for the Static Exercise

Subject	First trial	Second trial	Third trial	Fourth trial
1	15.0 lbs.	5.0 lbs.	0.5 lbs.	40%
2	15.0	0.5	5.0	40%
3	5.0	15.0	0.5	40%
4	5.0	0.5	15.0	40%
5	0.5	15.0	5.0	40%
6	0.5	5.0	15.0	40%

Each subject was asked to pull up on the handgrip until he reached the required force, and to hold this level for a total of sixty seconds. The subject was informed when the sixty seconds was up. A five minute interval was allowed between runs to let the muscle rest. For the 40% maximum strength exercise, the subject was asked to hold the force for as long as possible. The 40% maximum strength was always run last because a five minute rest period would not allow enough time for the muscle to relax sufficiently.

Data Reduction

The base level IEMG, or resting potential, is obtained under relaxed conditions. The ΔIEMG is the potential difference between the resting potential of the muscle and the potential of the muscle while in tension.

For the dynamic exercise, the area under the ΔIEMG curve for each cycle was evaluated with a planimeter. This value was then divided by the time interval of the cycle to get the average ΔIEMG. The value of vector impulse and scalar impulse at the end of a cycle had subtracted from it the value at the end of the previous cycle. This gave a change in the vector and scalar impulses for each cycle.

From the static exercise data, the value of the ΔIEMG at every ten second interval was determined and tabulated. An exception was made for the 40% maximum strength exercise. The interval over which the ΔIEMG was determined was increased to fifty seconds. The interval over which the change in vector and scalar impulses was taken was ten seconds except for the 40% maximum strength, where the interval was fifty seconds.

Because of physiological differences and differences in electrode placement among the subjects, each exhibited a unique ΔIEMG for a given force level. For comparison purposes, it is convenient to remove the differences by normalizing each ΔIEMG with respect to the corresponding maximum ΔIEMG. This was done for all six subjects and the result is called the normalized ΔIEMG.

CHAPTER IV

RESULTS AND ANALYSIS OF RESULTS

The scatter of the data points indicated that the variability among the subjects was large compared to measurement errors and thus a detailed treatment of measurement errors was not required.

All curves shown in this chapter are least squares straight lines fitted to the data points. For all equations, the y value will represent either ΔIEMG, vector impulse or scalar impulse, depending on which figure is being analyzed. The t value represents either exercise time or exercise cycle, depending whether the exercise is static or dynamic. SE is the standard error and r is the correlation coefficient.

Static Exercise

ΔIEMG

Figure 9 illustrates the ΔIEMG average over the subject's versus time for the 0.5, 5.0 and 15.0 lb. loads of the static exercise. The equations relating the ΔIEMG level at the skin and time are given below:

External load, lb.	ΔIEMG,μv.	r	SE
0.5	y=42	0.04	0.001
5.0	y=92	0.28	0.002
15.0	y=0.3 t + 193	0.80	0.004

The ΔIEMG varied with the load. The greater the muscle tension, the larger the ΔIEMG. For the 15.0 lb. load, the ΔIEMG increased with time, while for the other loads the ΔIEMG remained constant. This indicates that the 15.0 lb. load fatigued the muscle while the other loads did not fatigue the muscle to a measurable extent during this time period.

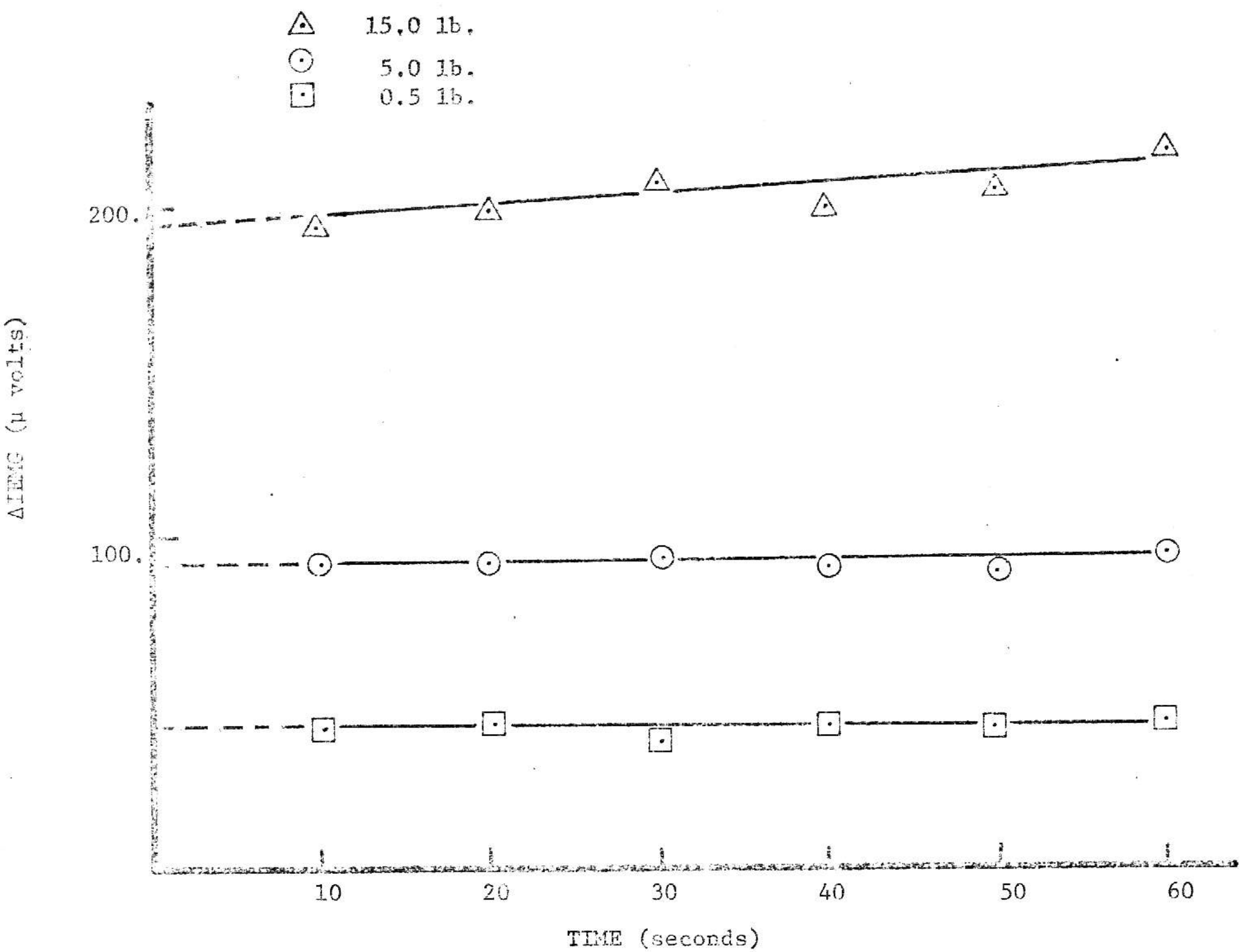

Figure 9: ΔIEMG versus Time for the Static Exercise.

Impulse

Figures 10 and 11 show averages over the subjects of the scalar impulse and vector impulse versus exercise time for the 0.5, 5.0 and 15.0 lb. loadings for the static exercise. Least squares straight line representations of vector impulse data are given below:

External load, lb.	Vector impulse, lb.-sec.	r	SE, lb.-sec.
0.5	y= 5.8 t - 14.2	0.99	10.10
5.0	y= 7.7 t + 20.1	0.99	10.93
15.0	y=16.0 t + 27.6	0.99	15.85

where y is in lbs.-sec. and t is in seconds.

Similar least squares fits for the scalar impulse data are given below:

External load, lb.	Scalar impulse, lb.-sec.	r	SE, lb.-sec.
0.5	y= 8.5 t - 27.0	0.99	17.01
5.0	y=10.3 t - 20.0	0.99	10.94
15.0	y=20.4 t - 55.1	0.99	30.48

where y is in lbs.-sec. and t is in seconds.

The graphs indicate that, for the static exercise, the vector impulse and scalar impulse increase linearly with time. The larger the load, the steeper the slope of the line. The slope of the scalar impulse is greater than the slope of the vector impulse for corresponding load levels. The ratios of slopes for the 0.5, 5.0 and 15.0 lb. loads are: 1.75, 1.30 and 1.38.

40% Maximum Strength Exercise

ΔIEMG

Figure 12 shows the relation between the normalized ΔIEMG and exercise time for the 40% maximum strength exercise. Intersection of the line with the 100% line indicates termination of the exercise by the subject.

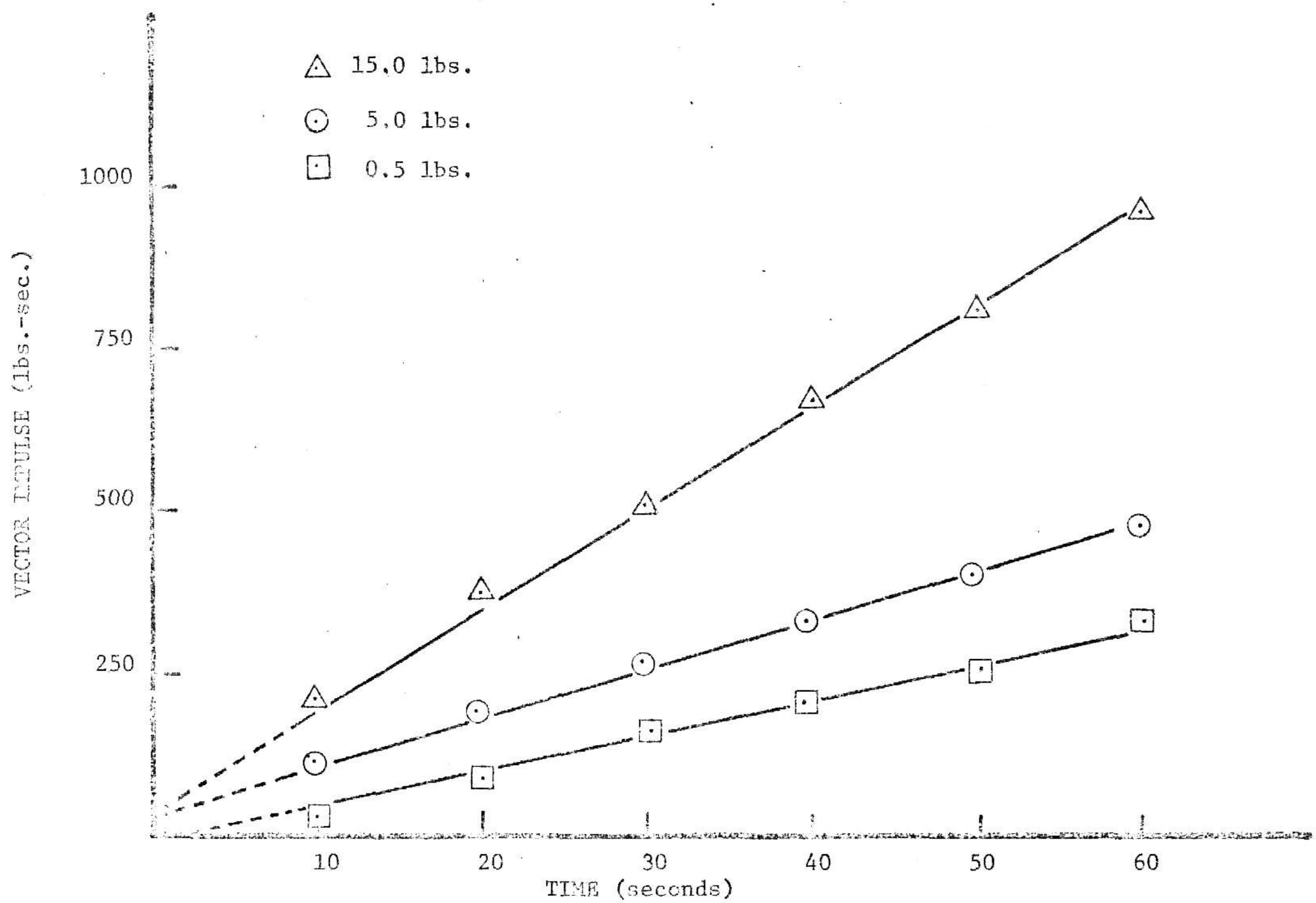

Figure 10: Vector Impulse versus Time for the Static Exercise.

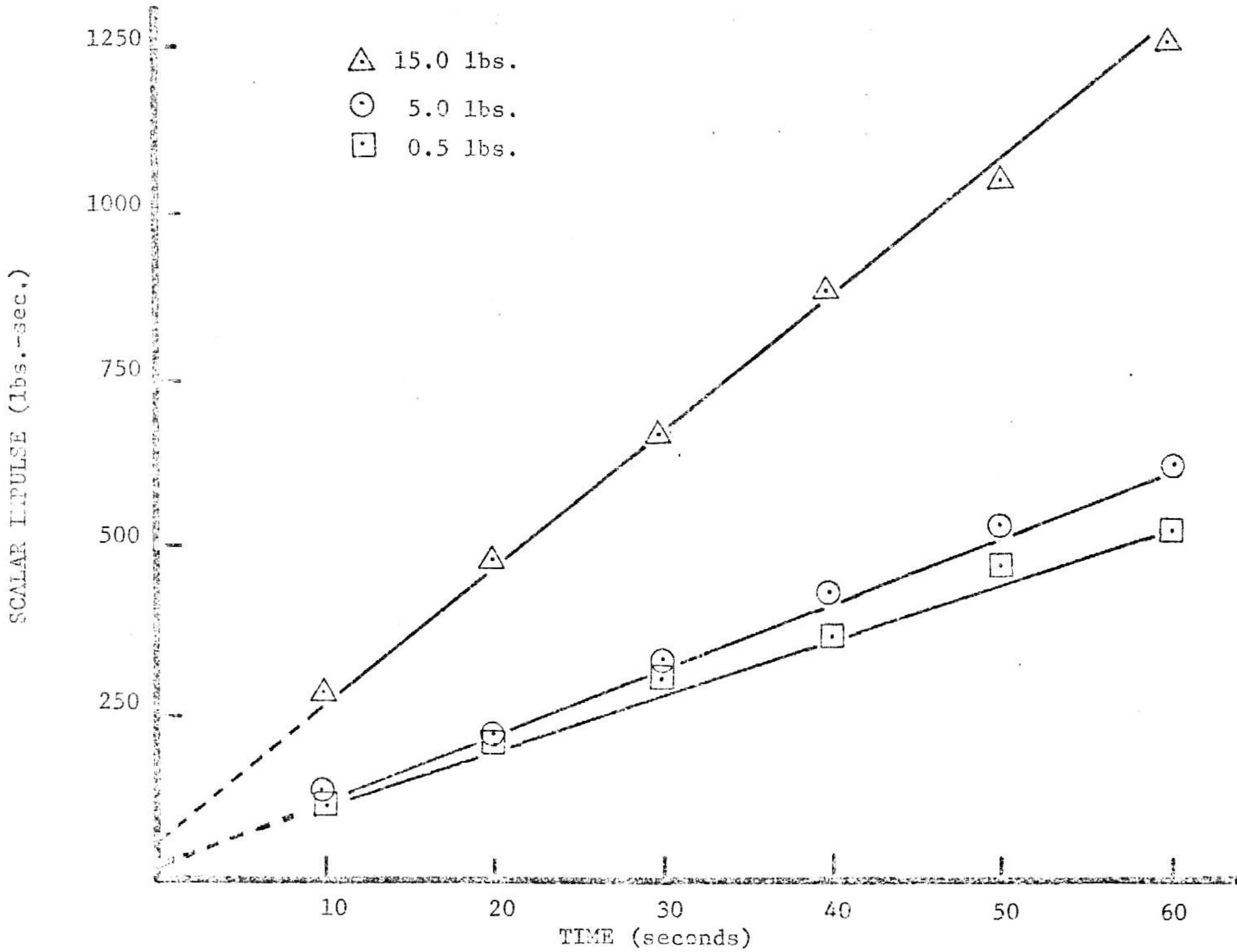

Figure 11: Scalar Impulse versus Time for the Static Exercise.

The relationship between the normalized ΔIEMG and time is given below for each subject:

Subject	ΔIEMG, %	r	SE, %
1	y=0.15 t + 43	0.90	8.11
2	y=0.13 t + 17	0.86	12.26
3	y=0.37 t + 38	0.96	5.80
4	y=0.24 t + 35	0.96	5.44
5	y=0.36 t + 31	0.90	9.82
6	y=0.22 t + 51	0.67	11.28

Ranking the subjects according to endurance limit from shortest to longest gives subjects 3, 5 and 6 (simultaneously), 4, 1 and 2. The actual order of termination was 6, 3, 5, 4, 1 and 2.

Figure 13 shows ΔIEMG versus exercise time for the 40% maximum strength exercise. The relationship between ΔIEMG and time is given below for each subject. The number on the graph, next to the sloping lines, is the subject number.

Subject	ΔIEMG, μv.	r	SE, μv.
1	y=0.29 t + 87	0.90	0.01
2	y=0.97 t + 136	0.85	0.09
3	y=3.16 t + 335	0.96	0.05
4	y=1.70 t + 254	0.96	0.04
5	y=2.46 t + 204	0.90	0.07
6	y=1.32 t + 306	0.66	0.07

With the exception of subject 1, the subject's final ΔIEMG was in the range of 594 μvolts to 961 μvolts with the average being 678 μvolts.

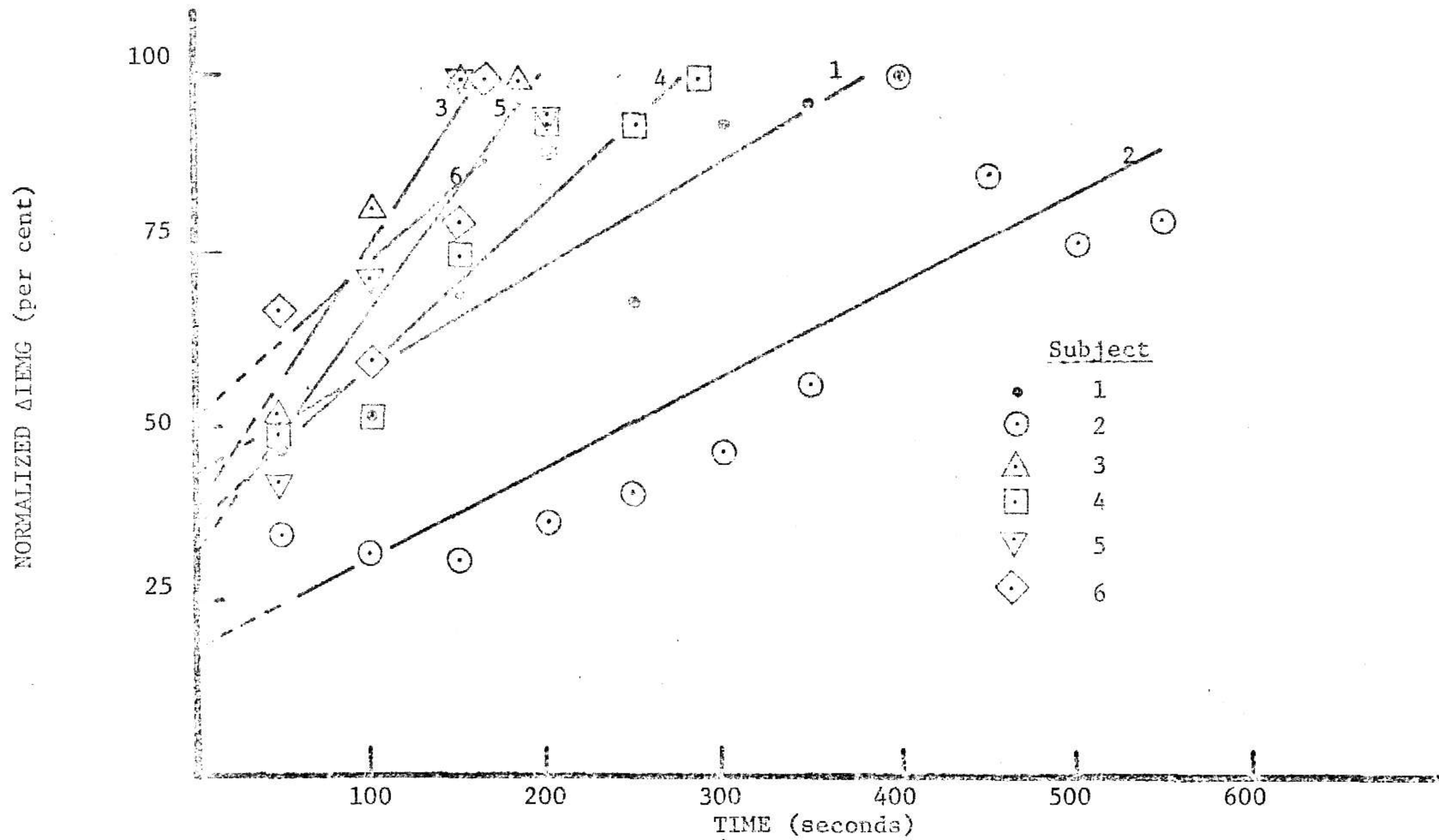

Figure 12: Normalized ΔIEMG versus Time for the 40% Maximum Strength.

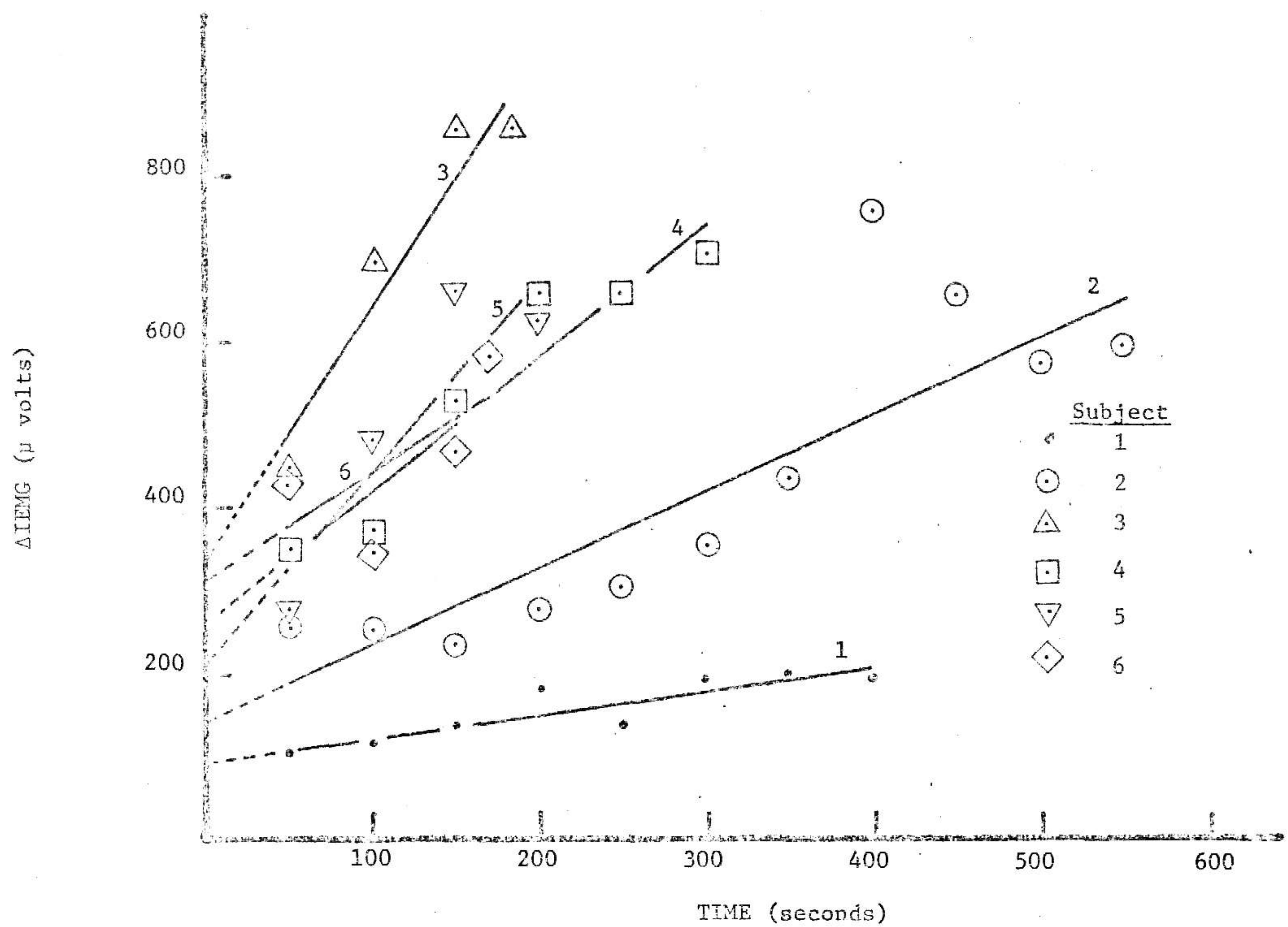

Figure 13: ΔIEMG versus Time for the 40% Maximum Strength.

Ranking the subjects in order of decreasing ΔIEMG gives: 3, 5, 4, 6, 2 and 1.

Impulse

Figure 14 shows the vector impulse versus exercise time for the 40% maximum strength exercise for each subject. Figure 15 shows the scalar impulse versus exercise time for the 40% maximum strength exercise for each subject. The vector impulse versus time equations for each subject are:

Subject	Vector impulse, lb.-sec.	r	SE, lb.-sec.
1	y=12.0 t - 585	0.99	125
2	y=14.1 t - 239	0.99	75
3	y=20.8 t - 285	0.99	83
4	y=20.7 t + 177	0.99	132
5	y=41.1 t - 509	0.99	340
6	y=26.9 t - 65	0.99	65

The scalar impulse versus time equations for each subject are:

Subject	Scalar impulse, lb.-sec.	r	SE, lb.-sec.
1	y=15.4 t - 725	0.99	147
2	y=14.3 t + 2	0.99	206
3	y=26.5 t - 343	0.99	57
4	y=22.0 t + 606	0.96	248
5	y=39.0 t + 32	0.99	117
6	y=31.8 t + 353	0.99	29

Dynamic Exercise

ΔIEMG

Figure 16 illustrates the average over the subjects of the ΔIEMG versus

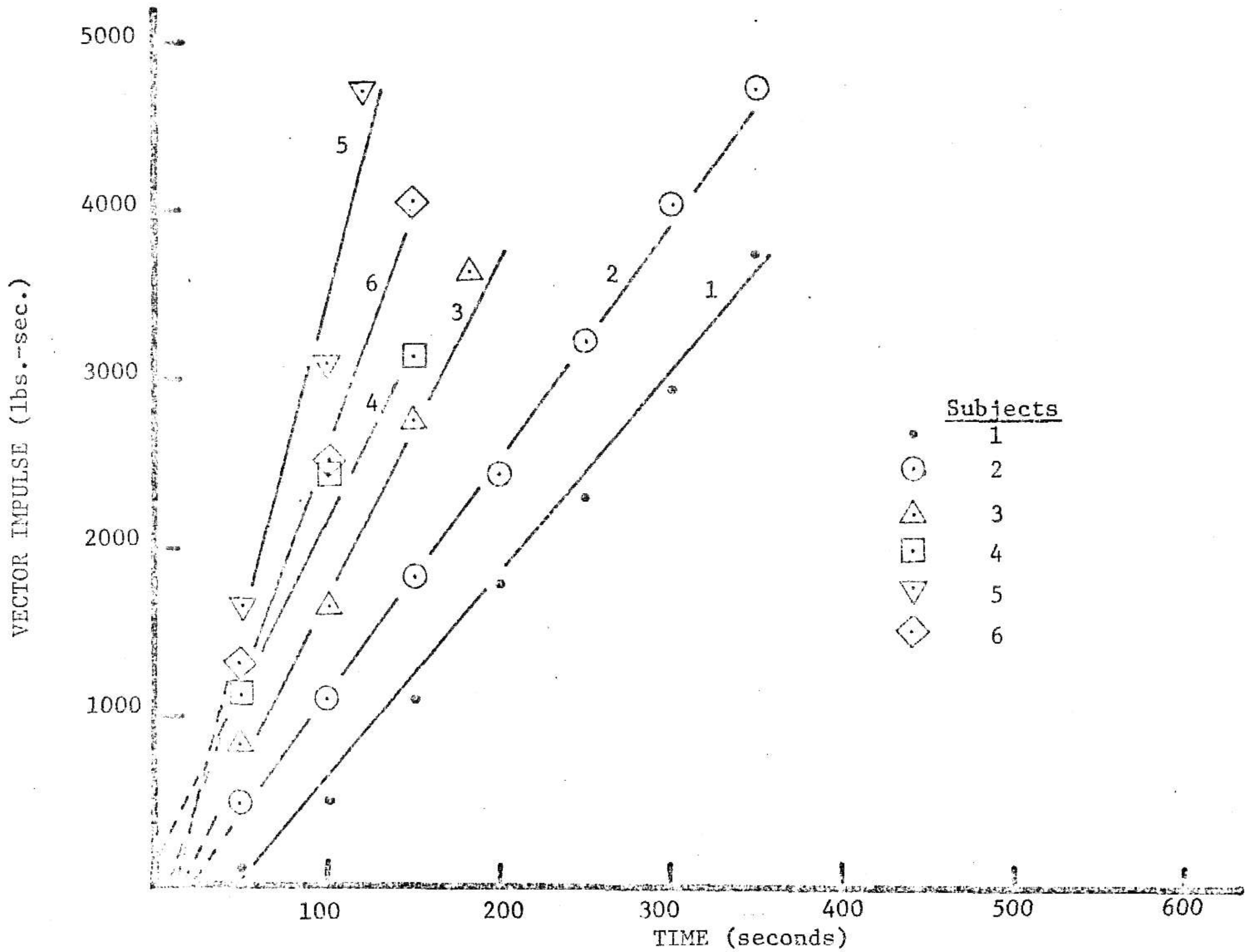

Figure 14: Vector Impulse versus Time for the 40% of Maximum Strength.

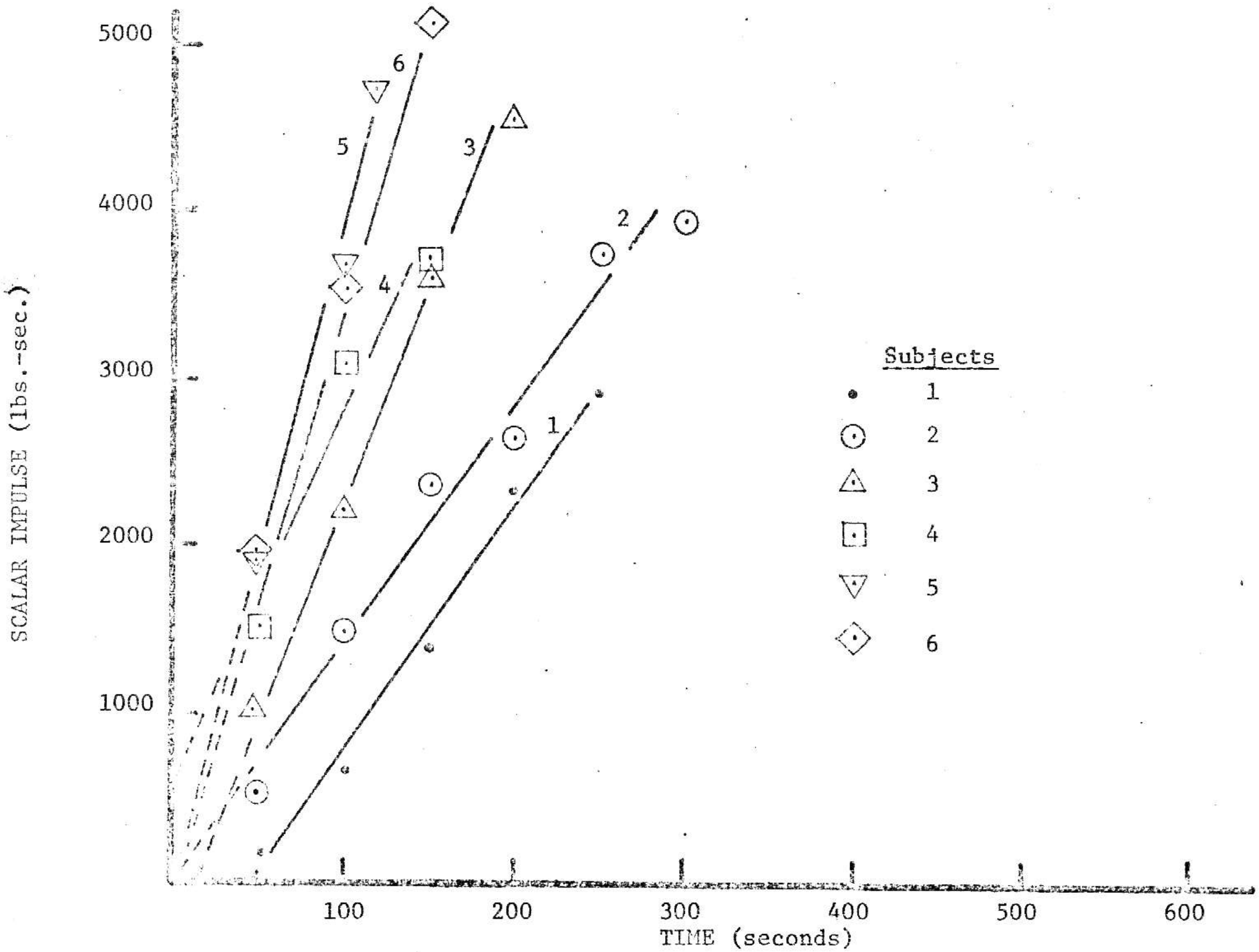

Figure 15: Scalar Impulse versus Time for the 40% Maximum Strength.

exercise cycle for the dynamic exercise. The equations relating the ΔIEMG and exercise cycle for this exercise are:

External load, lb.	ΔIEMG, μv.	r	SE, μv.
0.5	y=-2. t + 189	-0.71	11
5.0	y=-2. t + 194	-0.75	10
15.0	y=-1. t + 339	-0.36	27

This graph indicates that there was virtually no difference in ΔIEMG levels between the exercise at 0.5 lb. and the exercise at 5.0 lb., but the level for the 15.0 lb. loading was higher than for the other two. The ΔIEMG levels decrease with the number of load cycles for the two smaller loads. An increase in ΔIEMG with fatigue is normally expected so the exact meaning of this decrease is unknown. One possibility is an improvement in the smoothness of the cycle with time, thus compensating for any slight fatiguing which may have occurred.

Impulse

Figures 17 and 18 show the vector and scalar impulses averaged over the subjects versus exercise cycle. The equations relating the vector impulse and exercise cycle are:

External load, lb.	Vector impulse, lb.-sec.	r	SE, lb.-sec.
0.5	y=14.5 t + 18	0.99	2.4
5.0	y=19.4 t + 32	0.99	4.2
15.0	y=36.7 t + 40	0.99	6.6

The equations relating the scalar impulse and exercise cycle are:

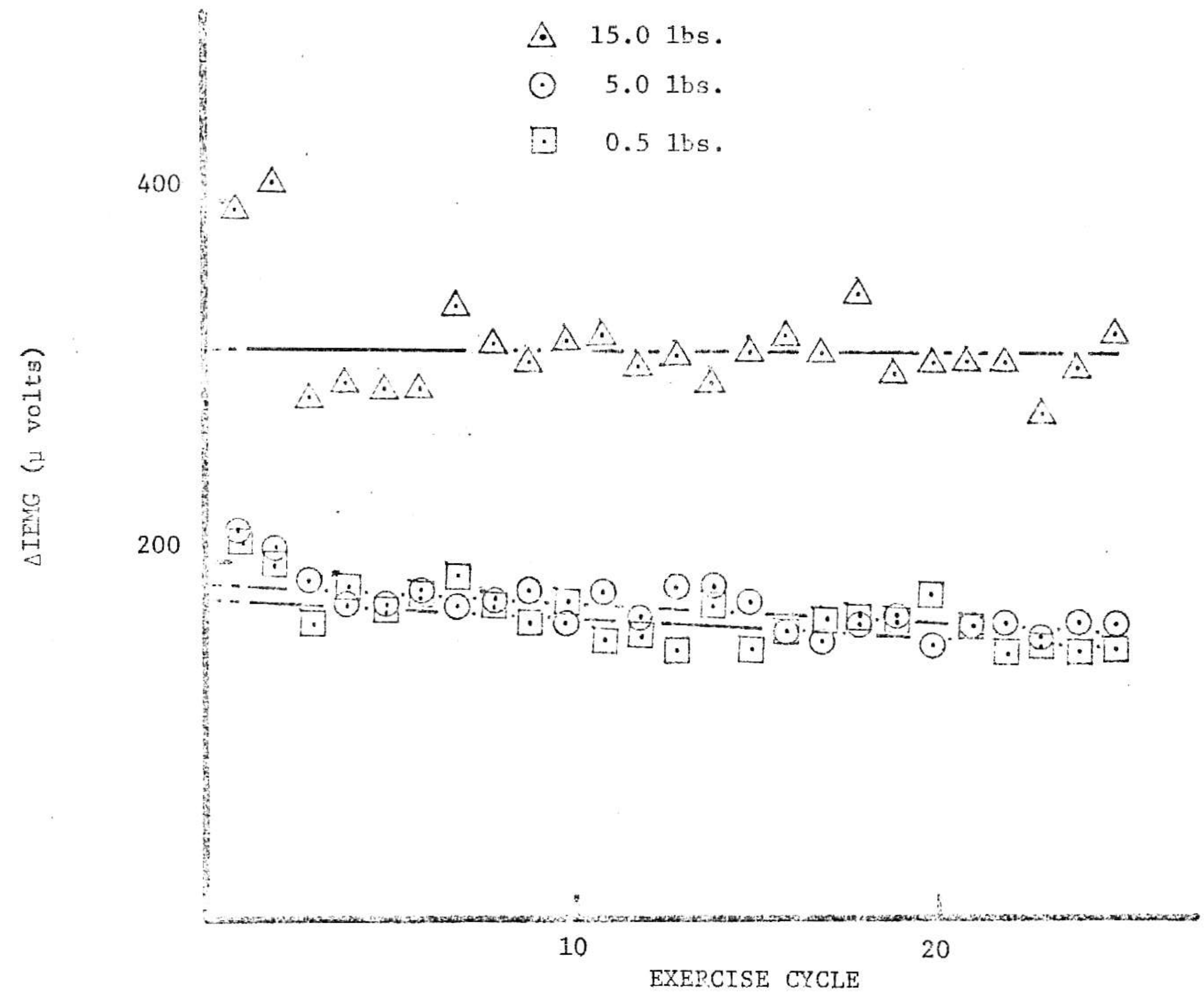

Figure 16: ΔIEMG versus Exercise Cycle for the Dynamic Exercise.

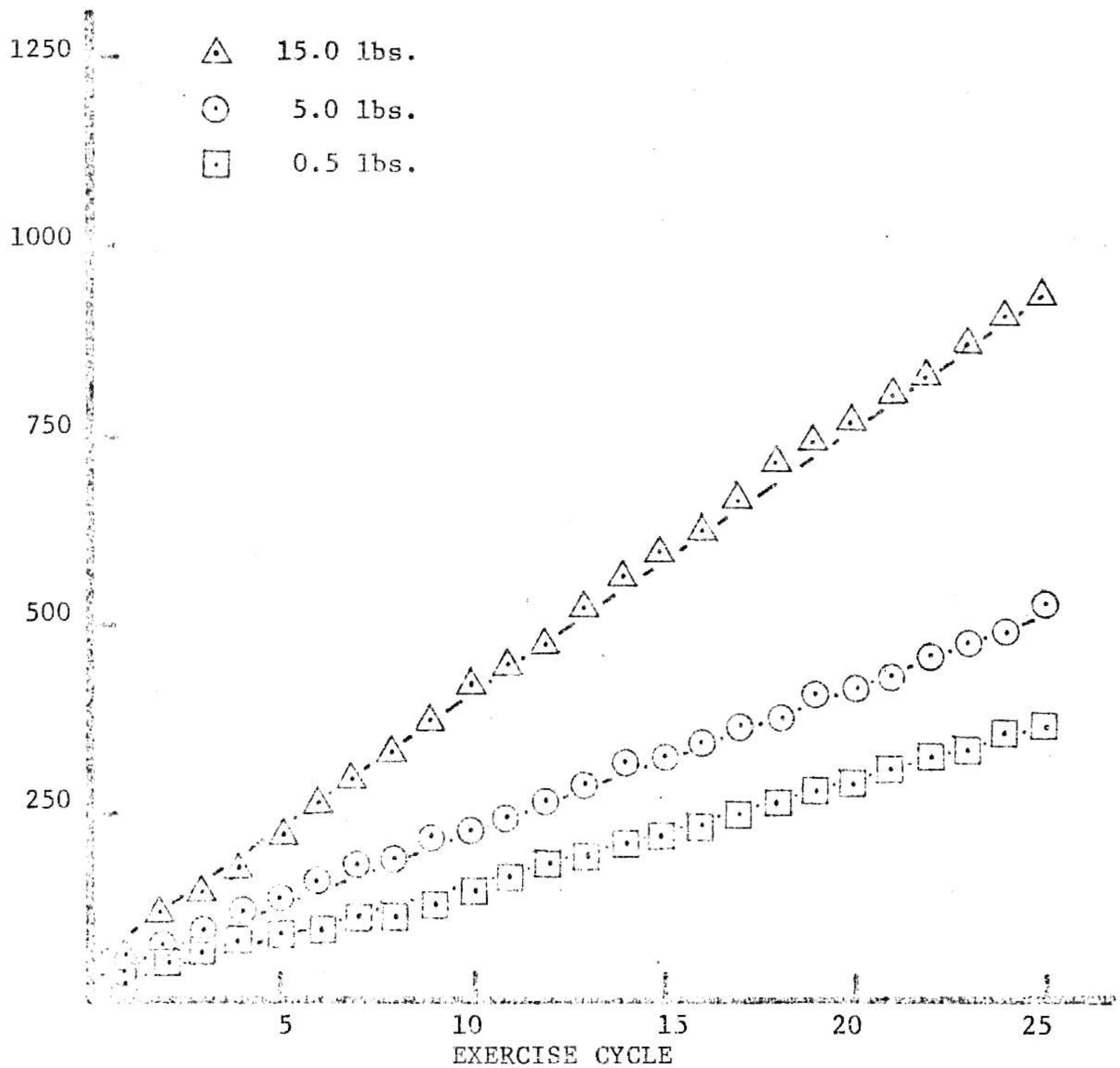

Figure 17: Vector Impulse versus Exercise Cycle for the Dynamic Exercise.

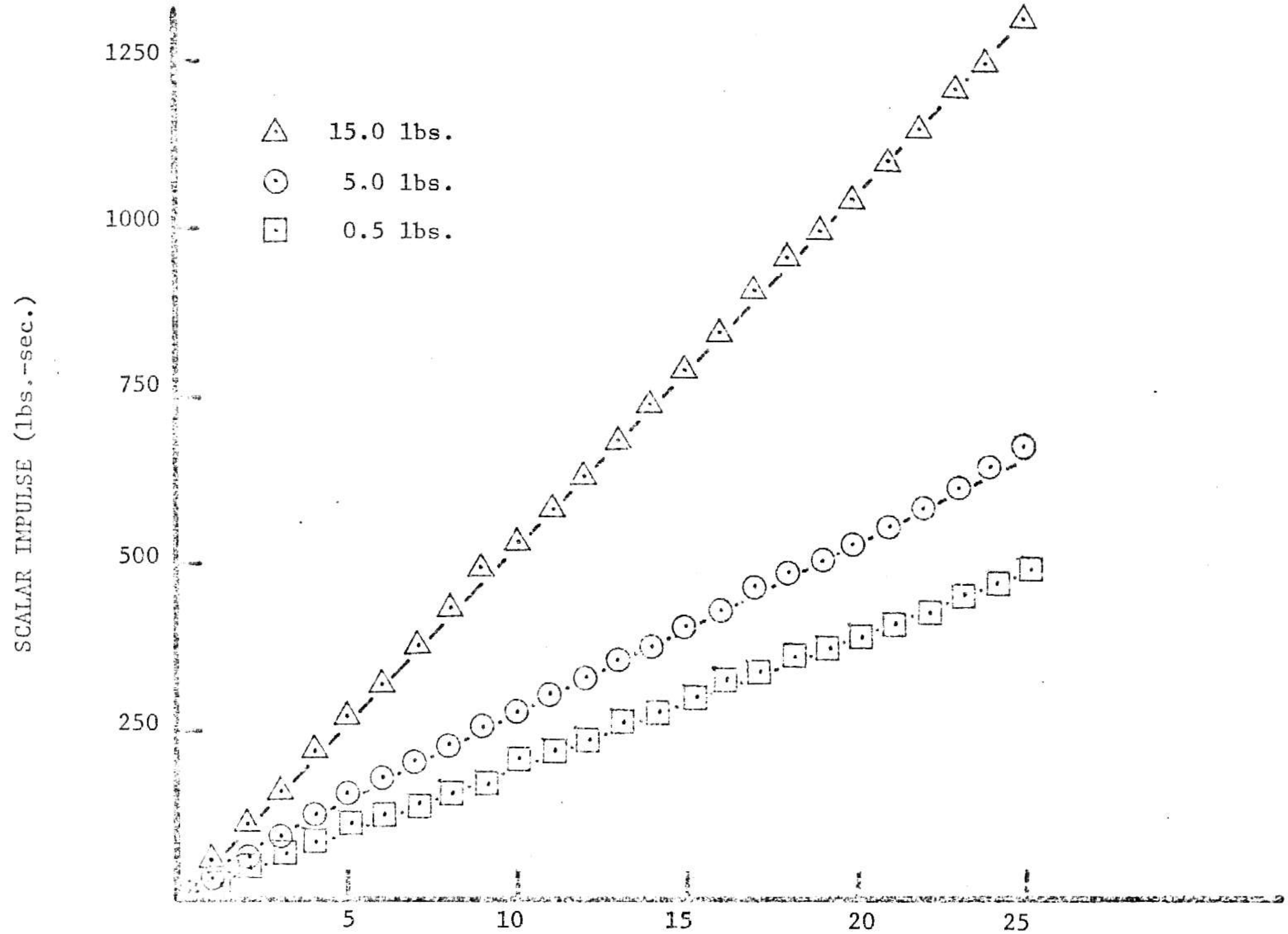

Figure 18: Scalar Impulse versus Exercise Cycle for the Dynamic Exercise.

External load, lb.	Scalar impulse, lb.-sec.	r	SE, lb.-sec.
0.5	y=19.2 t + 12	0.99	4.1
5.0	y=25.8 t + 21	0.99	5.5
15.0	y=52.3 t + 5	0.99	20.8

For the dynamic exercise, the impulses increased linearly with the number of cycles. The larger the load, the steeper the slope. The rate of increase of the scalar impulse is greater than that for the vector impulse. The ratio's of scalar impulse to vector impulse for the 0.5, 5.0 and 15.0 lbs. loads are: 1.32, 1.33 and 1.42.

CHAPTER V

SUMMARY

The purpose of this thesis was to investigate fatigue measurements through the use of the force platform and surface electromyogram.

The following is a summary of the results obtained from the tests:

1. Dynamic exercises

   A. The vector impulse and scalar impulse increased linearly with the number of exercise cycles and increased with load level.

   B. The scalar impulse was always greater than the vector impulse for corresponding conditions.

   C. The average ΔIEMG remained nearly constant for all cycles at a given load level, was the same for 0.5 and 5.0 lb. external loads, but increased substantially for the 15.0 lb. load.

2. Static

   A. For the 0.5 lb. and 5.0 lb. levels, the ΔIEMG remained essentially constant with time over the 60 second test interval.

   B. For the 15.0 lb. level the ΔIEMG increased linearly with time over the 60 second test interval.

   C. The vector impulse and the scalar impulse increased linearly with time at each force level and the rate of increase was related directly to load. The scalar impulse was always greater than the vector impulse for given conditions.

   D. The ΔIEMG increased with time for the static 40% maximum strength exercise.

The following are observations made by the subjects while performing the exercise:

1. The subjects followed the outlined procedure for the dynamic exercise without any noticeable difficulty. The subjects responded negatively when asked if their arms felt tired after the dynamic exercises. This suggests the load level and duration were too low to produce perceptible fatigue.

2. For the 0.5 lb., 5.0 lb. and 15.0 lb. static exercise, the subjects were able to maintain the required force levels without any difficulty. They responded negatively when asked if their arm felt tired after the completion of each of the static exercises. This suggests the load level and duration were too low to produce perceptible fatigue.

3. For the static 40% of maximum strength exercise, the subjects initially maintained the force level well, but then had difficulty maintaining these levels. They responded positively when asked if their arms were tired after the exercise. This suggests that significant fatigue was induced by the 40%, long duration tests.

CHAPTER VI

RECOMMENDATIONS FOR FURTHER STUDY

As mentioned earlier, the purpose of this study was to use the force platform and surface electromyogram as indicators of fatigue. This was done, but more experimentation is needed to develop a greater understanding of these measurement methods.

A study should be made to see what effect a light load for a long term would have on the ΔIEMG of a muscle.

Heavy load levels for long periods of time should be used to investigate the relation between the impulse or ΔIEMG and duration limits.

The loads used seemed to be too light or of too short a duration to cause fatigue above threshold levels. The most important data were obtained at the 40% maximum strength level. Heavier loads could be used to see what effect they would have on the relation between ΔIEMG, impulse and muscular fatigue.

CHAPTER VII

CONCLUSION

For low level static exercises, the vector and scalar impulses indicate a constant rate of increase with time. Although the ΔIEMG range is limited, this measure of cost grows with time, which indicates cumulative fatigue over a long task. Therefore, the ΔIEMG may be a superior indicator of fatigue for static, long term tasks above a threshold force level.

For the 40% maximum strength static test, the vector and scalar impulses show cost as linearly increasing with time at a rate directly proportional to load.

For simple motion tasks, such as in this experiment, there appears to be no difference between the vector and scalar impulses as measures of cost. Since the scalar impulse requires less computational equipment, it is preferable, but it should be noted that this comparison may change for more complex tasks.

In the dynamic tests, at low force levels, the ΔIEMG slightly decreases with the number of exercise cycles performed, while at the 15.0 lb. level, the ΔIEMG remains essentially constant with the number of cycles. It is not clear if the cyclic exercise, with rest between cycles is less tiring than a static load or whether the results are corrupted by errors of extraneous variations. Longer duration tests may reveal useful information about this phenomenon.

The instrumentation and data reduction schemes used in the experiment have proved to be successful and easy to use, especially the analog computer circuit for calculating the scalar and vector impulses. This is particularly significant for short cycle dynamic tests such as that used in this experiment. The ability to determine the ΔIEMG is another indication of the merits of the instrumentation and data reduction scheme used.

The force platform gives a measure of the individual output. Tasks performed by individuals who have the same output, will have the same force platform output.

ACKNOWLEDGEMENTS

The author wishes to express his deep appreciation to his co-major professors, Dr. C. H. Sprague and Dr. S. A. Konz, for their advice, valuable suggestions, and helpful directions. Thanks are due to Ron Dillion for his aid in helping to build the experimental apparatus.

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APPENDICES

APPENDIX A

CALIBRATION

Calibration of the tape recorder was required. Each channel was calibrated so a maximum input voltage would equal 100%. The output voltage corresponding to 100% was always equal to 2.44 volts. By knowing what the output voltage is, one can calculate the corresponding input voltage. Table A-I gives the maximum input voltages corresponding to 100% output for each channel.

Table A-I

Tape Recorder Calibration

Channel	Variable	Maximum Input Voltage (volts)
1	Vector impulse	50.0 Dynamic, 25. Static
2	Scalar impulse	50.0 Dynamic, 25. Static
3	IEMG	1.0 Dynamic and Static
4	Elbow angle, external load	4.0 Dynamic, 1.0 Static

It was necessary to determine the relationship between the analog computer output voltage and the "impulse" on the force platform. A subject was seated in the chair and the analog was adjusted to have a zero output when the subject was motionless and not exerting any forces other than body weight. A ten pound weight was placed on the platform and the analog was started. It remained on for 120 seconds. At this time, the voltages from amplifier one and four were recorded. Amplifier one was 18.0 volts and amplifier four was 8.8 volts. These two voltages were equal to 1200 pound-seconds (10 pounds X 120 seconds). For amplifier one, 1 volt equaled 66.8 pound-seconds, while for amplifier four, 1 volt equaled 136 pound-seconds. Amplifier one gave the scalar impulse and amplifier four gave the vector impulse.

Calibration of the force transducer was accomplished in the following manner. The force transducer was attached to the dual strain gauge amplifier. The digital voltmeter and tape recorder were connected to the amplifier. The discrete attenuator on the amplifier was set at 50 and the variable gain was at a maximum. A number of weights were attached and removed from the force transducer five times. Table A-II gives the average output voltage from the amplifier for each weight.

Table A-II

Calibration of the Force Transducer

Weight (lbs.)	Amplifier Output (volts)
0	0.64
1	0.61
3	0.55
5	0.48
10	0.31
20	0.00

The equation relating force and amplifier output is:

$$\text{Output, volts} = -0.032(\text{Weight, lbs.}) + 0.64$$

APPENDIX B

Procedure Outline Given to Each Subject - Dynamic

1) Sit on the chair and assume a comfortable position.

2) Fasten the seat and shoulder straps.

3) Place your right elbow so it is in line with the center of the pulley.

4) Place your hand in the hand grip apparatus.

5) Have the tester position the x,y,z positioner until your arm feels comfortable.

After the tester has attached the weight to the cable, the experiment will have the following procedure.

6) Raise your hand and forearm so the forearm moves from a horizontal to a vertical position. This lifting should be performed in two seconds.

7) After your forearm has reached the vertical position, hold it for one second and then lower it back to the horizontal position within one second.

8) Rest for three seconds.

9) Repeat steps six and seven until they have been executed a total of twenty-five times.

10) Rest for five minutes.

11) Repeat steps six through ten for each of two additional loads.

Procedure Outline Given to Each Subject - Static

1) Sit on the chair and assume a comfortable position.

2) Fasten the seat and shoulder straps.

3) Place your right elbow so it is in line with the center of the pulley.

4) Place your hand in the hand grip apparatus.

5) Have the tester position the x,y,z positioner until your arm feels relatively comfortable.

6) Lift on the lever until the number displayed on the voltmeter is equal to the number the tester wants you to achieve.

7) Keep that number displayed for sixty seconds.

8) Rest for five minutes.

9) Repeat steps one through eight for three more runs.

APPENDIX C

Table C-I

Average Data for the Static Exercise.

Force (lbs.)	Time (sec.)	ΔIEMG (μ volts)	Vector Impulse (lbs.-sec.)	Scalar Impulse (lbs.-sec.)
0.5	10	43	28	126
	20	44	98	204
	30	40	163	300
	40	42	209	370
	50	42	288	466
	60	44	330	514
5.0	10	92	107	135
	20	93	186	235
	30	94	260	331
	40	91	330	435
	50	90	409	538
	60	97	472	624
15.0	10	196	201	294
	20	200	374	494
	30	209	509	668
	40	200	668	899
	50	206	817	1060
	60	218	985	1260

Table C-II

Average Data for the Dynamic Exercise.

Force = 0.5 lbs.

Exercise Cycle	AIEMG (μ volts)	Vector Impulse (lbs.-sec.)	Scalar Impulse (lbs.-sec.)
1	211	37	32
2	199	51	52
3	165	60	68
4	184	74	85
5	174	86	108
6	181	102	124
7	192	116	139
8	175	130	165
9	166	149	187
10	175	163	204
11	156	179	225
12	158	193	242
13	155	209	262
14	174	221	283
15	151	240	300
16	160	249	324
17	166	265	347
18	168	281	365
19	169	293	379
20	182	309	392
21	162	323	414
22	149	339	434
23	152	351	452
24	147	365	474
25	150	379	480

Table C-III

Average Data for the Dynamic Exercise

Force = 5.0 lbs.

Exercise Cycle	ΔIEMG (μ volts)	Vector Impulse (lbs.-sec.)	Scalar Impulse (lbs.-sec.)
1	215	42	34
2	207	68	72
3	191	89	98
4	176	112	131
5	177	131	153
6	181	152	183
7	174	171	205
8	179	190	234
9	181	211	156
10	162	227	278
11	181	246	301
12	167	265	335
13	184	289	354
14	185	305	375
15	178	321	402
16	160	340	430
17	154	366	462
18	162	380	481
19	170	400	509
20	152	420	531
21	162	436	556
22	165	450	588
23	157	474	612
24	163	494	648
25	162	527	676

Table C-IV

Average Data for the Dynamic Exercise

Force = 15.0 lbs.

Exercise Cycle	ΔIEMG (μ volts)	Vector Impulse (lbs.-sec.)	Scalar Impulse (lbs.-sec.)
1	397	63	63
2	412	105	115
3	292	145	169
4	300	187	229
5	294	224	277
6	298	261	330
7	342	294	386
8	322	338	433
9	312	375	488
10	324	412	536
11	326	449	587
12	308	484	635
13	316	521	688
14	300	561	746
15	318	599	797
16	326	632	846
17	316	665	902
18	351	712	952
19	304	745	998
20	311	773	1050
21	310	808	1100
22	310	838	1150
23	282	878	1200
24	308	916	1250
25	324	944	1300

APPENDIX D

Calculating the Forces and Torques on the Hand.

$T_1=F_1R_1$

F_1=The Force on the edge of the Pulley

R_1=The Radius of the Pulley

$T_2=F_2R_2$

F_2=The Weight of the Hand plus the Forearm

R_2=The Moment Arm of the Hand plus the Forearm

$T_3=T_1+T_2=F_3R_3$

F_3=The Force Exerted by the Hand on the Handgrip Assembly

R_3=The Distance from the Elbow to the Handgrip Assembly

$$F_3=\frac{F_1R_1+F_2R_2}{R_3}$$

APPENDIX E

Table E-I

Forces and Torques Applied Against and By the Hand.

$R_1 = 6''$

Subject	F_1 (lbs.)	T_1 (in.lbs.)	F_2 (lbs.)	R_2 (in.)	T_2 (in.lbs.)	T_3 (in.lbs.)	R_3 (in.)	F_3 (lbs.)
	0.5	3.0				27.1		1.9
1	5.0	30.0	3.5	6.8	24.1	54.1	14.1	3.8
	15.0	90.0				114.1		8.1
	16.0	96.0				120.1		8.5
	0.5	33.0				26.9		1.9
2	5.0	30.0	3.5	6.8	23.9	53.9	14.1	3.8
	15.0	90.0				113.9		8.1
	17.0	102.0				125.9		11.3
	0.5	3.0				25.9		1.9
3	5.0	30.0	3.5	6.5	22.9	52.9	13.5	3.9
	15.0	90.0				112.9		8.4
	21.6	129.6				144.6		11.3
	0.5	3.0				26.8		2.0
4	5.0	30.0	3.7	6.4	23.8	53.8	13.3	4.0
	15.0	90.0				113.8		8.6
	22.8	136.8				170.6		12.1
	0.5	3.0				26.5		2.7
5	5.0	30.0	3.8	6.1	23.5	53.5	12.8	4.2
	15.0	90.0				113.5		8.9
	22.0	132.0				155.5		12.2
	0.5	3.0				24.6		1.9
6	5.0	30.0	3.5	6.1	21.6	51.6	12.8	4.0
	15.0	90.0				111.6		8.8
	27.0	162.0				183.6		14.4
Avg.								2.0
								4.0
								8.5
								[illegible]

APPENDIX F

Table F-I

SUBJECT DATA

Subject	Age	Ht. (in.)	Wt. (lbs.)	Max. Str. (lbs.)	40% Max. Str. (lbs.)	Grip Str. (lbs.)	Distance From Hand to Elbow (in.)	Wrist Circ. (in.)	Forearm Circ. (in.)	Weight * of Hand and Forearm (lbs.)
1	19	73	177	40.0	16.0	88.0	14.1	6.75	10.68	3.54
2	19	73	165	42.5	17.0	100.4	14.1	6.63	10.94	3.52
3	20	72	170	54.1	21.6	104.2	13.5	6.82	10.36	3.52
4	20	72	175	57.0	22.8	99.0	13.3	6.88	11.00	3.72
5	21	70	155	57.4	22.9	111.0	12.8	7.00	11.20	3.84
6	23	70	165	67.5	27.0	110.0	12.8	6.75	10.63	3.52

* The equation for calculating the weight of the hand plus the forearm is on page 59.

The equation for calculating the weight of the hand and forearm is:

$$\text{Weight, lbs.} = (0.738)\,(\text{Wrist Circumference, in.}) + 0.274\,(\text{Forearm Circumference, in.}) - 4.37$$

[3]

VITA

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Master of Science

Thesis: A Comparison of the Force Platform Output and the Electromyogram as Measures of Muscular Fatigue

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A COMPARISON OF THE FORCE PLATFORM OUTPUT AND THE ELECTROMYOGRAM AS MEASURES OF MUSCULAR FATIGUE

by

CARL T. NELSON

BSME, Worcester Polytechnic Institute, Worcester, Massachusetts, 1971

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1973

ABSTRACT

The purpose of this thesis was to investigate fatigue measurements through the use of the force platform and surface electromyogram.

Six male subjects performed a dynamic (isotonic) exercise and a static (isometric) exercise. The exercise primarily used the biceps brachii muscle. As the subject performed the exercise, the electrical activity of the muscle increased, and a force was exerted on the force platform.

Investigated was the vector impulse (the area under the resultant force-time curve), the scalar impulse (the area under the absolute values of the sum of the forces, along the three planes, -time curve) and the ΔIEMG (the moving time average of the EMG with respect to a zero-force baseline).

Results indicated that the vector and scalar impulse of the force platform always increased linearly as the exercise was performed. The conclusions were the same whether scalar or vector impulses are used for this plain motion task. The ΔIEMG remained constant throughout an exercise if the muscle did not measurably fatigue, but increased if the muscle did fatigue.