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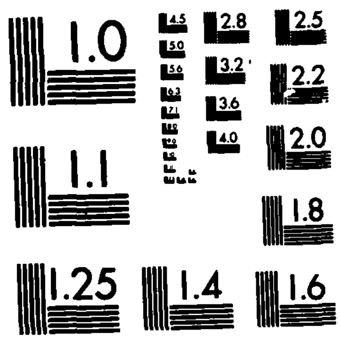

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COMPARATIVE ANALYSIS OF POSITIVE AND NEGATIVE LATERAL ACCELERATION ON ISOMETRIC FATIGUE IN THE FOREARM

Robert A. Johnson
Capt USAF

AFIT/GSO/EE/82D-1

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Wright-Patterson Air Force Base, Ohio

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The AFTI/F-16 is a six degree of freedom aircraft capable of lateral acceleration. The purpose of this investigation was to determine the difference produced by ±Gy acceleration on forearm fatigue. The Dynamic Environment Simulator (DES) at the USAF Aerospace Medical Research Laboratory was used to create a lateral acceleration environment. The DES and surface electromyogram (EMG) techniques were used to measure any differences in isometric strength, endurance, and recovery from

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) fatigue observed in the handgrip muscles of the right forearm under ±2Gy acceleration. Also, quantification of the fatigue produced by ±2Gy acceleration was investigated.

The results of this study indicate that isometric performance was degraded under -2Gy acceleration. A reasonable explanation for the degradation was radial nerve entrapment during -2Gy acceleration caused by the restraint system being used.

If head and shoulder restraints are used during lateral maneuvers the results of this study indicate their presence is a factor in pilot performance with +2Gy being superior to -2Gy. This study also suggested a way of analyzing the EMG signals that may permit quantification of isometric fatigue under lateral acceleration

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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

Robert A. Johnson, B.S.
Capt USAF
Graduate Space Operations

December 1982

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Preface

I would like to thank my wife June and our two children Kristen and Robbie for their love and support during my thesis effort. Also, my parents Robert and Helen Johnson and my wife's parents George (deceased) and Fern Stein deserve recognition for their love and guidance. I appreciate the interest and advice given by the three committee members which include my advisor Dr. Matthew Kabrisky, Dr. Lynn E. Wolaver and Major Joseph Coleman. I am very grateful to the people of the Air Force Aerospace Medical Research Laboratory for providing equipment, work space, and advice. In particular, I would like to thank my sponsor Dr. Ralph Luciani for his assistance in the experimental design and interpretation of results. My thanks also go to Mr. Robert Van Patten, Dr. Dana Rogers, Mr. John Frazier, and Mr. Tom Shriver for making the centrifuge schedule amenable to mine. I deeply appreciate the technical support provided by Mr. Dave Ratino, MSgt Greg Bathgate, and SSgt Ken Riggs. Also, I appreciate the advice of Dr. Daniel Repperger, and the programming support of Mr. Marvin Roarke, Ms Barbara O'Lear, and Mr. Bud Gould. Finally, I would like to thank Ms Karen Hudson and Ms Rachel Birtle for their assistance; Karen provided invaluable assistance on the statistical analysis and Rachel did an excellent job of typing and retyping my thesis. Thanks again to everyone involved in this effort.

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Abstract

The USAF Advanced Fighter Technology Integration F-16 is a six degree of freedom aircraft capable of lateral acceleration as well as conventional modes of flight. The purpose of this investigation was to determine the difference, if any, produced by positive and negative lateral (Gy) acceleration on forearm fatigue. The Dynamic Environment Simulator (DES) at the USAF Aerospace Medical Research Laboratory was used to create a lateral acceleration environment. The DES and surface electromyogram (EMG) techniques were used to measure any differences in isometric strength, endurance, and recovery from fatigue observed in the handgrip muscles of the right forearm under ±2Gy acceleration. Also, quantification of the fatigue produced by ±2 Gy acceleration was investigated.

The lateral acceleration environment for this experiment was created by the DES. The experiment was designed to measure the forearm strength, endurance, recovery from fatigue, and surface electrical activity of six subjects under ±2Gy acceleration. The subjects were volunteers and permanent members of the Aerospace Medical Research Laboratory Centrifuge Panel. The device used to measure isometric strength and endurance was the handgrip dynamometer.

The results of this study indicate that isometric performance was degraded under -2 Gy acceleration compared to +2 Gy acceleration. A reasonable explanation for the degradation was radial nerve entrapment during -2 Gy acceleration caused by the restraint system being used. The percentage drop in center frequency of the EMG signal was determined unreliable as a fatigue index und[illegible] [illegible]ate[illegible] acceleration.

If head and shoulder restraints are used during lateral maneuvers the results of this study indicate their presence is a factor in pilot performance with +2 Gy (away from right forearm) being superior to -2 Gy (toward right forearm). This study suggested a way of analyzing the EMG signals that may permit quantification of isometric fatigue under lateral acceleration.

COMPARATIVE ANALYSIS OF POSITIVE AND NEGATIVE LATERAL ACCELERATION ON ISOMETRIC FATIGUE IN THE FOREARM

I. Introduction

The advent of the USAF Advanced Fighter Technology Integration F-16 (AFTI/F-16) has introduced a new dimension to aircraft acceleration. The AFTI/F-16 has the ability to decouple the translational and rotational degrees of freedom and to control each one independently. The result is a six degrees of freedom (6DOF) aircraft capable of lateral acceleration as well as conventional modes of flight.

Linear motion in the lateral axis may be to the left (-Gy) or to the right (+Gy). The resulting inertial force will displace the pilot to his right for -Gy and to his left for +Gy.

When a pilot undergoes lateral acceleration he must exert isometric muscular contractions to control his body. The basic task of monitoring the heads-up display (HUD) becomes fatiguing when the pilot is exposed to ±Gy acceleration. Tracking will become more tiresome when force is suddenly added to or subtracted from the side-stick controller following a lateral maneuver.

A prototype of the AFTI/F-16 was flown in 1980. Although modest levels of lateral acceleration were experienced, around ±1Gy, it was determined that conventional restraint systems and physiological effects needed to be re-examined. The Air Force Aerospace Medical Research Laboratory (AFAMRL), in conjunction with the Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL), has undertaken a program to evaluate new restraint concepts, physiological parameters, and the biodynamic effects on the use of rudders and side-stick controllers for implementation of Gy commands.

The forearm, or more specifically, the handgrip muscles of the forearm were chosen to model the physiological parameter of fatigue in this study. The purpose of this investigation was to determine the difference, if any, produced by negative Gy acceleration and positive Gy acceleration on forearm fatigue. Quantification of the fatigue produced by either the positive or negative Gy environment will be accomplished by analyzing the electrical activity of the forearm muscles with the Surface Electromyogram (EMG). Knowledge of forearm fatigue in the lateral acceleration environment may prove useful in the design and placement of aircraft controls. Fighter tactics might even be affected if it can be shown that forearm fatigue is more pronounced when accelerating to one side or the other.

Background

This is the second AFTI/F-16 study to utilize the surface EMG in evaluating fatigue and recovery of endurance under lateral acceleration. The first study used the head-righting muscles of the neck as a model for fatigue. The results of the first study indicated that neck muscle fatigue increases as the lateral G load increases. An objective of the neck muscle study was to quantify neck muscle fatigue during lateral acceleration environments by analyzing the surface EMG signals of the muscles being recorded (Luciani, 3).

The surface EMG signal reflects the electrical activity of the motor units in the underlying muscle (12). A typical signal is shown in Figure

1. Piper (16) first observed a relationship between the amplitude and frequency components of the surface EMG signal. It was noted that during fatiguing isometric exercise the amplitude of the signal increased while the frequency decreased. The amplitude of the EMG signal is a function of the number of motor units recruited and the frequency of their discharge. The frequency of the EMG signal is a function of the Motor Unit Action Potential (MUAP) duration, the placement of the surface electrodes, the degree of motor unit synchronization, and the conduction velocity of the Action Potentials on the sarcolemma (12).

A reliable index of isometric muscle fatigue may have been developed over the years by the efforts of Petrofsky (12,13,14) and others by using Fourier analysis of the EMG waveform. The center frequency of the EMG power spectra, derived by Fourier analysis, is defined as that frequency which divides the power spectra in half. During fatiguing isometric contractions there is an increase in the low frequency components and a decrease in the high frequency components of the EMG. The result is a drop in center frequency; this drop is reported to be about 24% when comparing fresh muscle to fatigued muscle (12).

The time, or interval required to recover from fatigue is another important consideration since the lateral maneuvers encountered by a pilot will probably be repetitive. Although it requires approximately 24 hours for total endurance to recover from fatiguing exercise, a large percentage (around 80%) of endurance is recovered within 10 to 20 minutes (4). If the isometric contraction is sub-maximal the recovery time is even less (11).

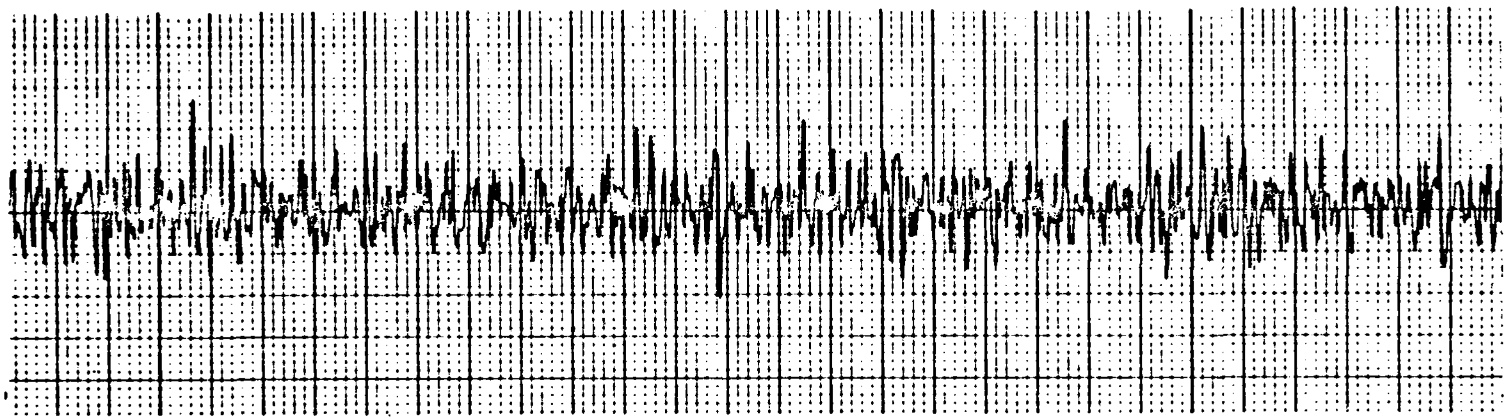

Figure 1. Surface EMG Signal

Objectives

The Dynamic Environment Simulator (DES) at the USAF Aerospace Medical Research Laboratory was used to create a lateral acceleration environment. The DES and surface electromyogram (EMG) techniques will be used to study the following objectives:

(1) To measure any differences in the strength developed by the handgrip muscles of the forearm under ± 2 Gy acceleration;

(2) To measure any differences in endurance, heart rate, percentage drop in center frequency, and peak center frequency, caused by ± 2 Gy acceleration. These measurements will be done by taking a nearly unfatigued muscle to fatigue;

(3) To measure any differences in the muscles ability to recover from fatigue caused by ± 2 Gy acceleration; and

(4) To quantify the fatigue produced by isometric contractions of the handgrip muscles of the forearm under positive and negative lateral acceleration

This investigation is a pilot study on the effects of lateral acceleration. Only one G level and one tension level will be examined. The results of this study will be a foundation on which a more thorough examination of various G levels and tensions can be conducted.

II. Materials and Methods

The Dynamic Environment Simulator (DES)

The lateral acceleration environment for this experiment was created by the DES. The DES is a human centrifuge capable of producing sustained acceleration of up to 20G. The DES is located at the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.

The main arm of the DES (Fig 2) has a radius of rotation of approximately 20 feet. The motion of the main arm produces sustained accelerations. The DES is capable of producing accelerations in the longitudinal, vertical, and lateral axes. It can also simulate two-axis and three-axis combined accelerations. The multiple axis accelerations are made possible by the motion of the main arm, the fork supporting the gondola, and the gondola itself. The fork axis is parallel to the ground and perpendicular to the main arm axis, which is vertical. The gondola axis is always perpendicular to the fork axis but can be made parallel to the floor or main arm axis by rotating the fork about its own axis. Although the direction of motion of the main arm is not reversible, the fork and gondola axis may be continuously rotated or oscillated in such a manner to produce either positive or negative accelerations along each of the physiological axes of the body.

The human payload platform for the DES is the gondola. The basic gondola structure consists of two hemispherical shells mounted on the main ring. The gondola was outfitted with the ACES II seat (Figure 3), shoulder and head restraints, rudder pedals, a hand-grip dynamometer where the side-stick controller is usually located, and a video display monitor (CRT). The shoulder and head restraints were installed to help

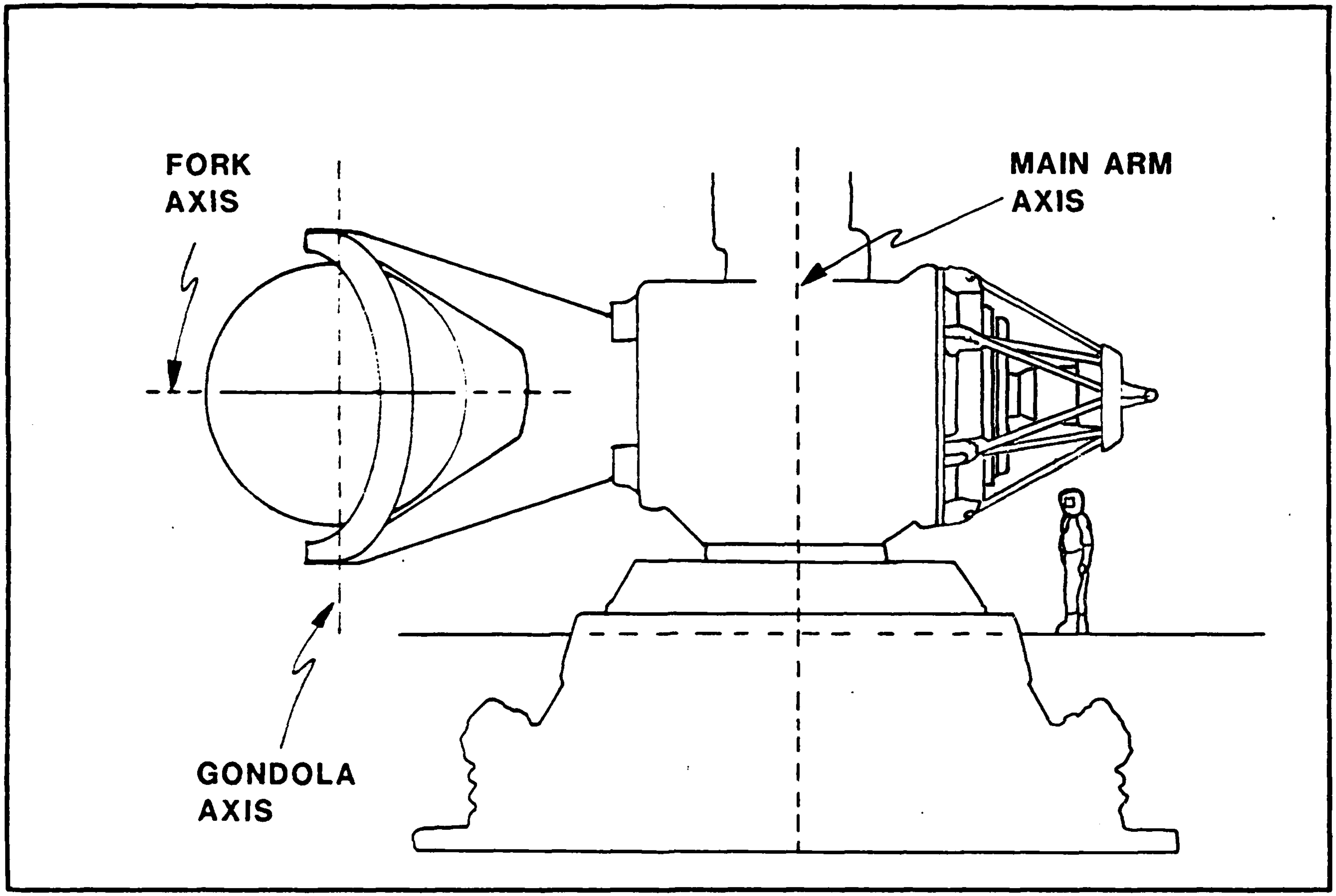

Figure 2. Dynamic Environment Simulator (DES)

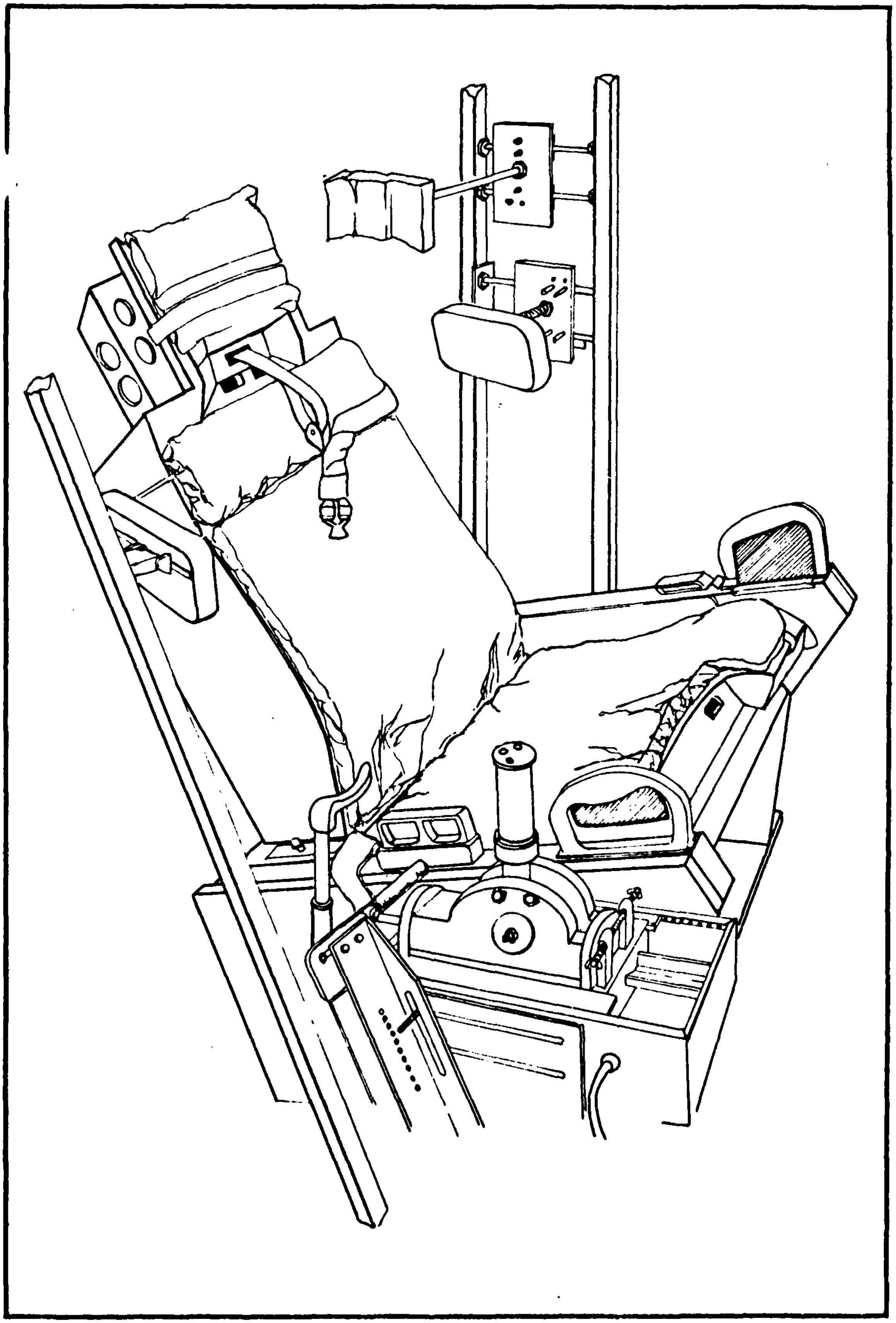

Figure 3. ACES II Seat with Handgrip Dynamometer

isolate the isometric fatigue experienced by the handgrip muscles of the forearm. It has been reported by Luciani (7) that significant neck and torso muscle fatigue is produced in the sustained lateral acceleration environment. The CRT was used to provide visual feedback to the subject on the amount of tension being applied to the handgrip dynamometer.

Experimental Design

This experiment was designed to measure the following parameters; forearm strength, endurance, and recovery from fatigue at ± 2Gy.

The isometric strength of the forearm has a wide variance among individuals. The average strength of the handgrip muscles is about 109 lbs in men and about 64 lbs in women (11). A term frequently used when referring to isometric strength is maximum voluntary contraction, or MVC. An MVC occurs when an individual exerts his maximum strength for a brief contraction, generally three seconds or less. MVC's are rarely exerted when flying an airplane; however, measurement of MVC is necessary for assessing isometric endurance.

Isometric strength measurements were obtained at the beginning of each data day. The subjects were seated in the gondola and restrained. The head and shoulder restraints were positioned so that the subject felt comfortable when he leaned against them. The restraints were placed on either the right or the left side depending on the $\pm$Gy exposure. The subjects positioned their feet parallel to one another on the rudder pedals with a knee angle of approximately 115°. The dynamometer was positioned so that the subject sat with his arm held dependent on the armrest and his elbow set at an angle of approximately 118°. With the subject in place he was accelerated to a baseline of +1.5 Gz. Prior to the first strength measurement the subject was accelerated to the peak G level, the rate of onset was 0.5 G/sec. Approximately three seconds after reaching the peak G level the subject saw a prompt on the CRT reading "SQUEEZE". He then performed an MVC for no more than three seconds, and remained at the peak G level for four more seconds before automatically returning to baseline. The subject rested at baseline for three minutes. This procedure was repeated twice to obtain three MVC measurements. The highest MVC was chosen as the subject's maximum isometric strength. The centrifuge was slowly stopped after the third contraction and the subject rested for ten minutes at +1Gz prior to the endurance measurement phase.

Shortly before the ten-minute rest period expired, the centrifuge was accelerated to the baseline G level in preparation for the isometric endurance measurements. Before being accelerated to the specified G exposure the subject was instructed to maintain a target tension upon receiving the "SQUEEZE" prompt. The target tension was chosen by taking 70% of that day's MVC. At the end of the ten-minute rest period the subject was accelerated to the peak G exposure. Approximately three seconds after reaching the peak G exposure the subject received the "SQUEEZE" prompt, he then maintained the target tension by squeezing the dynamometer and watching the CRT. The visual feedback was presented to him via a digital readout in pounds of tension. The tension was allowed to oscillate within 4% of the target tension. The subject maintained the target tension to fatigue, at which time the centrifuge returned to baseline.

The isometric contractions sustained while maneuvering an airplane would not, in general, cause a muscle group to completely fatigue. Jet pilots more typically exert a series of contractions at different tensions with variable rest periods, or intervals (12). The interval required for a fully fatigued or a partially fatigued muscle to recover strength and endurance is referred to as the rest interval. One, three, and ten-minute rest intervals were chosen for this experiment. The rest intervals were selected at random and after the specified time the subject was once again accelerated to the peak G level where he performed a 70% MVC contraction to fatigue.

Surface EMG signals were recorded during the fatiguing contractions to evaluate fatigue by looking at center frequency responses. The EMG electrode signals from the subject were amplified in the gondola and relayed to the medical monitor room for data recording. Amplifier settings remained constant during both fatiguing contractions. Standard ECG electrodes were also employed to monitor the heart rate and rhythm of each subject. The heart rate was also recorded and saved for analysis.

The acceleration profile for a typical data day can be seen in Figure 4 and Table I shows the experimental matrix as it was randomized for this set of experiments.

Handgrip Dynamometer

The handgrip dynamometer as shown in Figure 3 is the instrument used for determining the tension exerted by the handgrip muscles of the forearm. The handgrip dynamometer, or squeeze stick, was designed by government employees at the AFAMRL and instrumented with strain gauges by the Raytheon Corporation. The stick had to be built because there was no readily available commercial squeeze stick.

Four strain gauges were connected as a Wheatstone brige on a strain

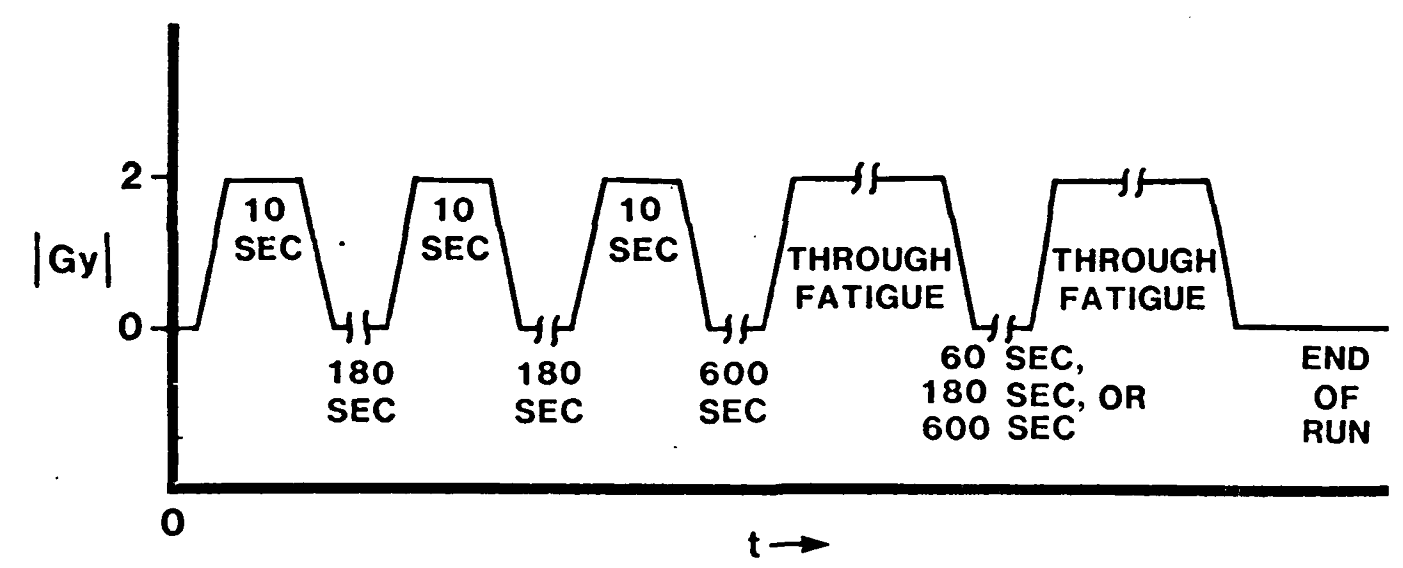

Figure 4. Daily ±2 Gy Acceleration Profile

TABLE I. Randomized Experimental Matrix

CONDITION	2Gy	INTER-CONTRACTION TIME (SEC)
1	POSITIVE	60
2	NEGATIVE	60
3	POSITIVE	180
4	NEGATIVE	180
5	POSITIVE	600
6	NEGATIVE	600

SUBJECT NUMBER	CONDITION					
1	2	1	4	5	3	6
2	4	6	5	1	3	2
3	3	6	1	4	5	2
4	6	3	4	2	5	1
5	1	6	2	3	4	5
6	3	5	1	4	2	6

sensing beam. The strain gauges, model CEA-06-125UT-350, were produced by Micro-Measurements. The exact configuration of the strain gauges is illustrated in Figure 5. This configuration results in accurate, consistent tension measurements whether tension is applied at the top, middle, or bottom of the squeeze stick. The results of a typical calibration test are shown in Table II. The output of the squeeze stick was amplfied in the gondola using a SRL strain gauge amplifier and transmitted via slip rings to the DES medical monitor and control room.

Subjects

Six male Air Force officers were chosen as subjects for this experiment. They are members of the AFAMRL Centrifuge Panel, a permanent volunteer group for on-going experimentation, who are well adapted to centrifuge acceleration.

All subjects had passed a flight physical examination as part of their panel membership; however, the subjects were also given a medical examination before and after each data day. The subjects were never required to participate in this experiment more than once in a 24-hour period. Typically the subjects participated only once per week. Their ages ranged from 23 to 27 years (mean ±SD, 24 ±2 yr), and they weighed from 164 - 197 lbs (177 ±13 lbs). They ranged from 67 to 73 inches in height. The personal equipment worn by the subjects included the anti-G suit, communications equipment, the standard USAF flight suit and gloves.

No flying skills were required to participate in this experiment; however, isometic strength and endurance training was conducted in a static environment prior to the actual experiments. The purpose of the isometric strength training was to bring the subject to his peak

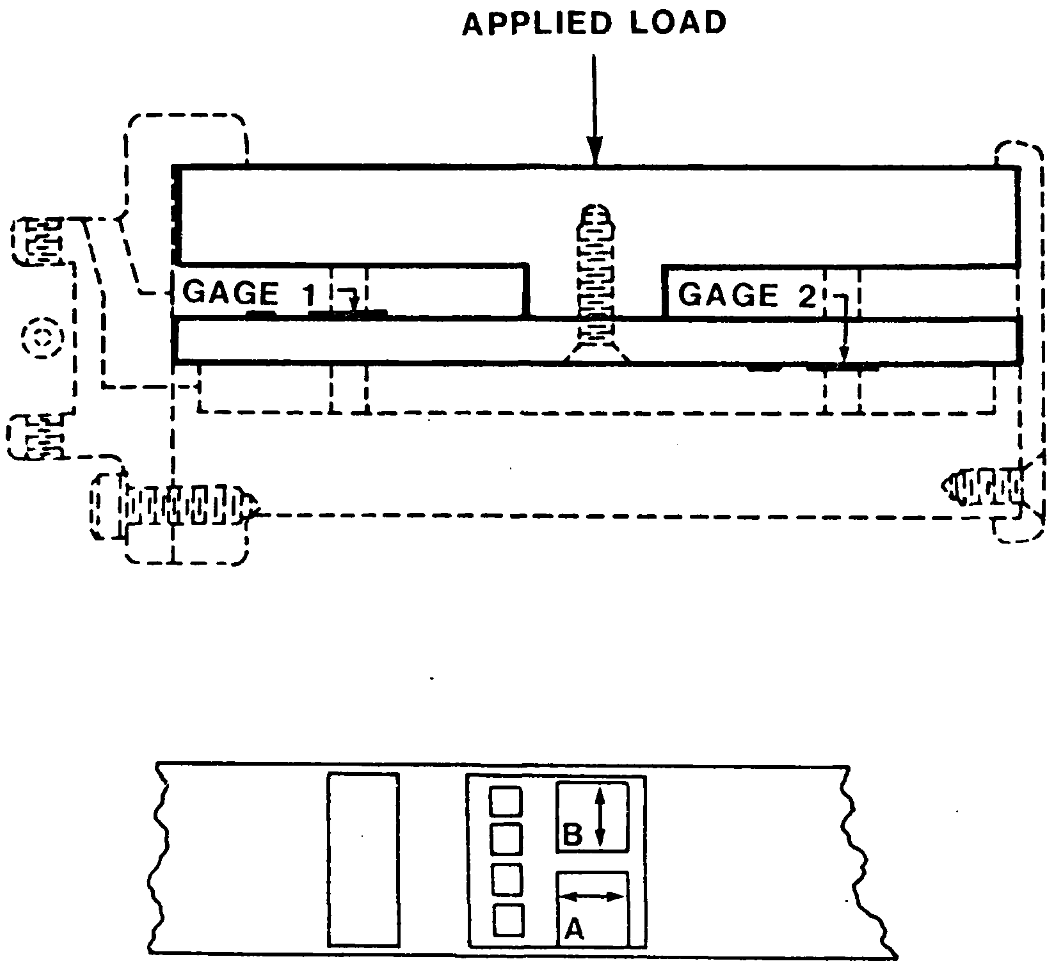

Figure 5. Strain Gage Configuration

TABLE II. Strain Gage Calibration Results

FORCE LBS	BOTTOM volts dc	MIDDLE volts dc	TOP volts dc
5	0.04	0.04	0.04
10	0.09	0.09	0.09
15	0.14	0.14	0.13
20	0.18	0.19	0.18
25	0.23	0.24	0.23
30	0.26	0.26	0.27
35	0.31	0.31	0.32
40	0.36	0.36	0.36
45	0.40	0.41	0.41

STRAIN GAGE AMP GAIN = 200

GAGE FACTOR : 1.00

isometric strength before the experiment and also to reduce the variation in strength from day to day. Most studies have shown that training will not increase isometric strength by more than 10%; however, it will enable the individual to exert a maximal effort repeatedly (11). The purpose of the isometric endurance training was to reduce the daily variation in endurance. The training was carried out in a chair equipped with the handgrip dynamometer. The subjects were asked to perform three MVC's and two fatiguing contractions a day; they accomplished this once a week for four weeks prior to the actual experiment.

Signal Acquisition and Processing

The subjects' right forearms were instrumented with "Con-Med" pre-pasted surface electrodes and EMG cables. The surface EMG signal acquired was the combined result of the handgrip muscles of the forearm; therefore, the electrodes were placed over the middle third of the forearm muscle mass (Figure 6). This distance varied from 2.8 to 3.1 inches among the six subjects. Prior to placement of the electrodes, the skin around the placement points was gently abraded using sandpaper and wiped with acetone. The reference electrode was placed between the primary electrodes on the opposite side of the forearm (Figure 6). Once the electrodes were in place all cables were attached and checked for <5K ohms resistance.

The surface EMG signal was amplified in the gondola using SRL Biopotential amplifiers and transmitted via slip rings to the DES control and medical monitor room. The instrumentation used to collect and analyze the surface EMG signal is shown in Figure 7. A Honeywell Model 5600 analog tape recorder (B) was used to record the signal. The FM

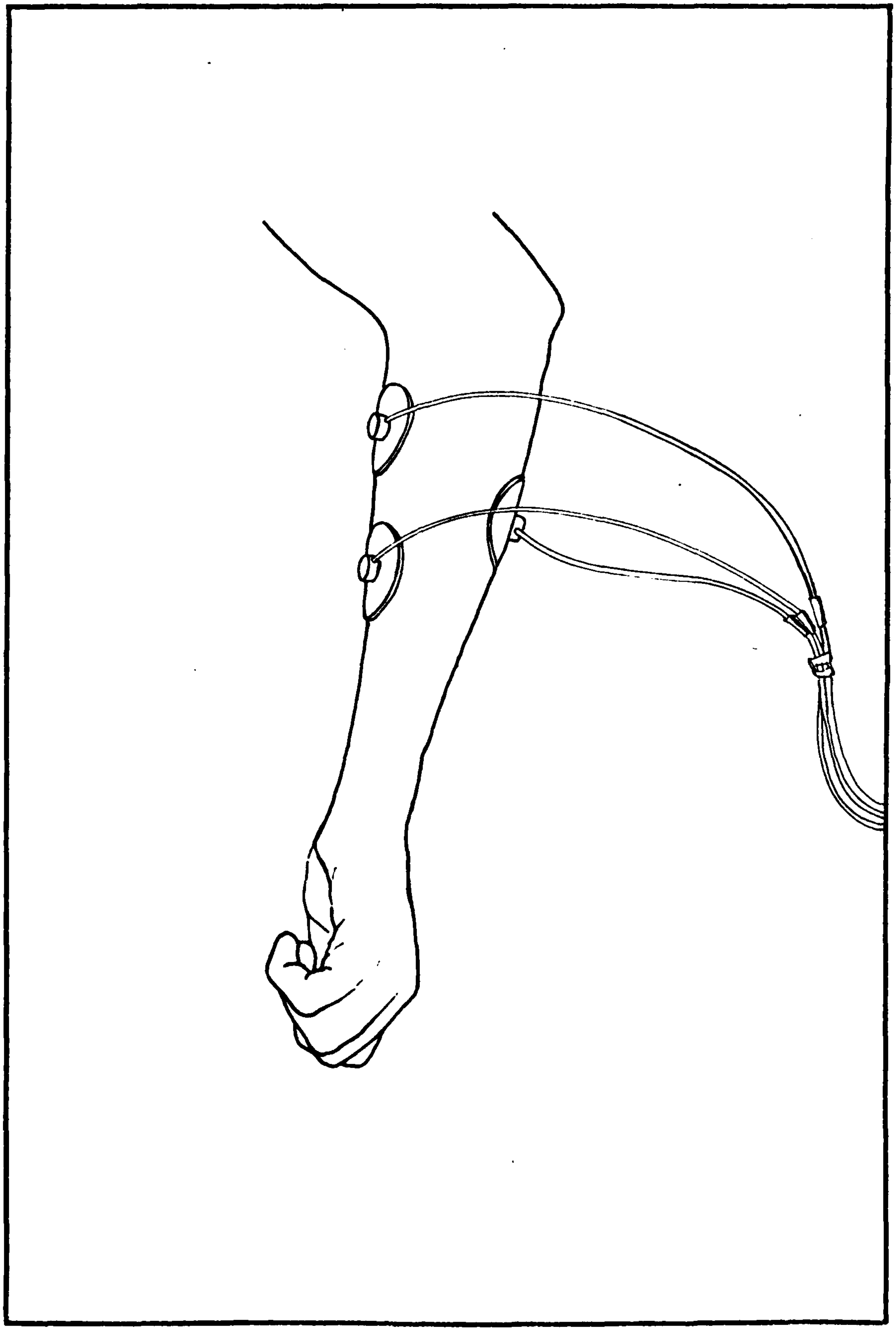

Figure 6. Forearm Electrode Placement

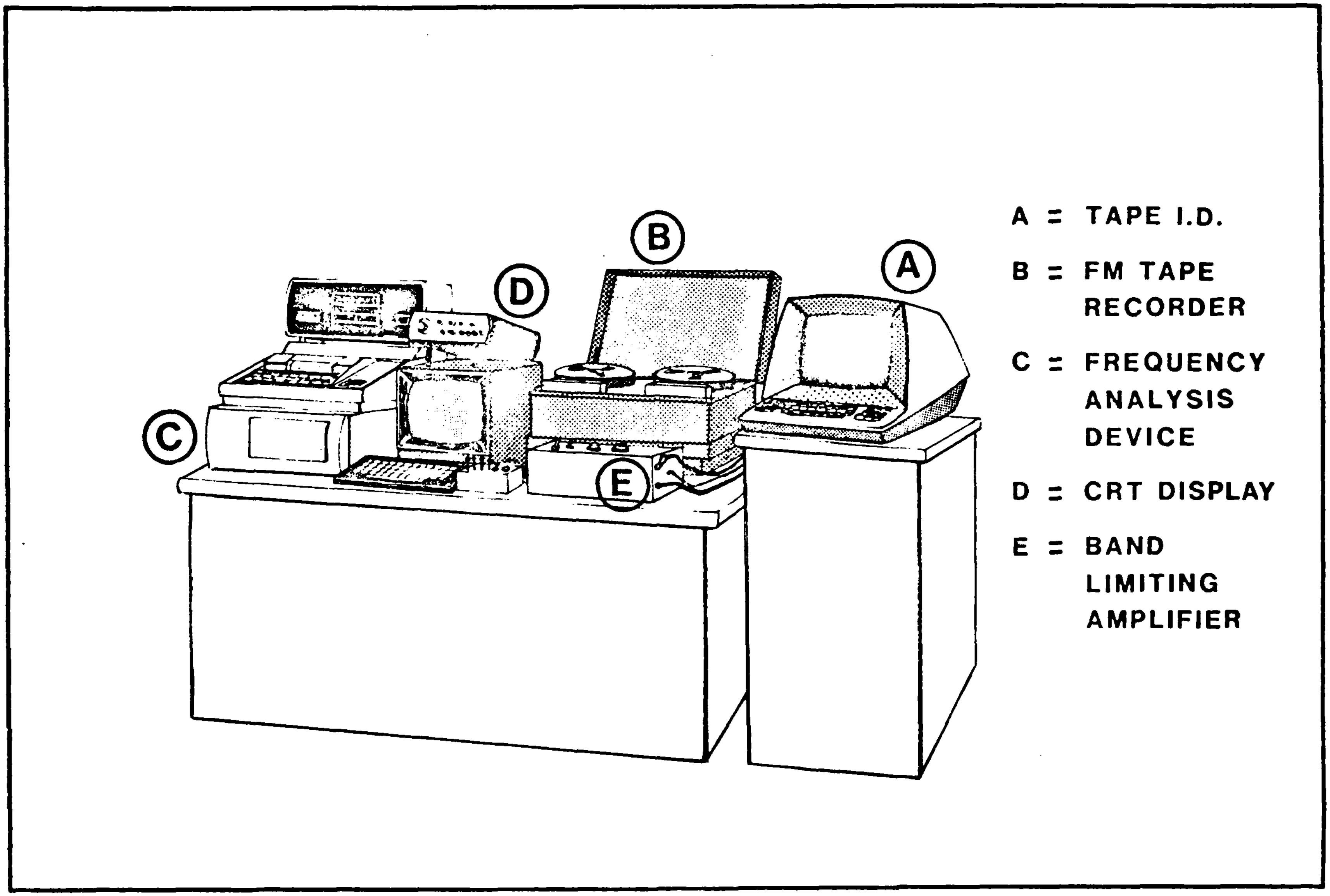

Figure 7. Instrumentation for EMG Recording and Analysis

recording mode provided a frequency response of 0-2.5 KHz at a recording speed of 7.5 inches per second. The Frequency Analysis Device (FAD) (C) was designed and built by Systems Research Laboratory (8). The software programming was done by government personnel at the Aeronautical Systems Division (ASD) Computer Center. An article describing the FAD has been reproduced with the author's permission and appears as the Appendix. The FAD enables the investigator to sample a surface EMG signal at a fixed rate of 1000 samples per second. The FAD will automatically collect, window, store in RAM, and calculate the spectrum of 58 data burst using an in-place Fast-Fourier Transform (FFT) algorithm. A data burst is made up of 128 data samples. The FAD operator can choose the number of data bursts to collect each second from one to eight. A rate of one 128 sample data burst per second was chosen to analyze the data from this experiment because of the amount of data collected on each subject in a given data day. The spectra, RMS histroy, and centroid frequency history may be displayed on the CRT (D). Uploading to another computer to accomplish high speed graphics is possible through a RS-232 serial port.

The tape identification was recorded on a separate channel and gives the date, time of day, acceleration parameters, study conditions, and subject name. The tape identification data is displayed on a Televideo Inc. Model 910 terminal (A) and is used to coordinate and synchronize the data stored on analog tape, with a resolution of one second. The maximum level of the amplified EMG did not exceed 1.8 volts rms, the maximum allowed by the tape recorder specifications.

The output of the tape recorder and the handgrip dynamometer was displayed on a multi-channel strip chart while the subject was accomplishing the muscular contractions. The strip chart recording provided an accurate means to measure the subject's endurance time.

Prior to entering the FAD the EMG signal passes through a forth order Butterworth low pass filter (E). The filter has a cutoff frequency of 375Hz and selectable amplification factors of 1, 2, 3 and 4. The frequency response of the bandlimited amplifier is flat to 250 Hz, the highest frequency normally of interest in an EMG (11). The primary job of the bandlimited amplifier is to prevent aliasing effects in the Fourier Transform calculations. Precautions were also taken to remove extraneous low frequency signals. The software contains a psuedo filter and DC through 8 Hz spectral components are never used in rms or centroid calculations even though they may appear in the spectral plots.

III Results

A separate ANOVA was conducted for the strength, endurance time, peak heart rates, drop in center frequency from the peak center frequency to the end of the contraction (percentage drop), and peak center frequencies on data obtained from each subject during the first fatiguing contraction for both the positive and negative 2 Gy directions. In addition, separate analyses were performed on all response variables above excluding strength and with the addition of percent recovery for data obtained during the second fatiguing contraction.

First Contraction Data

The main factor of interest here is direction. The hypothesis that direction (positive and negative 2 Gy) has no effect on strength, endurance, peak heart rate, drop in center frequency, and peak center frequency was tested.

Strength (lbs). The ANOVA indicates that there is evidence to reject the above hypothesis (p value = .0433) and conclude that direction has a significant effect on strength in the ±2 Gy environment. Table III indicates that there tends to be more strength in the + 2 Gy direction.

Endurance Time (Seconds). There is insufficient evidence to conclude that first contraction endurance time is significantly affected by direction (p value > .50). See Table III for means and standard deviations.

Peak Heart Rate (BPM). There is insufficient evidence to conclude that heart rate is significantly affected by direction (p value > .50). See Table III for means and standard deviations.

Drop in Center Frequency (Percentage). The analysis indicates that there is evidence to reject the above hypothesis (p value = .0012) and conclude that direction has a signficant effect on the drop in center frequency in the ±2 Gy environment. Table III indicates that there tends to be a greater drop in center frequency in the + 2 Gy direction.

Peak Center Frequency (Hz). Again there is insufficient evidence to reject the hypothesis (p value > .50). See Table III for means and standard deviations.

Second Contraction Data

In addition to the direction factor, rest interval time became of major interest here. An additional hypothesis that rest interval times have no effect on endurance times, percent recovery, peak heart rate, and peak center frequencies was tested also.

Endurance Time (Seconds). As in the first contraction there is insufficient evidence to conclude that endurance time is affected by direction (p value = .3660); however, there is sufficient evidence to conclude that rest interval time significantly affects second contraction endurance time (p value = .0002). Below are the results of Newman Keuls Multiple Comparison procedure conducted at the 0.10 level of significance.

Rest Interval	1 min	3 min	10 min
Mean	26.4	33.4	41.5

* Means that are underlined are not significantly different.

Conclude that all means are significantly different. Table IV contains the means and standard deviations for both positive and negative 2 Gy.

Percent Recovery. There seems to be sufficient evidence that rest

TABLE III. First Fatiguing Contraction Results

VARIABLE	POSITIVE	NEGATIVE
STRENGTH (LBS)		
MEAN	111.2	102.9
STD. DEV.	14.4	12.1
ENDURANCE (SEC)		
MEAN	45.9	47.9
STD. DEV.	13.9	18.0
PEAK HEART RATE (BPM)		
MEAN	124.1	126.1
STD. DEV.	21.3	31.4
DROP IN CENTER FREQUENCY (%)		
MEAN	34.2	23.5
STD. DEV.	8.0	11.1
PEAK CENTER FREQUENCY (HZ)		
MEAN	110.8	109.2
STD. DEV.	17.5	19.4

TABLE IV. Second Fatiguing Contraction Results

VARIABLE	REST INTERVAL (MIN)		POSITIVE	NEGATIVE
ENDURANCE (SEC)	1	MEAN	26.2	26.7
		STD. DEV.	8.2	4.3
	3	MEAN	32.2	34.7
		STD. DEV.	14.6	10.9
	10	MEAN	39.5	43.5
		STD. DEV.	9.0	11.8
PERCENT RECOVERY (%)	1	MEAN	54.5	67.7
		STD. DEV.	6.9	17.7
	3	MEAN	70.2	70.2
		STD. DEV.	19.8	13.7
	10	MEAN	89.0	88.5
		STD. DEV.	6.9	10.0
PEAK HEART RATE (BPM)	1	MEAN	127.0	119.8
		STD. DEV.	16.1	23.7
	3	MEAN	119.2	118.3
		STD. DEV.	20.0	25.7
	10	MEAN	118.2	123.2
		STD. DEV.	11.9	31.3
PEAK CENTER FREQUENCY (HZ)	1	MEAN	106.3	112.6
		STD. DEV.	23.8	27.3
	3	MEAN	103.6	119.9
		STD. DEV.	11.4	19.5
	10	MEAN	116.8	116.8
		STD. DEV.	26.2	12.6
DROP IN CENTER FREQUENCY (%)	1	MEAN	21.5	12.3
		STD. DEV.	12.6	12.9
	3	MEAN	17.7	20.0
		STD. DEV.	8.1	17.8
	10	MEAN	32.2	31.3
		STD. DEV.	12.1	7.7

interval times have a significant effect on percent recovery (p value = .0001), but there is insufficient evidence to conclude that direction significantly affects percent recovery (p value = .3103). Below are the the results for the Neuman Keuls test.

Rest Interval	1 min	3 min	10 min
Mean	61.1	70.2	88.8

* Means that are underlined are not signficantly different.

Conclude that all means are significantly different. Table IV contains the means and standard deviations for both positive and negative 2 Gy.

Peak Heart Rates (BPM). There is insufficient evidence to conclude second contraction peak heart rates are significantly affected by either direction or rest interval (p values .8148 and .8681). Table IV contains means and standard deviations.

Peak Center Frequencies (Hz). There is insufficient evidence to conclude second contraction peak center frequencies are significantly affected by either direction or rest interval (p values .2465 and .6348). Table IV contains means and standard deviations.

Drop In Center Frequency (Percentage). There was no ANOVA performed on this data because of large variance. Table IV contains means and standard deviations.

ANOVA Summary

In summary, there is evidence to believe that direction significantly effects strength and percentage drop in center frequency. In addition, endurance time was shown to be significantly affected by rest interval times; however, direction was not a significant factor.

Neither heart rate or peak center frequencies appear to be affected by either direction or rest interval; however, percent recovery was significantly affected by rest interval. When rest interval was a significant factor, the multiple comparison showed all rest intervals to be significantly different in all cases.

Initial and Second Fatiguing Contraction Comparisons

A further question of interest, in addition to those previously mentioned, involves the comparison of values from the first contraction to the second contraction within each experimental condition. Therefore, the data was grouped according to rest interval and direction. Differences were then performed by subtracting the second contraction response from the first contraction response for each subject. Means were then calculated and t tests were performed on the mean differences for each group (α = .05) to test the hypothesis that no difference exist between the first and second contractions, i.e., Ho: Mean differences equal zero. The results are displayed in Table V. It can be noted from Table V that none of the variables showed significance consistently with the exception of endurance time.

The above analysis suggests another factor of interest concerning endurance time. Since the change from the first contraction to the second contraction was significantly different from zero, with the exception of that which occurred during the 10-minute rest interval in the negative direction, one might be interested in determining if the change which occurs is the same for all rest intervals. For example, does a 10-minute rest interval between contractions result in less of a change than that which occurs as a result of a 1-minute or 3-minute rest

TABLE V. First and Second Fatiguing Contraction Results

	VARIABLE	T VALUE	P VALUE
POSITIVE Gy 1 MINUTE REST INTERVAL	ENDURANCE	5.28	0.0032
	PEAK HEART RATE	0.36	0.7359
	DROP IN C.F.	2.44	0.0588
	PEAK C.F.	0.70	0.5133
NEGATIVE Gy 1 MINUTE REST INTERVAL	ENDURANCE	2.52	0.0532
	PEAK HEART RATE	0.51	0.6343
	DROP IN C.F.	1.33	0.2395
	PEAK C.F.	-1.93	0.1110
POSITIVE Gy 3 MINUTE REST INTERVAL	ENDURANCE	2.99	0.0303
	PEAK HEART RATE	-0.08	0.9421
	DROP IN C.F.	5.54	0.0026
	PEAK C.F.	-0.36	0.7360
NEGATIVE Gy 3 MINUTE REST INTERVAL	ENDURANCE	3.26	0.0224
	PEAK HEART RATE	1.08	0.3305
	DROP IN C.F.	0.62	0.5644
	PEAK C.F.	-0.29	0.7803
POSITIVE Gy 10 MINUTE REST INTERVAL	ENDURANCE	3.36	0.0201
	PEAK HEART RATE	0.71	0.5081
	DROP IN C.F.	0.24	0.8206
	PEAK C.F.	-0.08	0.9401
NEGATIVE Gy 10 MINUTE REST INTERVAL	ENDURANCE	2.01	0.1804
	PEAK HEART RATE	0.85	0.4354
	DROP IN C.F.	-0.59	0.5849
	PEAK C.F.	-1.71	0.1629

interval? An ANOVA was performed on the differenced data and the change was found to be significant (p value = .0141) as a result of rest interval. The results of Newman Keuls Multiple Comparison conducted at the = 0.10 level is the following:

Rest Interval	10 min	3 min	1 min
Mean Difference	5.8	14.9	16.2

* Means that are underlined are not significantly different.

From the above analysis, there is evidence to conclude that the mean change in endurance time resulting from the 10-minute rest interval is significantly smaller than the changes which occur as a result of the 3-minute and 1-minute rest intervals. In addition, there is no evidence to conclude that changes occurring from 1-minute and 3-minute rest intervals are significantly different from each other.

Individual Variance in Center Frequency Drop

The means and standard deviation for individual subjects are given in Table VI. This data will be discussed later in the quantification of muscular fatigue section.

Individual Variance In Strength and Endurance

The means and standard errors for the individual subjects are given in Table VII. This data will be discussed later in relation to the isometric training accomplished by the subjects.

TABLE VI. First Contraction Percentage Drop in Center Frequency

SUBJECT	POSITIVE	NEGATIVE
1		
MEAN	32.0	14.0
STD. DEV.	4.4	17.6
2		
MEAN	34.0	26.3
STD. DEV.	5.0	1.5
3		
MEAN	43.3	38.0
STD. DEV.	14.0	6.2
4		
MEAN	29.7	23.5
STD. DEV.	8.0	6.4
5		
MEAN	36.0	20.3
STD. DEV.	5.3	1.5
6		
MEAN	30.0	19.0
STD. DEV.	4.6	9.8

TABLE VII. First Contraction Strength and Endurance

SUBJECT / VARIABLE	1		2		3		4		5		6	
	POS	NEG	POS	NEG	POS	NEG	POS	NEG	POS	NEG	POS	NEG
STRENGTH												
MEAN	120.6	99.7	123.8	120.9	93.2	90.6	120.4	107.9	109.6	107.0	99.4	91.4
STD ERROR (%)	3.8	1.7	7.6	6.1	10.6	1.6	7.9	9.7	14.4	3.0	3.8	9.3
ENDURANCE												
MEAN	29.3	31.3	42.3	40.7	67.7	79.0	41.7	40.7	56.7	45.0	38.0	50.7
STD ERROR (%)	12.0	18.7	18.3	24.8	14.9	1.3	2.8	9.3	1.0	21.9	14.7	43.0

IV Discussion

Strength

The subjects had significantly greater forearm strength when accelerated in the +2 Gy direction as compared to the -2 Gy direction. Absolute forearm strength can be affected by many factors. Some physiological factors include age, muscle temperature, and percentage of body fat. When measuring the relative forearm strength of a subject at +2 Gy or -2 Gy the physiological factors mentioned above cancel out and one must search for further explanations of the difference.

One possible explanation is the restraint system used during the experimentation. When the subject underwent -2 Gy acceleration he was pushed against the head and shoulder pads on the right side of his body. The handgrip dynamometer was located on the subject's right hand side and as a result the subject felt inhibited in his efforts to squeeze under -2 Gy acceleration. This feeling was expressed by all the subjects in terms of an uncomfortable, crushed feeling that was not experienced under +2 Gy acceleration. No studies could be found that show a forearm strength relationship between +2 Gy and -2 Gy; however, tracking performance studies show that although tracking error is elevated under -2 Gy when compared to +2 Gy (4) it is even higher without shoulder pad support (21). It seems reasonable to assume this relationship might also exist when considering forearm strength.

Other factors that might cause a strength difference for +2 Gy compared to -2 Gy are numerous. Heart rate, blood flow, circulatory occlusions, nerve entrapment, oxygen uptake, and respiratory differences to name a few. It is doubtful that these factors would affect the MVC because the lateral G exposure times are short and the actual contraction time is three seconds or less. An area where respiratory and circulatory effects of lateral acceleration may be significant is fatiguing isometric contractions which will be discussed next.

Initial Fatiguing Contraction

The endurance times for the 70% MVC submaximal contractions were not significantly different when comparing ±2 Gy. These results disagree with a number of studies which show a negative correlation between strength and endurance (2,3,11). Although these studies involved different muscle groups they indicate that as strength increases relative endurance decreases. Assuming that this relationship is accurate the question arises as to why the relative endurance in the -2 Gy direction is not greater. To answer this question one must examine the effect of circulation and respiration on isometric endurance times and the cardiopulmonary effects of lateral acceleration on the individual subject.

For an individual performing fatiguing isometric forearm contractions in a static environment resarchers have noted a dramatic increase in blood pressure and ventilation with only a modest increase in heart rate and oxygen uptake (11). Heart rate was the only one of these parameters measured during this experiment. The peak heart rates were as high as 177 BPM during this experiment. In contrast, the heart rate in a static environment during isometric contractions rarely exceeds 120 BPM (15,20). It is not known whether this increase is in response to the isometric contractions under G or just the additive effect of isometric exercise and exposure to lateral G. For further discussion of this point see the Conclusions and Recommendations chapter.

The results of the current study show no significant difference in the peak heart rates attained by subjects in the ±2 Gy environment. A study by Popplow (17) indicates that there is a difference in the average heart rate at ±2 Gy with -2 Gy causing a higher average heart rate than +2 Gy for 25 second exposures. This is probably due to the fact that the subjects in Popplow's study were not performing fatiguing isometric contractions. The relationship between fatiguing versus non-fatiguing isometric contractions in a lateral acceleration environment is not well known. It has been observed in previous static environment studies that the heart rate response is directly proportional to the isometric tension exerted by the handgrip muscles of the forearm (5,11). This relationship was not observed in the data collected during this experiment.

Although blood pressure, oxygen uptake, and ventilation were not measured during this experiment some insight into the effects of lateral acceleration on oxygen uptake and ventilation were gained from Popplow's (17) study. He found no significant difference in ventilation under ±2 Gy but there was evidence to conclude that the SaO_2 drop was greater for +2 Gy compared to -2 Gy. If the latter relationship is correct, it would indicate a performance drop under +2 Gy and this does not seem to be the case.

Blood flow through a muscle is an important factor in isometric endurance times. Myers and Sullivan (10), Stevenson and Cain (19), and others have shown that endurance is greatly reduced when blood supply to the active muscle is occluded. Lind, et al. (6), however, found that blood flow is almost totally occluded at tensions above 70% MVC by the pressure built up within the muscle. If Lind is correct then blood flow should not be a major factor in this experiment because all contractions are at 70% MVC.

In summary, no sound explanation for the reduced relative endurance under -2 Gy can be found from observing peak heart rates, oxygen uptake, ventilation, or blood flow. One reasonable explanation that deserves attention is the possibility of radial nerve entrapment caused by pressure on the right shoulder during -2 Gy acceleration.

> The position of the radial nerve as it winds round the humerous makes it specially liable to injury. Apart from penetrating wounds and fractures of the humerous, it may be compressed in the axilla through the use of a crutch, and when the arm of an anesthetized patient is allowed to hang over the edge of the operating table. It may also be compressed during sleep, especially when the patient is intoxicated (1).

Since the radial nerve supplies sensibility to the middle of the forearm the possibility of entrapment causing reduced relative endurance under -2 Gy acceleration should not be overlooked.

Second Fatiguing Contraction

For the intial fatiguing contraction the assumption was made that the muscles were fresh, or unfatigued. This was not the case for the second contraction. The degree to which the muscles recovered from fatigue is expressed by a ratio of the second contraction endurance time over the first contraction endurance time. The relative endurance times for the second contraction were not significantly different under ± 2 Gy; therefore, the percent recovery is not affected by direction, it is however, affected by rest interval. The percent recovery was approximately 61%, 70%, and 89% for 1-minute, 3-minute, and 10-minute rest intervals respectively. The general shape of this curve can be seen in Figure 8. As can be seen the rate of recovery is high for the one-minute rest interval but gradually drops over time.

In general, none of the variables measured during the second contraction seems to be affected any differently under +2 Gy when compared to -2 Gy. These observations are in line with those of the initial fatiguing contractions. A comparison of the first and second fatiguing contraction data showed no significant relationships in the differences under ±2 Gy except that which occurred after a 10-minute rest interval in the -2 Gy direction. This comparison indicated that there was no significant difference in the initial contraction endurance time and the second contraction endurance time. One might infer from this that recovery is more complete under -2 Gy; however, more analysis should be done before making such a claim.

Insight into the physiological parameters of fatigue and recovery from fatigue are very important; however, the value of point estimates such as those derived from this experiment is somewhat limited. A typical operational scenario for the AFTI/F-16 pilot probably would not include holding a high percentage MVC until fatigue and then repeating it sometime later. More typically, the pilot will exert various levels of strength for various amounts of time. This being the case it would be desirable to have an easily measurable technique for quantifying fatigue.

Quantification of Fatigue

As mentioned earlier an apparently reliable technique for estimating muscular fatigue has been developed by Petrofsky (12) and others. This

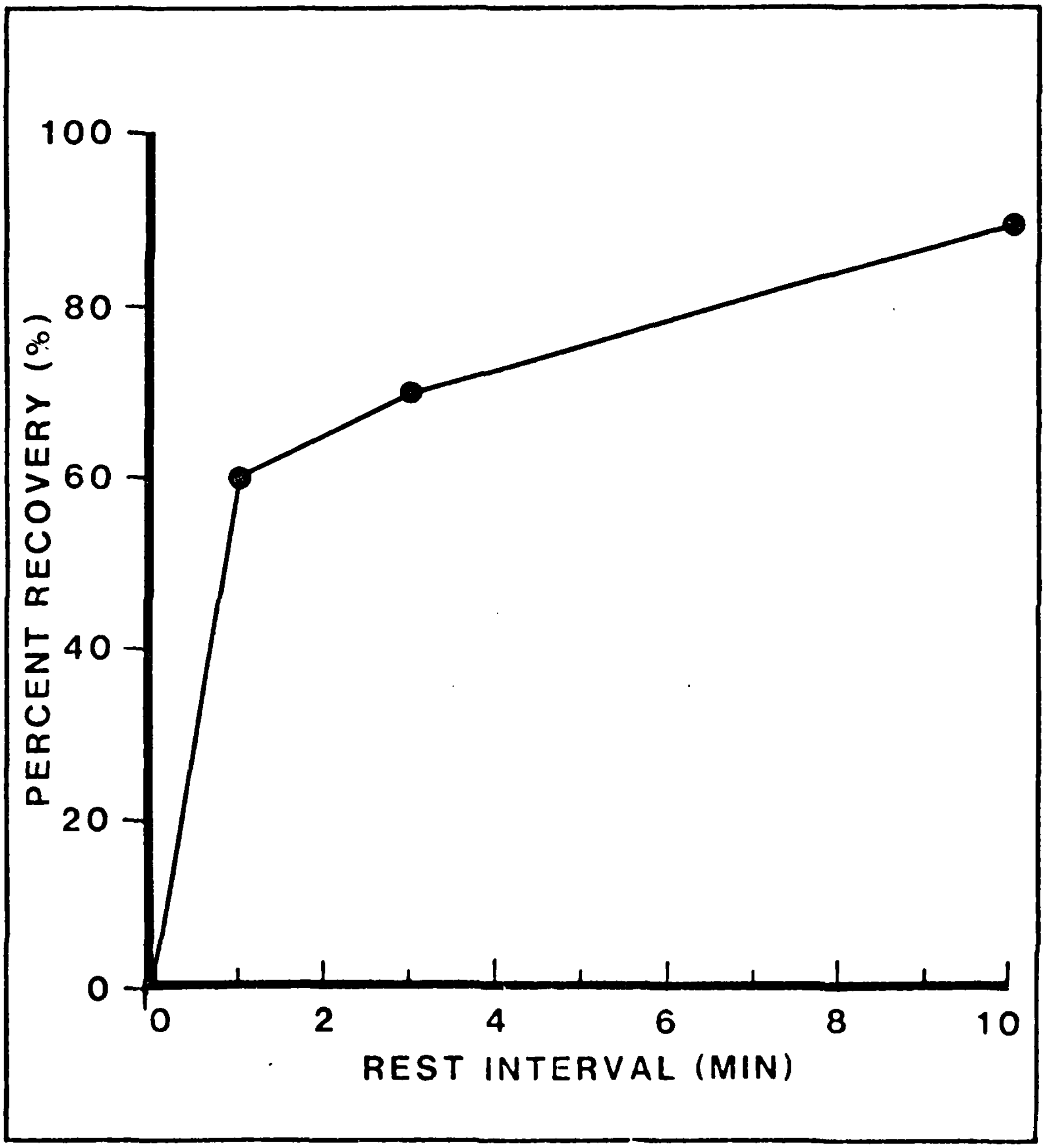

Figure 8. Percent Recovery Versus Rest Interval

method incorporates the center frequency as a fatigue index. More specifically, the drop in center frequency throughout the duration of a fatiguing isometric contraction was observed to fall at about 24%.

The results of this experiment do not show a reliable 24% drop in center frequency. The drop in center frequency under -2 Gy acceleration was approximately 24%; however, the standard deviation was 11%. The drop in center frequency under +2 Gy acceleration was approximately 34% with a standard deviation of 8%. If a large part of the variation is due to individual differences in center frequency drop, perhaps an individual fatigue index could be developed for each subject. Table VI shows the individual variance of the center frequency drop by subject. Here again the variance is quite large in most cases. Besides an inconsistent drop in center frequency from unfatigued to fatigued muscle the pattern of the drop varied from run to run. Figure 9 shows two separate initial fatiguing contractions for the same subject. Based on these results one might conclude that the drop in center frequency is not a reliable index of fatigue under lateral acceleration.

It is interesting to note that although the peak center frequencies were not significantly different under ±2 Gy, the drop in center frequency was greater under +2 Gy compared to -2 Gy (Table III). This phenomenon might be caused by the contraction of other muscle groups in order to relieve the discomfort of -2 Gy acceleration. If this were occurring the signals would be detected by the surface EMG electrodes and result in higher center frequency at fatigue. In order to confirm this hypothesis more research would need to be done; however, the implication is that operational maneuvers in the -2 Gy direction are more tiresome in general.

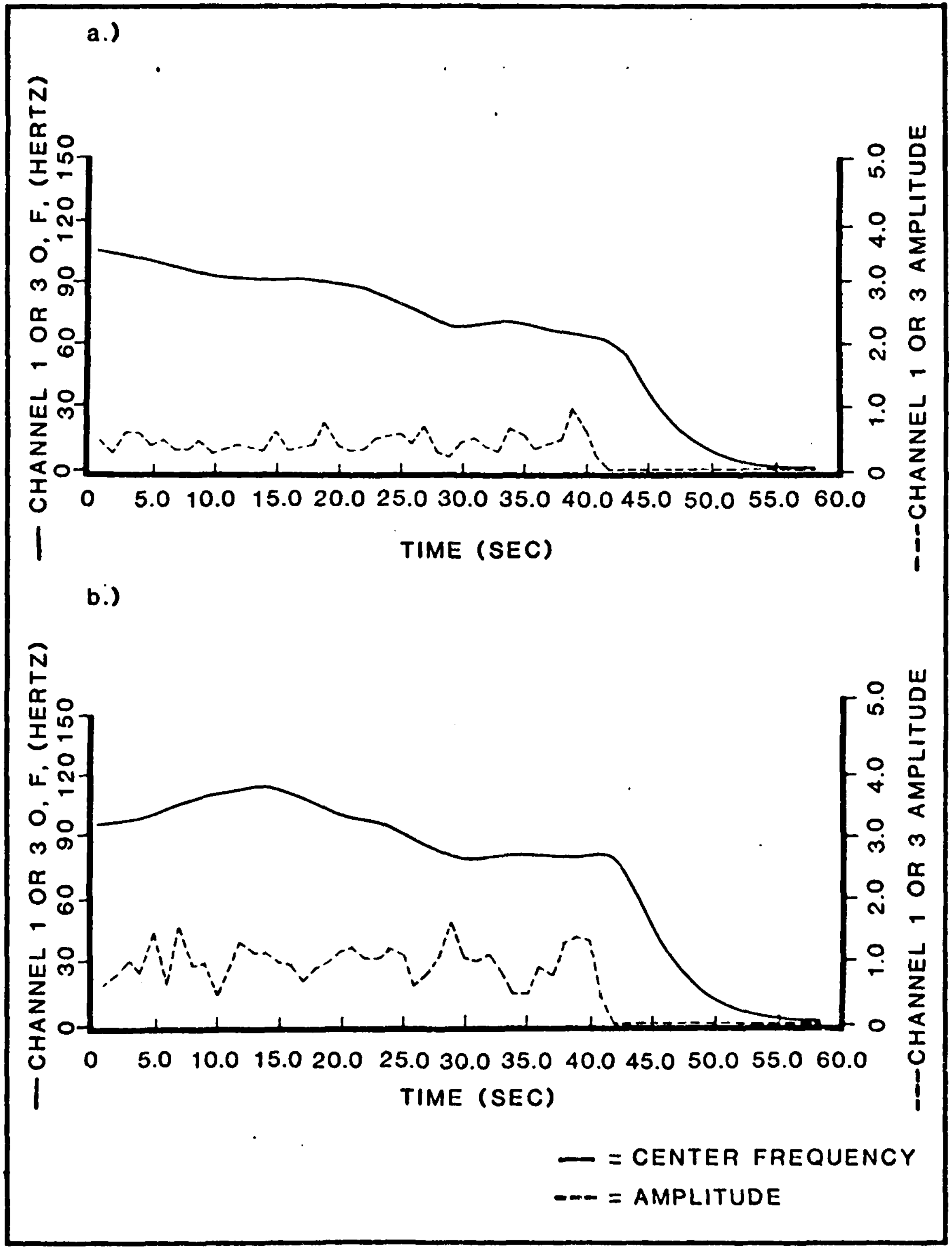

Figure 9. Center Frequency and Amplitude Versus Time Profiles

Although the drop in center frequency did not prove to be a reliable index of fatigue in this experiment, the surface EMG data base provided by this study will play a key role in current work being done to uncover a fatigue index. Repperger (18) is working on an approach to integrate the amplitude of the signal over time. The change in slope of the amplitude may be unique at the fatigue point. This type of information might prove useful in an operational environment as a warning to the pilot that he will be fatiguing shortly.

Isometric Strength and Endurance Training

As can be seen in Table VII the standard error for strength was less than 8.5% in most cases, which is consistent with other studies (11). The standard errors for endurance were, in general, much higher than for strength but are in relative agreement with a study by Martens and Sharkey (9) indicating standard errors of 11% and 18% for strength and endurance respectively.

In summary, more training would have been beneficial to the results of this effort; however, given the time constraints of this project the training was adequate to give statistically significant results.

V Conclusions and Recommendations

If a head and shoulder restraint system is used in the operational AFTI/F-16, and it appears that at least the shoulder pads will be used, the results of this study indicate their presence is a factor in pilot performance. There is more forearm strength in the +2 Gy direction with no drop in relative endurance compared to the -2 Gy direction. No readily apparent physiological changes could be found to cause a strength and endurance difference in +2 Gy compared to -2 Gy, although research is sparse in these areas. Some intuitively appealing evidence points to the right head and shoulder pads causing pressure and discomfort during -2 Gy acceleration, and this in turn causes decreased performance during -2 Gy acceleration. The fact that the side-arm controller is located on the right hand side is apparently causal in these effects, but placing it on the left hand side would probably only reverse the results and not improve the situation. Some evidence also exists to indicate overall physical fatigue could be increased during -2 Gy acceleration if indeed other muscle groups are being recruited to relieve the pressure and discomfort produced under -2 Gy acceleration. Although this study is limited in its scope the results should not be overlooked when considering tactical maneuvers for the AFTI/F-16 pilot.

Measurement of the effect of radial nerve entrapment on relative endurance would be difficult; however, the medical monitor may desire to check the condition of the radial nerve periodically. If radial nerve compression during -2Gy acceleration causes a loss in sensibility to the forearm, then higher or more sustained G levels might damage the nerve. Checking the conduction velocity of the radial nerve above the forearm before and after lateral acceleration would indicate if the nerve fiber is being damaged (1).

Research is currently underway seeking less obtrusive restraint concepts. Even if inertial or conforming restraint systems could be developed to relieve pressure and discomfort in any G environment, the problem of quantifying isometric fatigue and predicting endurance will still exist. If a reliable fatigue index can be developed as a result of this and future studies it will be of benefit not only to the AFTI/F-16 program but to all types of military, commercial, or private endeavors requiring isometric exercise. The possibility of integrating the amplitude of the EMG signal over time may prove to be a very successful quantification technique. A study done in 1968 (10), using the right biceps as a model, determined that the amplitude of the EMG signal became larger at fatigue and the slope of the amplitude became steeper with time. This study employed a simultaneous timed integration of the rectified electromyographic signal every 4 seconds. With the results of the current study, using the right forearm as a model, Repperger (18) is developing a more sophisticated algorithm to integrate the amplitude of the EMG signal. If the amplitude of the signal has some unique characteristics at fatigue that make it a reliable fatigue index at 70% MVC, then other percentage MVC's and a variety of lateral G levels need to be examined. In the event that integration of the amplitude is consistent for a wide range of percentage MVCs and lateral G levels this technique could be used to correlate tracking scores and fatigue using different restraint systems.

If the hypothesis that a degradation in isometric strength and endurance does occur in the -2 Gy environment because of the head and shoulder restraint is true, it would not preclude further examination of the physiological changes brought about by lateral acceleration. For although the restraint system may have direct impact on pilot performance, the long-term physiological impact of lateral acceleration may affect the mental and physical health of the pilot. A great deal of work remains to be done in this area. This study was limited to one G level and one MVC percentage measure of endurance. The rest intervals studied were relatively large and few in number. The rest intervals under one minute especially need to be studied because of their likelihood in an operational environment.

The blood pressure response to isometric exercise and lateral acceleration needs to be studied. This will require an automatically inflatable cuff. Before being used the cuff will need to be tested to see if it supplies accurate readings under G. This should be an interesting problem in itself.

One major weakness of this study was the lack of a control on the parameters that were measured. In future studies, the subject could be exposed to lateral acceleration with and without tension being applied to the handgrip dynamometer; thereby determining the extent to which heart rate, for example, is affected by isometric fatigue and lateral acceleration compared to lateral acceleration alone. At this time the relationship is unknown.

The idea of a control could be employed when measuring any of the parameters. Obtaining surface EMG signals under $\pm$ Gy without tension could be done to see if muscular activity is more prominent under - Gy. This would support the hypothesis that overall fatigue is increased under -Gy.

Finally, it should be noted that high technology, lateral acceleration aircraft are limited mainly by man's ability to perform under lateral stress. The advances in restraint systems must be accompanied by a better understanding of the physiological effects of lateral acceleration in both the short run and in the long run.

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Appendix: Frequency Analysis Device

The Frequency Analysis Device (FAD) was built by Systems Research Laboratory and consists of an Intel System 80/30 micro-computer, a 12 bit multiplexing analog-to-digital converter, a TRW 16x16 bit multiplier/accumulator, an ASCII keyboard, and a Matrox CRT controller with Leedex monitor (Figure 10).

The 80/30 system was equipped with 48K of user RAM for data storage and 8K of ROM for analysis firmware. To improve the system throughput, the TRW multiplier/accumulator was used for all data windowing and Fast Fourier Transform (FFT) calculations. The CRT controller was used to provide high resolution, 512x512 pixels, graphical displays. A fixed sample rate of 1000 samples per second was set via a precision interval timer resident within the 80/30 system.

Firmware

The flow diagram of the FAD analysis algorithm is shown in Figure 11. The FAD operator selects the number of 128 sample data bursts to collect each second, the optimum analog-to-digital converter gain, and threshold level to be used for elimination of undesirable low level frequency components. Data collection is initiated by an external trigger. To reduce aliasing effects in the FFT calculations, each data burst sample is weighted with a Blackman window. The Blackman window is defined as:

$$W(n) = .42 - .5 \text{ COS}(2\ n/N) + .08 \text{ COS}(4\ n/N)$$

where

$N = 128$ = Number of samples per data burst

$n = 0, 1, 2, \ldots\ldots, N-1$ = Sample point index

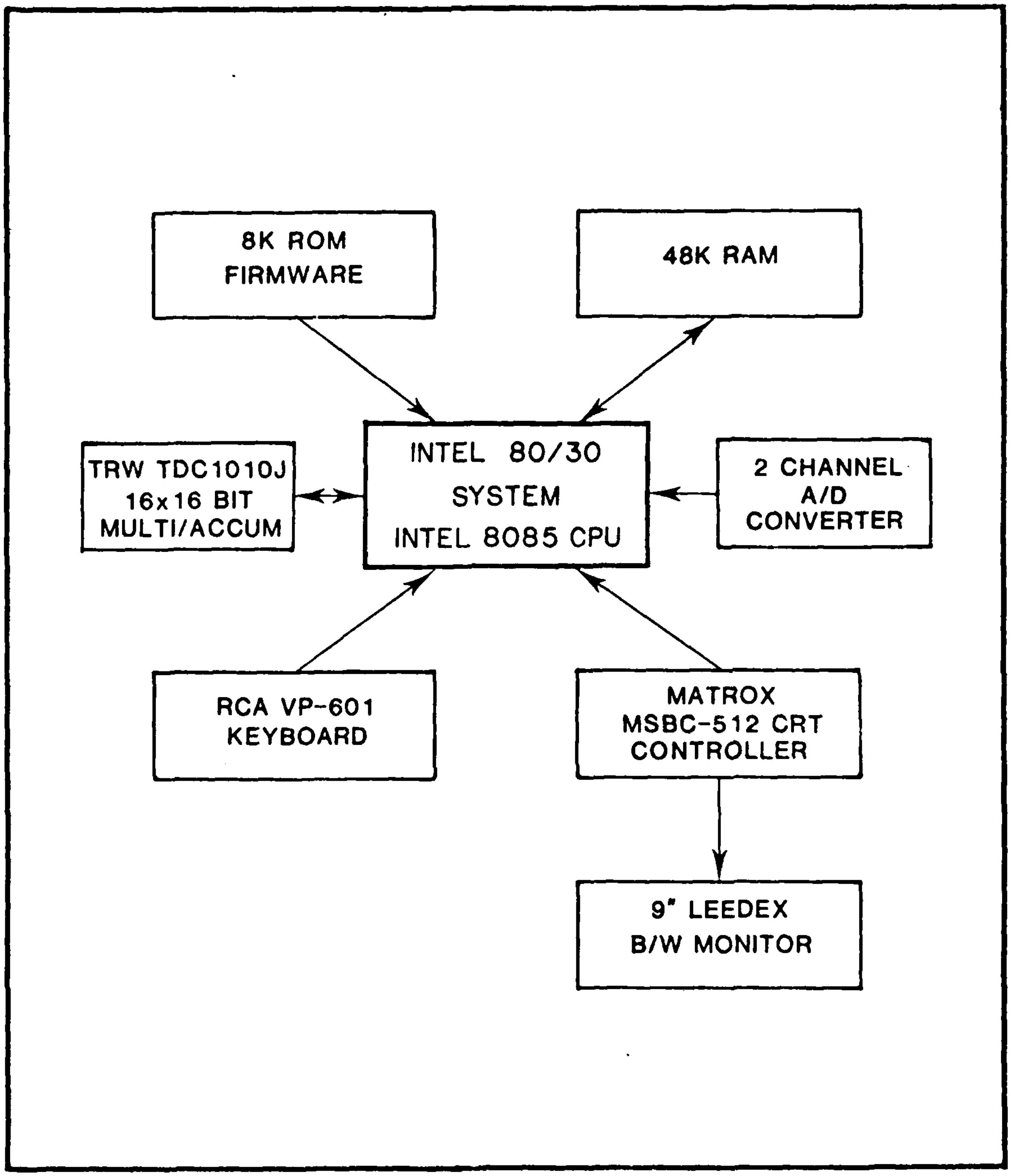

Figure 10. FAD Hardware Configuration

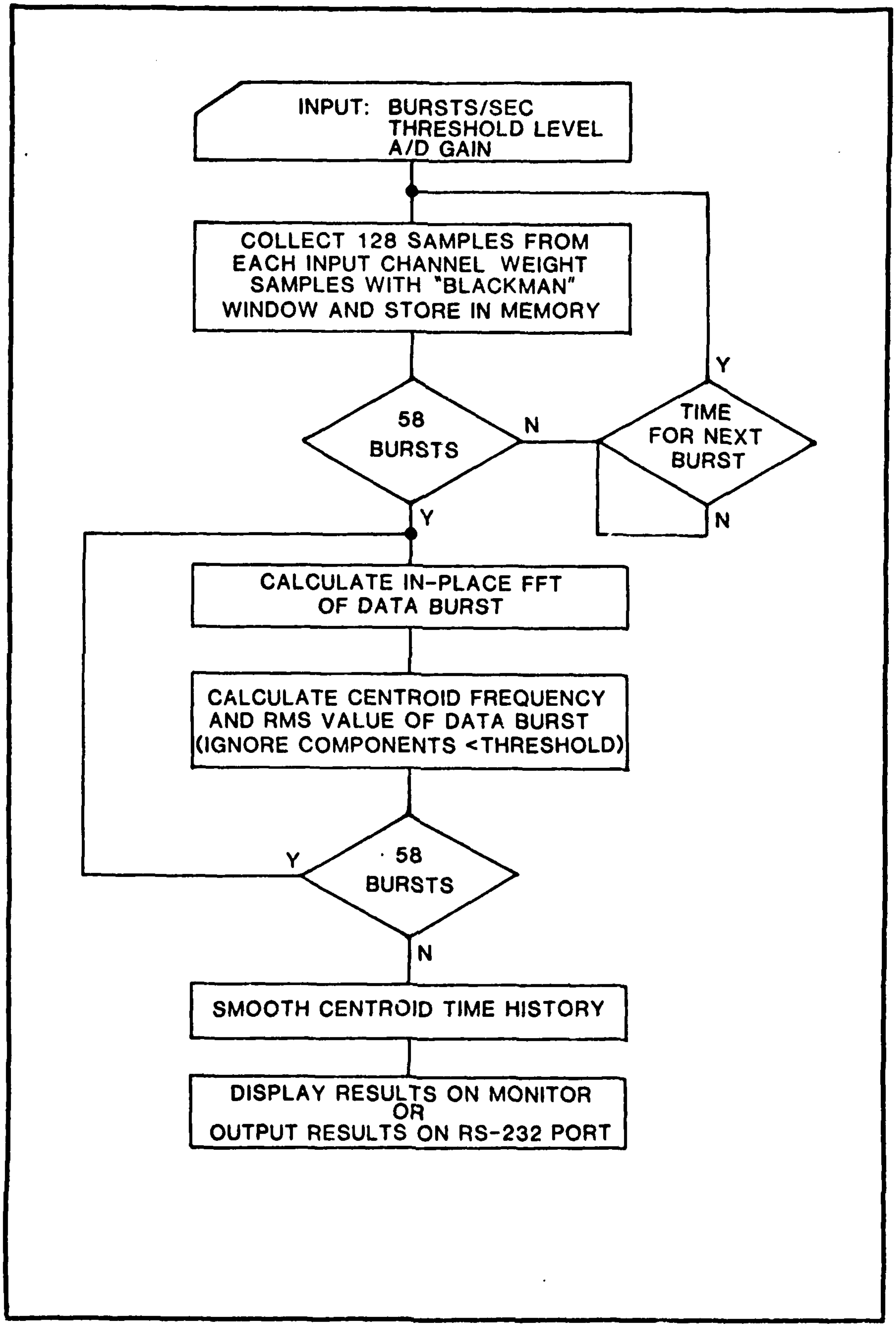

Figure 11. Frequency Analysis Flow Diagram

W = Weighting factor

After 58 data bursts are collected, windowed, and stored in RAM, the spectrum of each data burst is determined using an in-place FFT algorithm as defined by

$$A(k) = \sum_{n=0}^{N-1} W(n)X(n)Y(nk)$$

where

k = Frequency component index

X(n) = n-th sample of data burst

$$Y(nk) = e^{\frac{nk}{-jn}}$$

The RMS value and centroid frequency of each data burst is used to characterize the EMG time history. The centroid frequency is defined to be:

$$C = \sum_{k=3}^{63} kA(k) / \sum_{k=3}^{63} A(k) \quad /.127$$

Only those frequency components having amplitudes greater than the selected threshold are used in calculating the RMS and centroid frequency values. Long term trends in the EMG centroid frequency are found by smoothing the resulting time history.

The spectra, RMS history, and/or centroid frequency history may be displayed on the CRT or output on a RS-232 serial port for printout. Uploading to another computer for further analysis is also possible through the serial port.

Program Initialization occurs immediately after either system power is turned on or the reset key is depressed. A "Spectral Analysis Program" burst page will then appear on the CRT monitor. Transmitting a carriage return will cause a short description of available commands to appear on the CRT. A second carriage return will cause entry into the command level (transmitting an "escape" character at any point will cause immediate entry to the command level).

While in the Command level, the following commands may be entered: S, C, Spectra/sec, A, D, W, P, H (Figure 12).

The "S" = (set A/D converter gain) command allows the user to select an analog-to-digital converter gain of 1, 2, 4, or 8 or have the computer determine the optimum gain setting based on the current signal on channel 0 input. Upon entering the "S" command the CRT cursor will prompt for input of the gain parameer. If the autogain, "A", parameter is set, the computer will prompt the operator to place the maximum expected signal on channel 0 input.

The "C" = (collect data) command will cause the computer to request the number of spectra to take every second by moving the cursor to the "SPECTRA/SEC" parameter. Based on this parameter, data is sampled as indicated in Figure 13. If "SPECTRA/SEC" = 8, continuous sampling will occur. The spectra associated with each data set is identified as spectra 1, etc., as indicated above. A total of 58 data burst will be collected. Therefore data collection will take from 7.25 seconds to 58 seconds depending upon the value selected for "SPECTRA/SEC".

The "A" = (analyze) command causes the computer to calculate the amplitude spectrum and frequency centroid for each of the 58 data sets stored in memory. Care should be taken to insure that data was collected prior to execution of this command.

Entering the "D" command will prompt the operator to enter the parameters required to identify the data to be plotted. The user is first requested to enter the type of plot desired (spectra or frequency

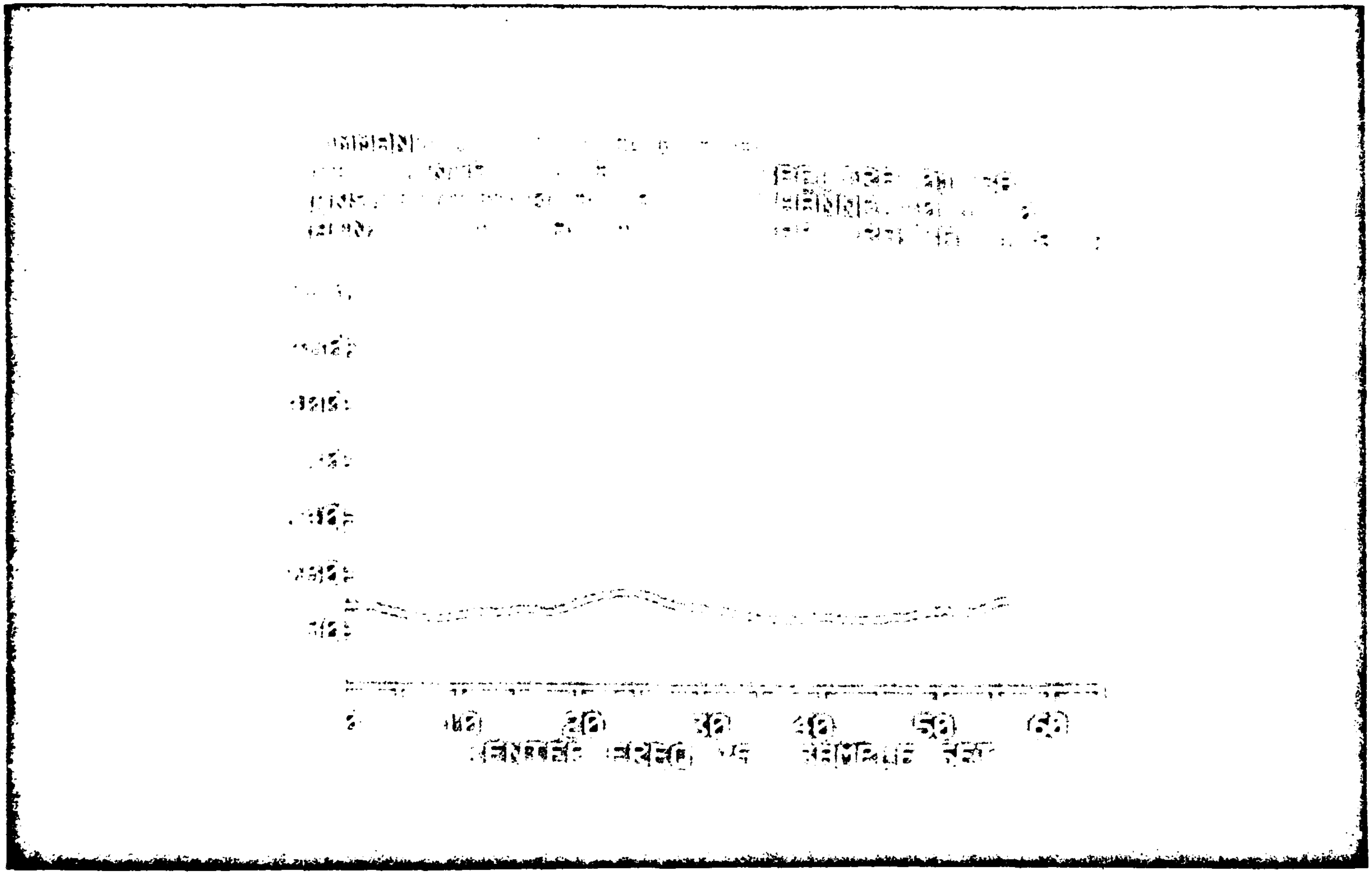

Figure 12. Center Frequency Plot and FAD Command Functions

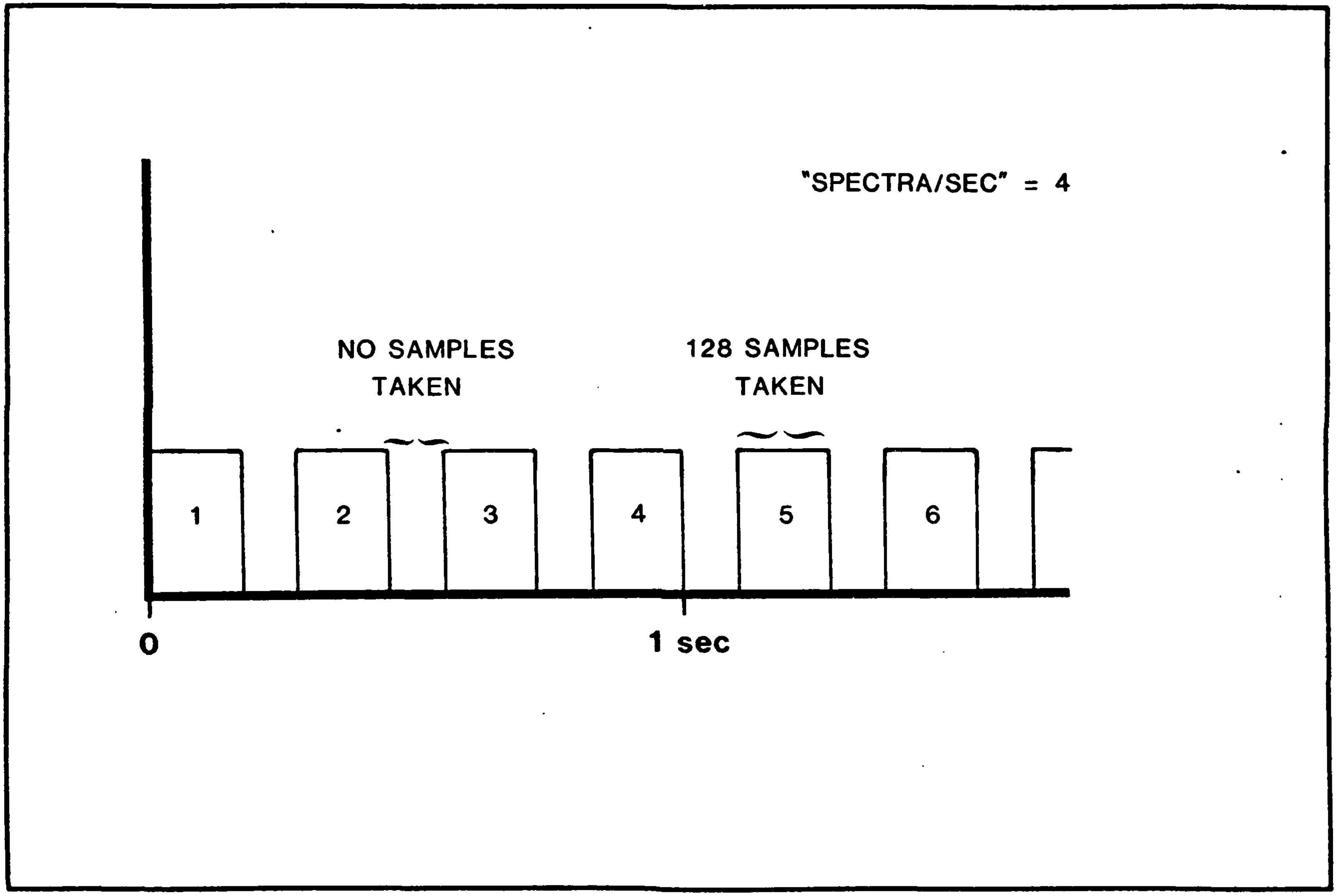

Figure 13. Signal Sampling Schematic

centroid plot). If a centroid ("C" parameter) is requested, the computer will request the channel to display (see Figure 12). Immediately upon entry of the channel number the 58 centroid frequencies will be plotted.

If a spectral plot ("S" parameter) is requested, the user is requested to enter the range of spectra to plot - using the numbering scheme discussed previously. The user is then requested to enter a sensitivity value (see Figure 14). The sensitivity value determines a minimum magnitude threshold. Any spectral component below this magnitude will not be plotted. A sensitivity of "9" sets the threshold at 0 volts. The sensitivity parameter may be used to enhance the clarity of the significant spectral components by suppressing low level components.

The "P" command causes a plot to be displayed according to the existing parameter values. Additional information is therefore not requested prior to plotting.

The "W" = (write to RS-232 port) command operates like the "D" display command except the user is prompted to enter the baud rate of the receiving device. Both channels of information are always output together as a series of records. Two blank records are transmitted between spectra. No threshold can be set with this command (sensitivity = 9 always).

The "H" = (help) command will cause a short description of all commands to be displayed on the monitor. Entering a carriage return will return the user to the command level.

Depressing the "Escape" key any time an input is requested causes the following parameter initialization:

"SPEC/CENTR" = S "SPECTRA" = 01-58

"SENSITIVITY" = 9 "CHANNEL" = 0

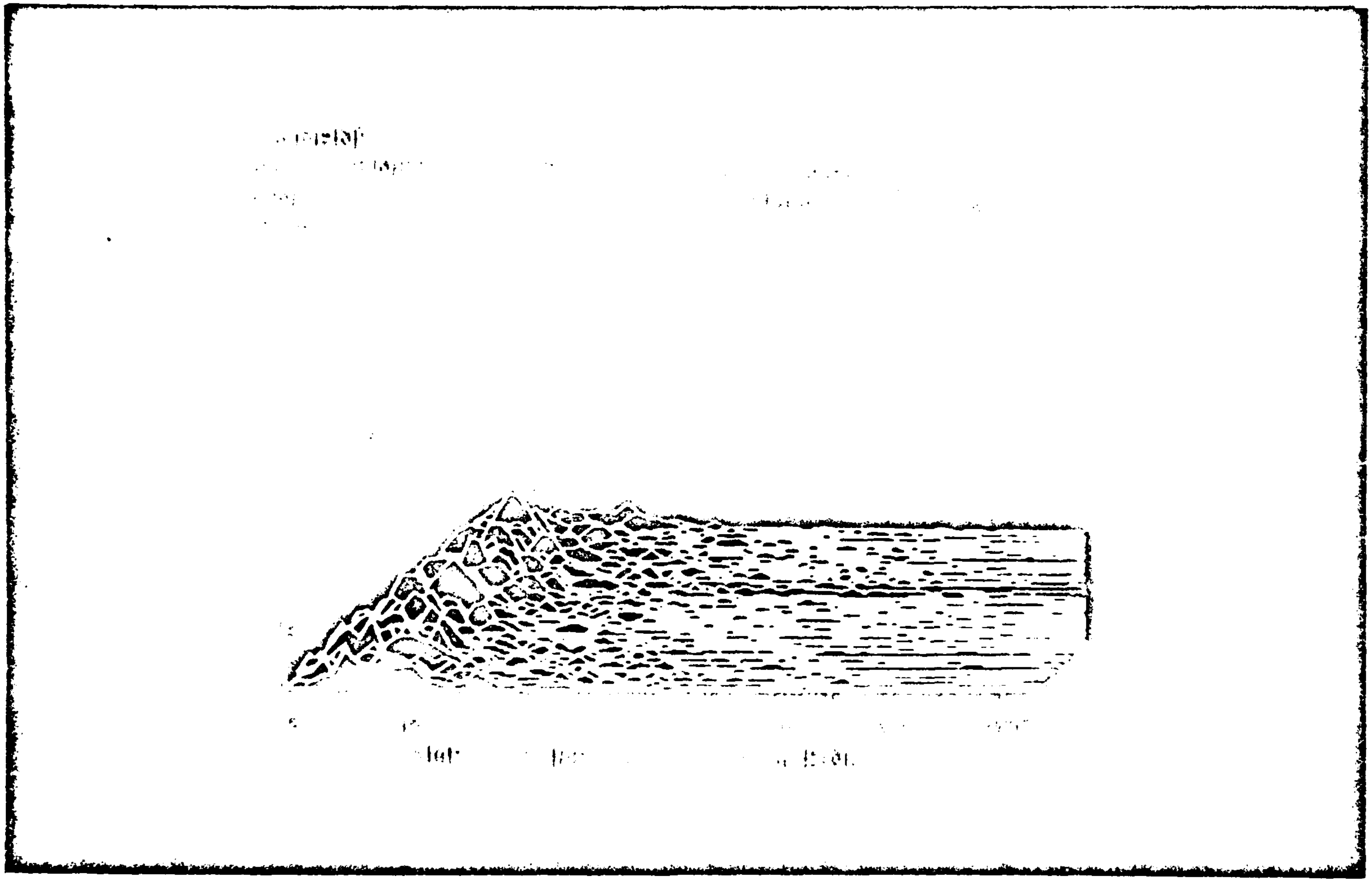

Figure 14. Power Spectrum of EMG Signal and FAD Command Functions

The "GAIN" and "SPECTR/SEC" parameters are not altered. Entry to the command level occurs immediately.

Validation of the Frequency Analysis Device

The two main considerations that are of concern to a user of the FAD are whether the resultant electromyogram (EMG) center frequency and rms analysis is: (1) accurate and, (2) reproducible. A wide range of tests were conducted in order to determine the accuracy and reproducibility of the FAD's output. During the conduction of these tests, several techniques for utilizing the FAD in a proficient manner were derived. These techniques, as well as the methods used to determine the accuracy and reproducibility of the FAD's output, will be dealt with in this section.

Accuracy

The following tests were conducted to measure the accuracy of the center frequency (centroid) determinations produced by the FAD. The first was a basic test that consisted of validating the FAD's capability to determine the frequency of single sinewave inputs. To test this capability, a sinewave generator was connected to the FAD through a bandlimited amplifier (0 to 375 Hertz). The generator's frequencies were set by means of a frequency counter. The FAD command settings were set at sensitivity=9, gain=1, and spectra/second=8. The bandlimited amplifier's gain was set at one and the generator output amplitude was 0.7 Vrms for all the frequencies. In the course of conducting this test it was determined that correct frequency results (±2%) were achieveable with FAD input voltages as low as 0.1 Vrms or as high as 0.8 Vrms (see Table VIII).

TABLE VIII

FAD Single Sinewave Frequency Determinations

	Input Frequency Hertz	FAD Center Frequency Spread Hertz
1	30.0	30.7 - 31.1
2	49.9	49.2 - 49.8
3	80.0	79.4 - 80.2
4	100.0	99.7 - 100.1
5	200.8	200.4 - 200.6
6	299.4	298.9 - 299.3

The maximum error present in the data in Table VIII is 3.6%. As expected, the error is highest at the lowest frequency. However, the majority of center frequency determinations are well within 0.5% of the actual input frequency. These tests thus indicate that the FAD is capable of determining the frequency of a single sinusiodal waveform.

Another test was conducted to determine the accuracy of the FAD in analyzing a waveform containing more than a single frequency component. Two sinewave generators, one connected to each input of an inverting summing amplifier, were used to generate a waveform composed of two frequency components. The bandlimited amplifier, set to a gain of one, was also used in this test. The generated sinewave frequencies and amplitudes were measured respectively with a frequency counter and digital voltmeter. The results of this test are shown in Table IX. Only the first ten of the 58 spectra calculations are shown due to limitations of space. The highest error of the 58 results was 1.2%. This figure was due to a 137.55 Hertz determination. It is assumed that if the FAD can determine the frequency composition of this waveform, it can also accurately determine the center frequency of a more complex waveform composed of numorous sinewaves. A further test of the FAD's ability to determine center frequency was conducted with a squarewave as the input signal. The FAD calculated a correct fundamental frequency plus the correct relationship between the squarewave's dc component, the fundamental, and the harmonics up to a frequency of 500 Hertz.

TABLE IX

Center Frequency

$$CF = \frac{f_1(a_1) + f_2(a_2)}{a_1 + a_2}$$

where:
CF = center frequency

F_1 = 100 Hertz a_1 = 0.4 Vpeak

f_2 = 160 Hertz a_2 = 0.6 Vpeak

CF = 136 Hertz

Spectra	CF
1	0136.5156
2	0136.4688
3	0136.5000
4	0136.3750
5	0136.3906
6	0136.4844
7	0136.5781
8	0136.7344
9	0136.9531
10	0137.1406

The ability to obtain EMG rms data added another dimension to the analysis of the EMG. As mentioned previously, the rms data provides a quantitative means of measuring muscle tension. The rms determinations were derived from the amplitude of values used in calculating the center frequencies (centroids). In order to minimize the errors caused by the squaring and square root operations required in calculating an rms value, the calculation was optimized for maximum EMG signals of 2.5 volts peak (the output range of the analog tape recorder). Table X contains the results of a test conducted to measure the accuracy of the FAD's rms determinations. A 200 Hertz sinewave was varied in amplitude from 0.2 Vrms to 1.77 Vrms. The FAD command settings were set at sensitivity = 9, gain = 1, and spectra/second = 8.

Considering the low level of input signals, the FAD produces reasonably accurate rms data. Voltages below a value to 0.1 Vrms were indeterminate at a gain setting of one. However, if the FAD's input gain is increased to two, a 0.1 Vrms input results in a rms determination of 0.08 Vrms, an error of minus 20 millivolts.

TABLE X

FAD Accuracy

Input Vpeak	Voltage Vrms	FAD RMS Determination	Error %Actual	Error %F.S.
2.5	1.77	1.91	7.9	5.6
2.0	1.41	1.50	6.4	3.6
1.41	1.00	1.03	3.0	1.2
1.06	0.75	0.77	2.6	0.8
0.707	0.50	0.49	2.0	0.4
0.28	0.20	0.16	20.0	1.6

A FAD gain setting of two to four is normally used in analyzing a recorded EMG. Therefore, a 0.1 V rms signal is measurable, but at the reduced accuracy indicated above. Because rms values are not used in the center frequency analysis, the FAD can determine the frequency of a 0.1 V rms sinewave within ±2% at a gain of one. In other words, low amplitude signals affect the accuracy of the rms calculations to a greater extent than the center frequency calculations.

Reproducibility

To check the reproducibility of both the center frequency and rms

FAD calculations, a segment of an EMG signal recorded on analog tape was repeatedly analyzed by the FAD and the individual results compared. The FAD has the provision of being triggered by an external pulse which initiates the EMG analysis. The EMG segment is then automatically sampled and the FFT calculated. A trigger pulse is recorded on one of the analog tape recorder channels at the moment the initiation of an EMG analysis was desired (i.e. maximum voluntary contraction or reaching a designated lateral acceleration level). This trigger pulse thus enables repetitive analysis of the same EMG segment.

Twenty replications of the same EMG segment was analyzed by the FAD. The FAD sensitivity was nine, the gain setting one, and the spectra/sec eight. The bandlimited amplifier gain equaled one. Figure 15 shows the graphical results obtained from two of the twenty replications. The straight lines in the graphs are linear regression lines. A visual comparison of the two graphs indicates that they are very similar.

The mean and standard deviation for both the estimated y intercepts and slopes that were obtained from the 20 regression lines were calculated and are listed below:

	N	Mean	Std Dev	Min	Max
y intercept	20	143.521	1.51	141.85	146.11
slopes	20	-5.515	.3995	-6.68	-5.08

In addition, an F test was performed on the data obtained from the two replications that yielded the minimum and maximum y intercepts to test for coincidence of the two regression lines.

The F ratio=.143 was found to be insignificant at the 0.05 level indicating that there is insufficient evidence to conclude that

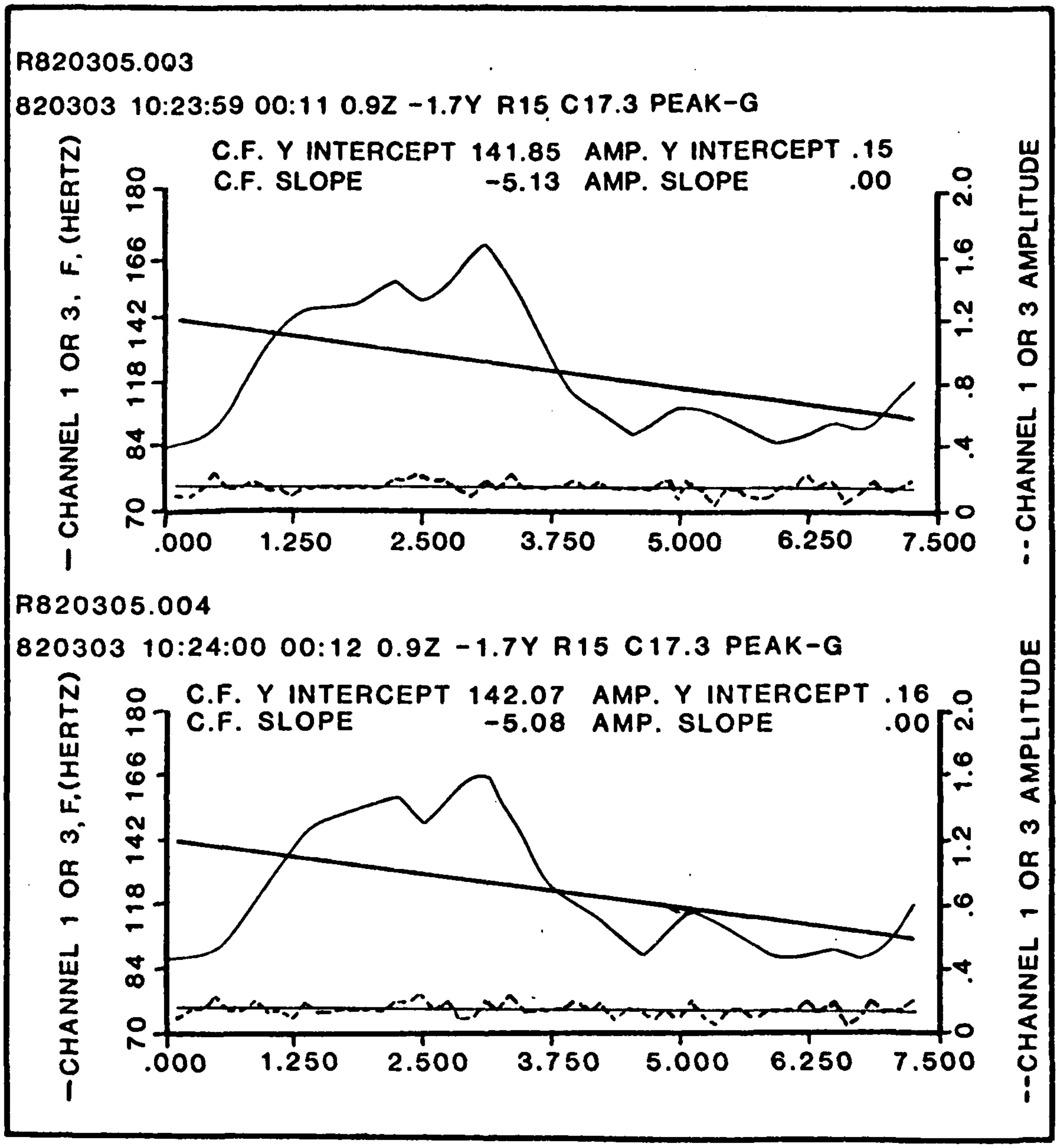

Figure 15. Two Replications of the Same EMG Data

differences exist in these two lines; which implies that all other data obtained which yielded y intercepts within this range do not differ significantly as well.

Instrumentation Technique

The instrumentation used to collect and analyze the electromyograph is shown in Figure 16. The electromvograph was recorded on line using a Honeywell Model 5600 analog tape recorder. The FM recording mode provided a frequency response of 0 - 2.5 K Hz at a recording speed of 7.5 inches/sec. The Frequency Analysis Device (FAD) is shown beneath the Texas Instruments Silent 700 ASR Terminal which finishes printouts of the data displayed on the monitor. An identification code containing the date, time of day, acceleration parameters, study conditions, and name of subject was recorded on a separate tape channel. This tape identification provides a means of coordinating and synchronizing the identification of data stored on analog tape, with a resolution of one second. An IMSAI 8080 furnished the identification code. Its terminal, a Televideo Inc. Model 910, is shown in the picture. The aluminum box contains bandlimiting amplifiers.

Care was taken to insure that the maximum level of the amplified EMG signal did not exceed 1.8 volts rms - the maximum input allowed by the tape recorder specifications. Four separate EMG signals, two on either side of the neck, were recorded on four channels of the seven channel tape recorder. EMG signals vary in amplitude according to the location of the electrodes and the degree of tension that the respective neck muscles undergo. Therefore, the gain of each Systems Research Laboratory EMG amplifier was individually set so as to make full use of the dynamic

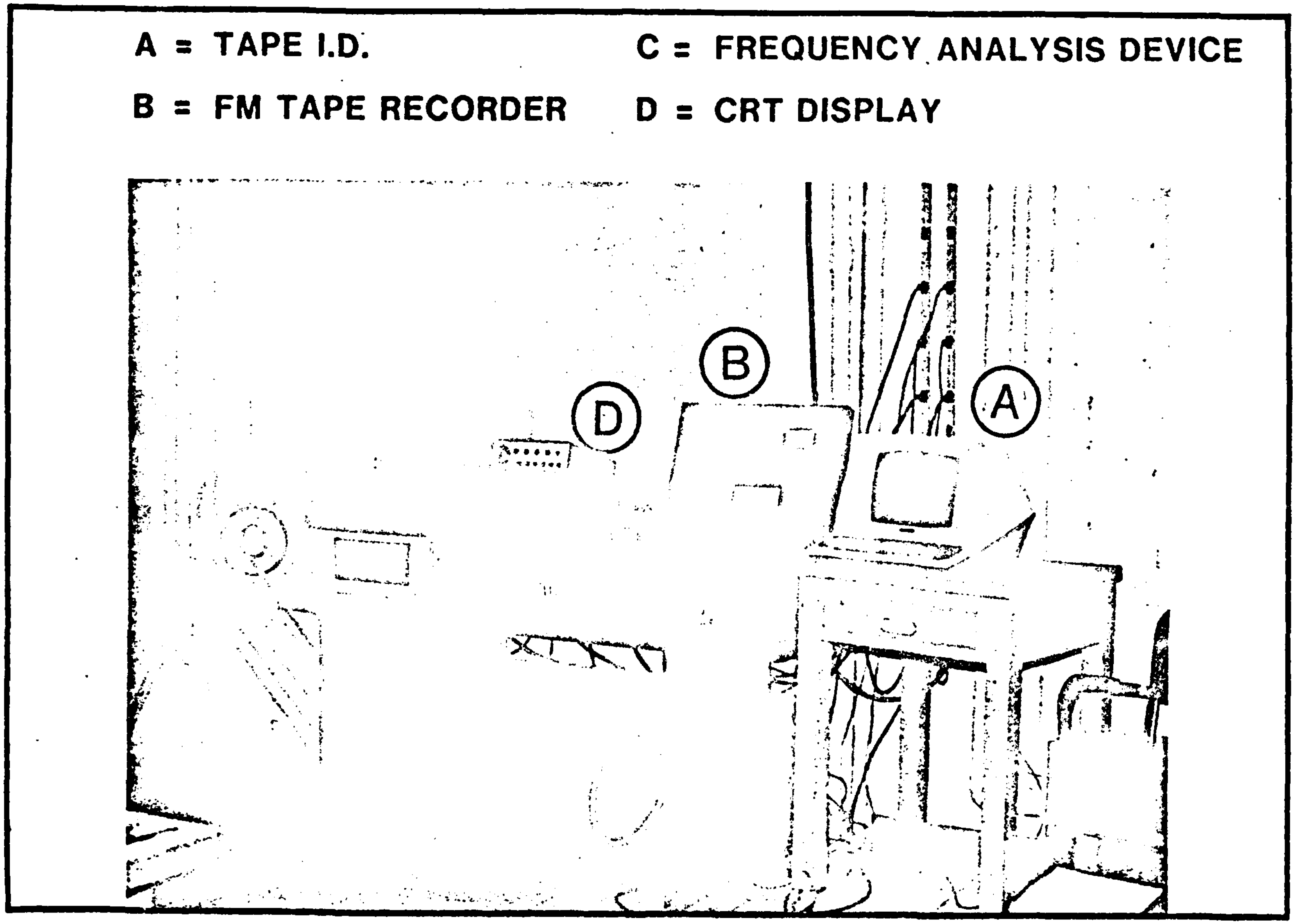

Figure 16. Instrumentation for EMG Recording and Analysis

range of the tape recorder.

The output of the tape recorder was displayed on a multichannel strip chart recording while the EMG was being recorded. Thus, any degradation of the EMG signal due to loose electrodes, a malfunctioning EMG amplifier or tape recorder becomes readily apparent. The strip chart recording also provides useful information on the relative amplitudes of each of the electromyograms. The FAD can independently set the gain on each of its two input channels. The bandlimited amplifier can also be used to individually amplify the two channels of EMG so that they are approximately equal before being input to the FAD. This equalization technique provides resolution of the two EMG signals.

The bandlimited amplifier consists of a fourth order Butterworth low pass filter with selectable amplification factors of 1, 2, 3 and 4, and a cutoff frequency of 375 Hz. The frequency response of the bandlimited amplifier is flat to 250 Hz, the highest frequency normally of interest in an electromyogram. Aside from amplifying, the amplifier also alleviates aliasing effects in the Fourier transform calculations. Aliasing is the phenomenom of downward spectral transposition of signal energy when a continuous waveform contains some unsuspected components at frequencies higher than one-half the sampling frequency. The resultant output waveform is therefore a lower frequency than the waveform sampled.

Precautions were taken to minimize the possible introduction of extraneous signals into the electromyogram. The software contains a pseudo filter. DC through 8 Hz spectral components are never used in rms or centroid calculations even though they may appear in spectral plots. This low frequency negation prevents the appearance of errors in the rms or centroid calculations due to baseline shifts. A check was made for the presence of 60 Hz noise before each data collection session. If the 60 Hz noise exceeded three percent of the maximum EMG signal, corrective measures were taken to reduce the noise to that acceptable level.

Vita

Robert Andrew Johnson was born on 13 June 1951 in Greeneville, Tennessee. He graduated from high school in Dayton, Ohio in 1969 and attended Wright State University from which he received the degree of Bachelor of Science in Biology in June of 1976. Upon graduation, he was employed by a commercial firm for two years at which time he reccived a commission in the USAF through the OTS program in October 1978. His first assignment was to the NORAD Cheyenne Mountain Complex in Colorado Springs, Colorado. He served as a Surveillance Officer, Orbital Analyst, and Space Defense Analyst prior to becoming the Assistant Chief, Orbital Analysis Branch. He held this position until entering the School of Engineering, Air Force Institute of Technology, in June 1981.

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