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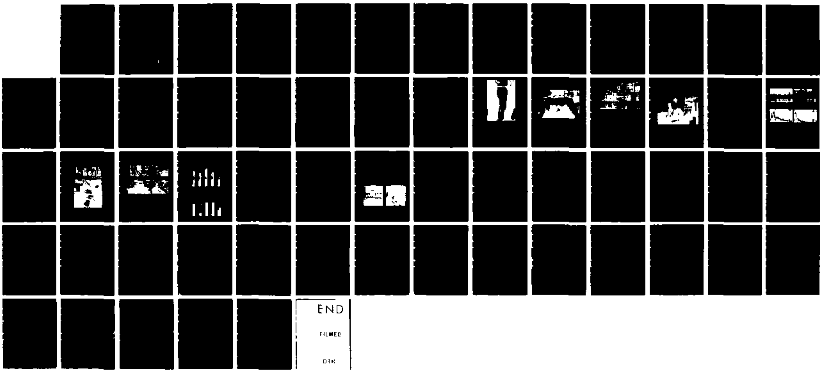

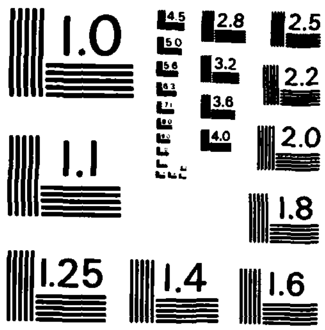

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THE EFFECTS OF HELICOPTER VIBRATION ON THE SPINAL SYSTEM

FINAL ~~Annual Progress~~ Report

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David Wilder
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July 1984

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Initial work was performed to determine the objective correlates in vibration and posture as etiologic agents in low back pain in UH-1-H pilots. Existing pilot/UH-1-H cockpit relationships were measured and utilized in a UH-1-H cockpit simulator. Correlations were made between muscle EMG activity and force produced. Basic studies were performed to determine the effect of muscle fatigue on the muscle EMG activity. This basic work leads to work to be done studying the effects of the UH-1-H environmental factors on pain onset and duration.

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INTRODUCTION

Severe, acute and sometimes debilitating backaches have been reported by pilots of two-bladed helicopters. Vibration is probably a major contributor to the problem, but a lack of information on muscular tolerance to vibration and the role of vibration in fatigue makes a solution through appropriate equipment design exceedingly difficult. Chronic back ailments in aircrewmen having several thousand hours of flight experience deplete the aviation manpower resource and reduce its effectiveness. The cause of the ailments is thought to be vibration-induced damage to the spine. Data on joint morphology resulting from long-term exposure to vibration do not exist, but are essential for establishment of standards to limit the hazard. Crewman integration into sophisticated or closed-loop fire control systems has been proposed in the Advanced Combat Vehicle Technology program and the Advanced Attack Helicopter program. Vibration plays a significant role in the effectiveness of man in such systems, yet there is insufficient information to adequately account for human response in the design of such systems. Vibration is known to adversely affect health. However, standards do not exist which relate vibration exposure in the military-unique environment to these known hazards.

To assess these effects in the Army rotary wing aviator, the investigators planned to gather biomechanical data to assess these hypotheses:

a. The biomechanical effects of helicopter vibration will be significantly modified by the posture of the aviator, and thus the layout of the controls, the cockpit, and the seat design.

b. The effects of these vibrations will be sufficient to cause soft and hard tissue stress and subsequent injury.

The investigators felt that they could make a unique contribution toward this end because they have a history of assessing the biomechanics of vibration environments and various conditions of low back pain. The point of the work for the Army was to provide objective correlates for the assessment of the effect of vibration and seating to pain production in the pilot. The volunteer population available consisted of people who had no history of low back pain or flight in UH-1-H helicopters. Thus, there was an opportunity to assess the onset and duration of pain during the simulated vibration/flight environment in these unaffected, healthy normal subjects.

The first year of work (on contract: University of Vermont Extramural Contract No. DAMD 17-82-C-2153) dealt with developing methodologies and equipment in concert with recommendations from USAARL. The past year's work specifically addressed: 1) the normal orientations of the UH-1-H pilot's lower body segments; 2) the methodologies for obtaining muscle electrical activity of the lower back (Andersson, Ortengren, Schultz 1980; Johnson 1978); 3) the effect of muscle contraction-induced fatigue on muscle electrical activity (Lindstrom, Magnusson, Petersen 1970; Lindstrom, Kodefors, Petersen 1977; Lloyd

1971; Petrofsky, Dahms, Lind 1975; Petrofsky 1980; Viitasaalo and Komi 1977), and 4) methodologies to correlate muscle electrical activity (EMG) and discomfort of subjects during a two-hour static (non-vibrating) flight simulation (Aitken 1969). And, the past year's work has shown that: 1) center frequency shifts of the surface EMG power spectral density function (PSDF) associated with muscle fatigue during isometric loading to fatigue can be observed in the erector spinae musculature; 2) characteristic erector spinae surface EMG changes have provided a non-invasive, quantitative and objective indicator for assessing lower back muscle fatigue, and 3) each subject has a unique erector spinae surface EMG versus load relationship which may differ from others or from the group.

METHODS, MATERIALS, AND RESULTS

Subject Testing Performed

The past year saw three different tests performed. The first was to determine the orientations of the lower body segments of the seated pilot. Four pilots (all male) from the Vermont Air National Guard were instrumented to provide these data (TABLE I).

To determine the correlation of muscle electrical activity (EMG) with isometric load produced, twenty subjects (10 male, 10 female) (TABLE II) were monitored for their load versus EMG correlations. Muscle fatigue due to sustained isometric loading to fatigue was also evaluated in the same twenty subjects. The degree of fatigue was quantified by a shift in center frequency of the power spectral density function of the EMG signal (in the range of 1-200 Hz).

To evaluate the new set-up of the helicopter seat, 4 pretests were conducted to validate the monitoring of signals in the static flight position. Analysis of EMG signals proved to be too low for spectral analysis, which prompted modification to gains.

To date, seven subjects from the group in Table II (3 male, 4 female) have been tested, seated for two hours in the UH-1-H cockpit simulator in only a static mode, to determine their EMG changes and level of pain in a static, seated configuration.

Relative Body Segment Orientation of the Pilot Seated in the UH-1-H Cockpit

Postural measurements were obtained on four male pilots in a UH-1-H aircraft at the Army National Guard in Burlington, Vermont, with the goniometers velcro-strapped to their legs and hips (Figs. 1 and 2). Pilots were asked to adjust the seat and foot pedal position to their normal flight posture. Knee flexion and pelvic angles were measured while the pilots were seated, with feet touching the pedals and hands gripping the cyclic and collective. Pilots could quickly and easily adjust their posture to the seat and pedals with a minimum back-and-forth adjustment.

Two areas of limb and postural support were observed while in the flight position. Common among the pilots was the resting of the right arm on their right leg while grasping the cyclic, and both heels touching the floor with feet resting against the pedals. All pilots remarked that these two supports helped stabilize the movement of the cyclic and foot pedals, creating friction on their movement during flight. The height and weight of the men covered a large range to compare the deviation of height and weight to individual angles of hips and knees. Considering the height range of 165.1 cm to 185.4 cm and the varying lengths of the appendages, the angles measured were similar with a small standard deviation (Table I). Based on so little motion as detected by goniometers during simulated flight, a standard (or mean) posture was determined for subject testing after conference with USAARL.

Three-Dimensional Field Vibration Data

The investigators sent their TEAC (Model R70-A) FM cassette data recorder to the Contracting Officer Technical Representative at USAARL, to obtain three-dimensional vibration recordings (Appendix I). Data were collected from an Endevco triaxial accelerometer attached to the UH-1-H seat rail. These vibration data were obtained for use in the UH-1-H vibration environment simulation.

UH-1-H Cockpit Environment Simulation

Detailed drawings and measurements were made in the cockpit of the UH-1-H aircraft of positions and relative distances of seat to pedals, collective, and cyclic. With these guidelines, a simulated cockpit environment of the seat and controls was fabricated on an aluminum platform with a steel supporting frame (Figs. 3 and 4). The cockpit platform was then supported by four vertical cables and attached to our vibration simulator by two load cells to monitor reaction force. The device was also capable of providing side-to-side and vertical vibration environments.

Fabrication of Amplifiers for Obtaining Back Muscle Electrical Activity Data

A custom 4-channel EMG amplifier was fabricated to process the surface biopotentials of the spinal musculature activity (Appendix II). The amplifier delivered a clean output with a high signal to noise ratio. Other electronic characteristics:

Signal to noise ratio:	30:1
Input Impedance	2 megohms
Filtering	Low pass at 10 KHz 60 Hz rejection
Frequency Response	DC - 70 KHz

After completion of Isometric Fatigue Testing, a pre-test of 4 subjects in the static flight position was conducted to assess the monitoring and recording system. Upon analysis, the recorded EMG signal was found to be too low in three cases for spectral analysis. After a conference call with Wells and Shanahan at USAARL to report this finding, the EMG amplifiers were modified to provide five additional ranges of gain to boost the EMG signal. Amplifiers were modified and now have six different gain settings providing the surface EMG amplitudes sufficient for spectral analysis.

Protocol for Skin Preparation and Electrode Placement for Obtaining Muscle Electrical Activity Data

The electromyographic signals were picked up by means of bipolar surface electrodes placed approximately 3 cm lateral to the midline of the back 3 cm apart vertically (Fig. 5) and the silver-silver chloride electrodes 12.5 mm in diameter (In Vivo Metric Systems) were filled with a conductive gel that interfaced with the skin. Application site was lightly sanded and prepared with a skin conditioner ("Skin Cleaner", In Vivo Metric Systems item #E403) to maximize adhesion and conductivity. Because of variable torso sizes, it was felt that Andersson's protocol of placing the electrodes a set distance from midline was inappropriate. Our modified technique of placing electrodes on the belly of the erector spine muscle determined by palpation (on the first test day) ensured a better placement for maximum EMG signal amplitude. An indelible mark was made to indicate electrode positions for following test days. Interelectrode resistances were measured and ensured to be less than 5 K ohms. Four channels of data were recorded on the TEAC FM data recorder: left and right erector spinae EMG activity, RMS value of right EMG, and force as indicated by a load cell attached to the chest harness.

Implementation of Spectral Analysis

Muscle EMG activity was monitored before and after isometric loading to fatigue tests. Typical EMG amplitude versus time signals are shown in Figure 6. Note that the "before" signal seemed to be much more compressed, indicating a higher frequency than the "after" signal. Using the Wavetek/Rockland model #5820A spectrum analyzer, one can see in the power spectra for these signals (Fig. 6) that there has indeed been a decreased signal from a higher to a lower frequency. It is this phenomenon of a decrease in the frequency of the EMG signal with fatigue that can be used to monitor muscle fatigue. As the spectrum analyzer could be controlled by the DEC 1123 minicomputer, a program was written (Appendix III) to compute the center frequency of the spectrum analyzed between one and two hundred Hertz. This is a single-number evaluation of the EMG spectrum, essentially the frequency at which the centroid of the plot area occurs.

Protocols and Programs for Load and EMG Data Acquisition and Analysis (Figure 7)

Data were gathered at each test point of interest. Force produced by the extension (pull on the load cell) of the subject in the seat and muscle EMG activity were recorded on a FM cassette data recorder (TEAC model #R-70A). The force and EMG data were analyzed via a DEC MINC 1123 lab computer. Additional EMG analysis was performed using a Wavetek/Rockland model #5820A spectrum analyzer, but that is dealt with in the previous section.

The following analyses were considered appropriate based on work by Andersson, Ortengren, and Schultz 1980 and Johnson, 1978. A brief program (Appendix IV) was written in BASIC to sample force and EMG data over a one-second period, sampling both channels at a rate of 1,024 points/second. So, there are 1,024 data points stored for each channel. The force data are then integrated over one second via this algorithm:

$$F = (1/T) \sum_{i=1}^{1024} (F_i \Delta t)$$

Where: F_i = instantaneous force at i

Δt = time step between samples (for these tests, t = 1/Sample Frequency)

So: $\Delta t = 1/1024 = 9.766 \times 10^{-4}$ sec

T = sample duration (used T = 1 sec for these tests)

The EMG data are similarly integrated over one second:

$$V_{EMG} = (1/T) \sum_{i=1}^{1024} (V_{EMG_i} \Delta t)$$

Where: V_{EMG_i} = the instantaneous EMG voltage at i

The root mean square value of the EMG signal over one second is also computed:

$$V_{RMS\ EMG} = \left[(1/T) \sum_{i=1}^{1024} (V_{EMG_i}^2 \Delta t) \right]^{1/2}$$

The EMG signal was also full wave rectified in order to detect the occurrence of signal peaks above a given level. The routine counted the number of times the EMG signal peaked at a value greater than the RMS value of the EMG signal.

Protocol and Results of Isometric Force vs. EMG Tests

In order to determine whether muscle electrical activity could indicate fatigue of the muscles, it was first necessary to find the correlation between the force the muscles were able to produce and their electrical activity (objective correlates)

Twenty subjects were evaluated for their force versus EMG activity. Each subject was tested on each day over a six-day period. The first day of testing was a day of training for the subject to become acclimated to the test. Generally, the testing on each day consisted of monitoring the subject's EMG activity and force production during a maximum (MVC) or percentage of maximum voluntary contraction. Subjects were seated in a UH-1-H seat while wearing a seat belt and maintaining a femur-to-back angle of 70-80°. A chest harness was worn which transmitted the horizontal forces from the torso to a vertical support (Figs. 8 and 9). The force exerted was monitored by a load cell and displayed on a digital read-out so the subject could see his force level and maintain a steady contraction. Prior to each day's fatigue test, three MVC efforts were performed using the maximum as the 100% MVC. Subjects also held, for a few seconds, various percentages of their MVC (80, 60, 45, 37.5, 30).

To date, data have been analyzed for the first five of the twenty subjects tested. The data gathered from the first five subjects were: 1) load vs. time; 2) left erector spinae EMG vs. time, 3) right erector spinae RMS EMG vs. time, and 4) load vs. root mean square EMG from the right erector spinae. The data (load vs. time, left EMG vs. time, right RMS EMG vs. time) were recorded on the FM cassette data recorder. The last set of data (load vs. rms right erector spinae EMG) was also plotted on a (x-y) flatbed plotter. The right side EMG data were passed through a rms to DC converter with a one-second time constant. These data were plotted with respect to load to show when the subject had "leveled out" in his or her MVC effort. Only after the subject had "leveled out" when applying a load (100, 80, 60, 45, 37.5, or 30% of MVC) w[illegible] the data recorder activated to record (over 8-10 seconds) 1) load v[illegible] [illegible]e and 2) left erector spinae EMG vs. time.

Data from the cassette recorder were digitized and a[illegible]ed to obtain: 1) integrated force over one second; 2) integrated (left) [illegible] over one second; 3) root mean square (left) EMG over one second, and 4) number of peak values of EMG which occurred greater than the rms EMG over one second (see section on "Protocols and programs for data acquisition and analysis"). These variables were then compared to each other and to the data obtained on the flatbed plotter (load vs. "rms" right erector spinae EMG).

Specifically, the following correlations (using the "MINITAB" statistical routines, Appendix V, were made [Table III]): 1) integrated force to force measured from flatbed plotter (reason: how well do these two force recording techniques compare); 2) integrated left EMG vs. rms right EMG (reason: compare analysis techniques); 3) rms right EMG (from rms to DC converter) vs. force measured from flatbed plotter (reason: evaluate force vs. EMG correlation), 4) integrated left EMG vs. integrated force (reason: evaluate this technique of force vs. EMG correlation); 5) left peaks vs. integrated force (reason: find validity of "peaks" count measurement), and 6) left peaks vs. integrated left EMG (reason: find correlation of peaks to EMG).

Correlations of EMG vs. load were made in both of the following manners: linear EMG vs. linear load and log (10 x "X" variable) vs. log (10 x "Y" variable). However, no comparisons were made between: log "X" variable vs. linear "Y" variable or linear "X" variable vs. log "Y" variable.

The reason for investigating the relation between log (10 x "X") vs. log (10 x "Y") was as follows: Andersson found a linear relationship between EMG and load, however the loads in our study exceed the loads reported by Andersson (1980). In our study some of the individual tests produced a better "r^2" value with the log-log correlation than the linear-linear correlation. However, when collective data from all five subjects were combined, the log-log curve fit did not produce a better correlation between force and muscle EMG activity than the simpler linear fit.

The correlations to date (n=5 subjects) show that peaks counting does not correlate well with either force or EMG activity. The EMG activity (as processed by the electronic RMS-to-DC converter) and measured force (taken from the flatbed plotter-produced records) correlation is better than the correlation of EMG vs. force as processed by the lab computer. However, as the data analyzed were from the first five of twenty subjects tested, further analysis is needed.

Protocol and Results of
Isometric Muscle Fatigue Tests

Since a correlation was found between muscle force production and EMG activity, the next step was to evaluate the fatigue of the muscle via spectral analysis of the EMG signal. Previous workers (Lindstrom, Magnusson, Petersen 1970; Lindstrom, Kodefors, Petersen 1977; Lloyd, 1971; Petrofsky, Dahms, Lind 1975; Petrofsky 1980; Viitasaalo and Komi, 1977) have shown that there is a change in muscle firing frequency before and after exertion. A spectrum analyzer was used to determine the shift of the center frequency (in most cases the frequency decreased, the frequency never increased) of the EMG power spectrum density function (PSDF).

After completing isometric load vs. EMG tests, a 10-minute rest was allowed before starting each day's fatigue test. Five days of fatigue tests were conducted at either 80,60,45,37.5, or 30% of the subject's initial MVC for that day. A constant force was held until exhaustion or until pain interrupted their isometric contraction.

Protocol:	3 maximum voluntary contractions (3 seconds)	
	80% MVC	5 seconds
	60% MVC	5 seconds
	45% MVC	5 seconds
	37.5% MVC	5 seconds
	30% MVC	5 seconds

All held for 5 seconds, with 2 minutes rest between

10-minute rest

Fatigue test to exhaustion - at one of the % MVC

Analysis of the EMG signal's spectral activity was determined over a 6-second period at the beginning and end of the 5 fatiguing tests. Using the index counter on tape recorder and observing recorded EMG signals on an oscilloscope ensured sampling occurred at the beginning and end of the test period.

Table IV and Figure 10 show the results of the decrease in center frequency for the group of 20 subjects. Statistics were compiled for individual groups (males and females) on both left and right EMG center frequency decreases.

For all fatigue tests center frequency decreased when comparing the beginning to end of test. Comparisons were made between sides for the same sex and between sexes for same side. The only significant difference in changes occurred between sexes on each side at the 30% MVC level, where the females decreased in activity significantly less. The significance of this work indicates that there is no difference in the changes between sexes for the same side or between sides for the same sex except at the 30% MVC level.

Protocol and Preliminary Results of
Static UH-1-H Cockpit Seating Tests

Subjects were seated in the UH-1-H seat and adjustments made to seat height and distance to pedals to conform to the standard flight position of pilots (Fig. 4). After placement of electrodes on the back, EMG signals were monitored to observe their amplitude and gains were adjusted to display an amplitude suitable for recording. Subjects were instructed in how to grasp the cyclic and collective and told they could remove the left hand from the collective for one minute every half-hour (guidelines from USAARL). Instrumented into the cyclic were the controls for an Atari video game, which subjects were instructed to use in order to concentrate on a "mission".

One maximum voluntary contraction was performed to establish a 60% contraction level to be used prior to and at the end of two-hour seating test. Chest harness used for horizontal loading was the same as that used in the isometric fatigue study. It was removed during the two-hour seating test. The two-hour test period began when initial EMG signals were recorded (time = 0). Recordings were then made every 15 minutes for a total of 9 samples. Also recorded was the time of onset of pain and level of pain at onset and at 15-minute periods following, using the visual analog scale (Aitken, 1969). At the conclusion of two hours, the harness was reapplied and the 60% MVC was held to fatigue. Following the test, subjects were monitored on the duration of time for which the pain persisted.

Protocol: MVC - 60% MVC for 5 seconds
Sample EMG - time: 0,15,30,45,60,75,90,105,120
Record onset of pain and intensity of pain
60% MVC to fatigue.
Follow-up on duration of time pain persisted.

To date, 7 subjects have completed this testing. Preliminary results exhibited by VAS indicate all subjects perceived some level of pain, and processing of EMG (PSDF) has shown varying decreases of center frequency.

DISCUSSION

The investigators have performed the ground work to determine the objective correlates in vibration and posture as etiologic agents in low back pain in UH-1-H pilots. Existing pilot/UH-1-H cockpit relationships were measured and utilized in constructing a UH-1-H cockpit simulator. As muscle electrical activity was to be used to monitor muscle fatigue and to be correlated to pain onset, basic correlations between muscle EMG activity and force produced were made. Also, basic studies were performed to determine the effect of muscle fatigue on the muscle EMG activity. With this basic work done, the investigators feel they are ready to start objectively studying the effects of the UH-1-H environmental factors on pain onset and duration.

SUMMARY

1. A subject pool, with no previous experience of low back pain or UH-1-H experience was located for use in this study.

2. The investigators experienced the UH-1-H ride quality.

3. The UH-1-H pilot body segment orientations were determined.

4. A tape (for later simulation use) was obtained of the three dimensional vibrations of a UH-1-H during a mission.

5. A UH-1-H cockpit (with seat) simulator was constructed.

6. A 4-channel electromyography (EMG) amplifier was constructed.

7. The protocol for reproducibly locating the appropriate points on the erector spinae muscle bellies and attaching the EMG electrodes there, was developed.

8. A spectrum analyzer was obtained and implemented for EMG and vibration waveform analysis.

9. Protocols and programs to collect and correlate force and EMG activity data (via a DEC MINC 1123 minicomputer) were implemented.

10. Correlations were obtained between muscle electrical activity and force produced.

11. Decreases in muscle EMG frequency were correlated with muscle fatigue (decrease in center frequency of EMG power spectral density function).

12. Initial tests were made of the effects of sitting in the UH-1-H cockpit simulator in a static mode.

CONCLUSION

The first year's research involved developing instrumentation, techniques, and methodologies to assess the effect of muscle contraction, including fatigue, on the EMG electrical activity of the erector spinae musculature.

This research has shown that: 1) center frequency shifts of the *surface EMG power* spectral density function (PSDF) associated with muscular fatigue during isometric loading to fatigue can be observed in the erector spinae musculature; 2) characteristic erector spinae surface EMG changes have provided a non-invasive quantitative and objective indication for assessing lower back muscle fatigue, and 3) each subject has a unique erector spinae surface EMG versus load relationship which may differ from others' or from the group.

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Table I

Anthropometric and limb segment orientation on pilots monitored in flight position

	x	S.D.
Weight (kg)	74.5	10.9
Height (cm)	174.6	8.9
Knee angle (°)	119.5	6.6
Hip angle (°)	102.5	2.1

Table II

Anthropometric data of 20 subjects used in the EMG vs. force, muscle fatigue, and static seating tests

		Males	Females
Age (years)	x	27.7	27.0
	S.D.	5.6	5.3
Height (cm)	x	177.3	164.2
	S.D.	6.1	5.7
Weight (kg)	x	74.1	57.4
	S.D.	7.0	5.5

TABLE III

Correlation of variables involved in determining relationship between force and erector spinae EMG activity. (n = 5)

Variables: Dependent	Variables: Independent	Intercept	Slope	r^2 Adj for D.O.F.
linear	linear			
Force	Measured force	.0158	1.06	86.0
(L) EMG	(R) RMS EMG	.103	.960	60.8
(L) peaks	Force	1.24	.250	21.9
(L) peaks	(L) EMG	1.24	.243	25.0
(R) RMS EMG	Measured force	.0023	.871	72.9
(L) EMG	Force	.101	.815	54.7
Log (10x: X)	Log (10x: Y)			
(R) RMS EMG	Measured force	.174	.991	72.5
(L) EMG	Force	.487	.675	49.0

TABLE IV

Comparison of % Center Frequency Decrease

MVC	Side	Males x	Males SD	Males n	Females x	Females SD	Females n	t	dof	p
80%	L	19.4	13.7	10	17.6	10.0	10	0.354	18.3	NS
	R	18.4	12.0	10	18.3	9.5	10	0.021	19.0	NS
	t	0.174			-0.183					
	dof	19.659			19.948					
	p	NS			NS					
60%	L	17.0	10.9	10	15.4	10.6	10	0.354	19.984	NS
	R	17.7	11.3	10	16.4	9.1	10	0.283	19.130	NS
	t	-0.141			-0.249					
	dof	19.974			19.552					
	p	NS			NS					
45%	L	21.9	7.3	10	18.4	11.0	10	0.838	17.377	NS
	R	19.4	7.0	10	18.2	9.2	10	0.328	18.672	NS
	t	0.782			0.044					
	dof	19.965			19.394					
	p	NS			NS					
37.5%	L	17.6	7.4	10	17.4	11.3	10	0.047	17.245	NS
	R	16.8	7.1	10	18.4	10.6	10	-0.397	17.469	NS
	t	0.247			-0.204					
	dof	19.966			19.919					
	p	NS			NS					
30%	L	12.0	5.1	10	20.2	7.5	8	-2.642	13.532	.01
	R	12.2	5.1	10	20.9	8.2	8	-2.622	12.741	.025
	t	-0.088			-0.178					
	dof	20.0			15.874					
	p	NS			NS					

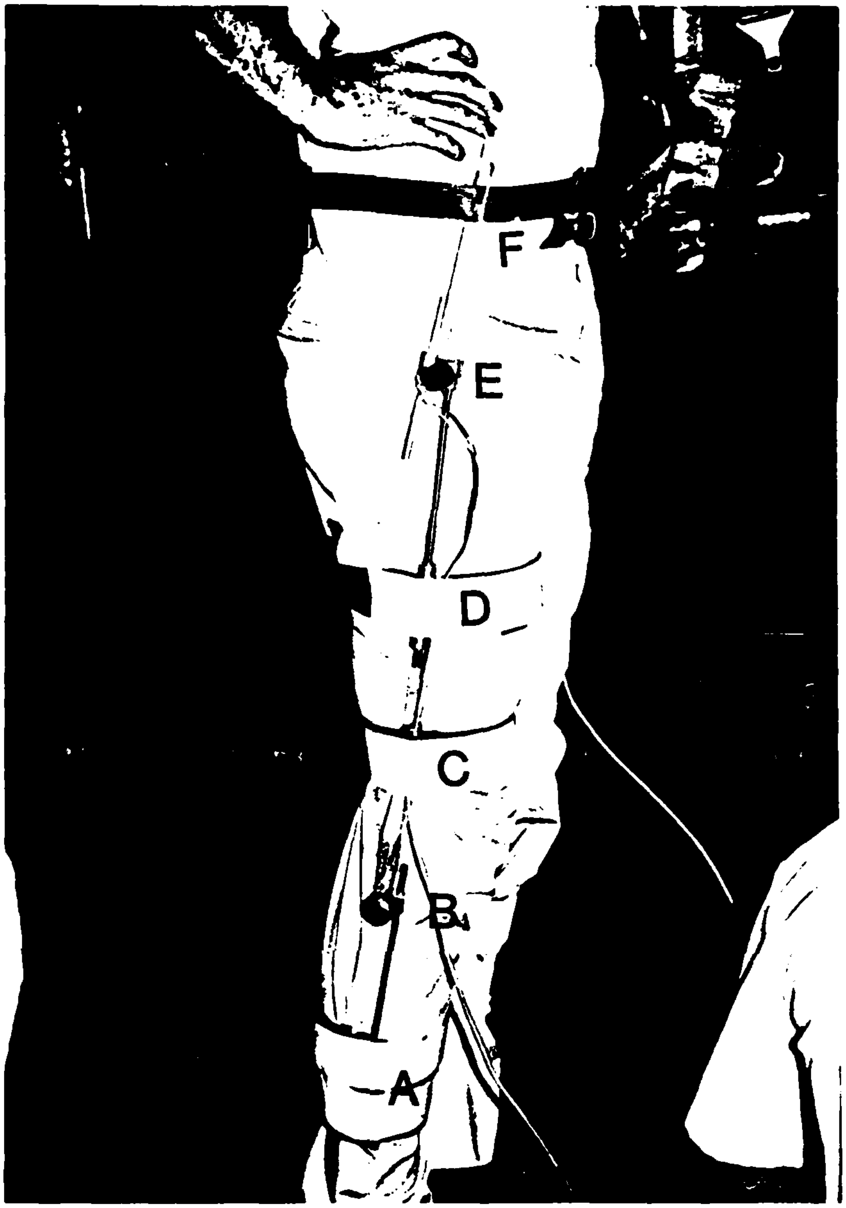


Fig. 1.

Electrogoniometry equipment to determine body segment orientation.

A. Calf electrogoniometer strap.
B. Knee angle electrogoniometer
C,D. Mid-thigh electrogoniometer strap.
E. Thigh/trunk angle electrogoniometer.
F. Trunk electrogoniometer strap.

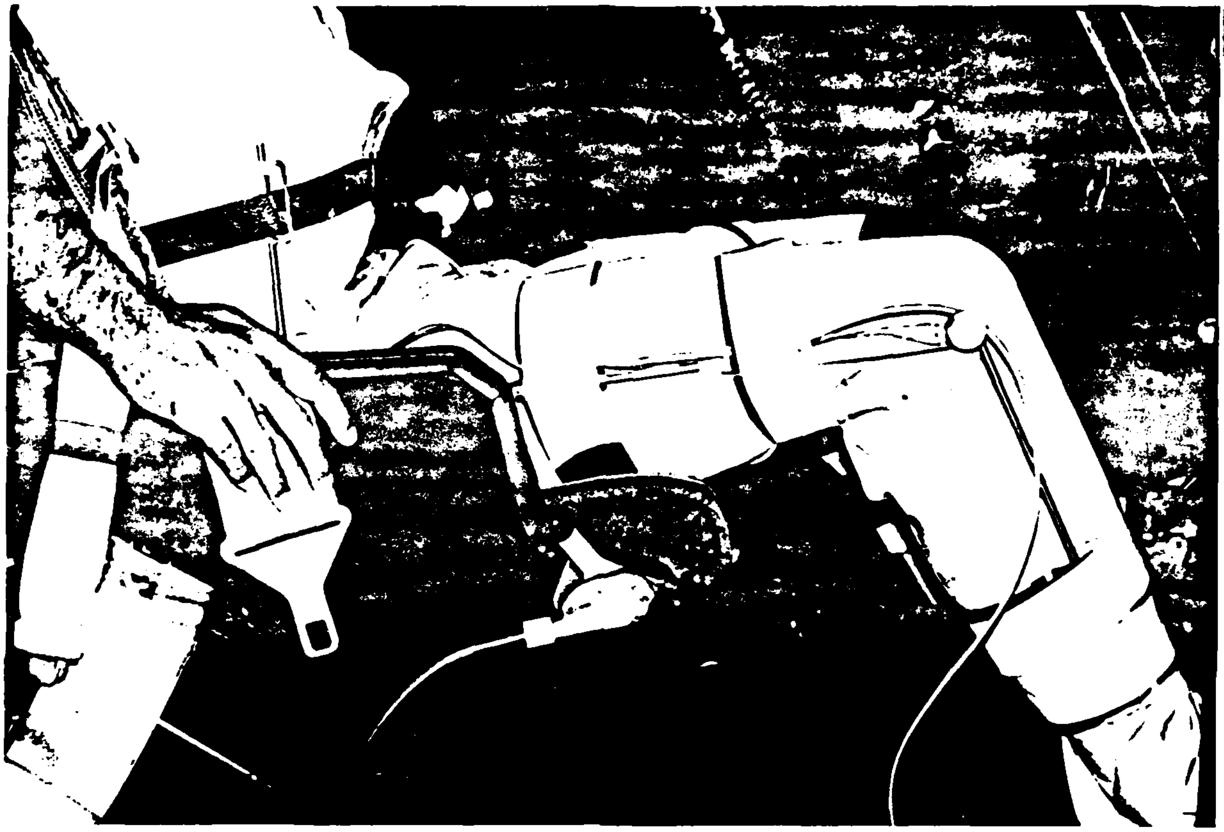


Fig. 2.

Electrogoniometry equipment to determine body segment orientation.

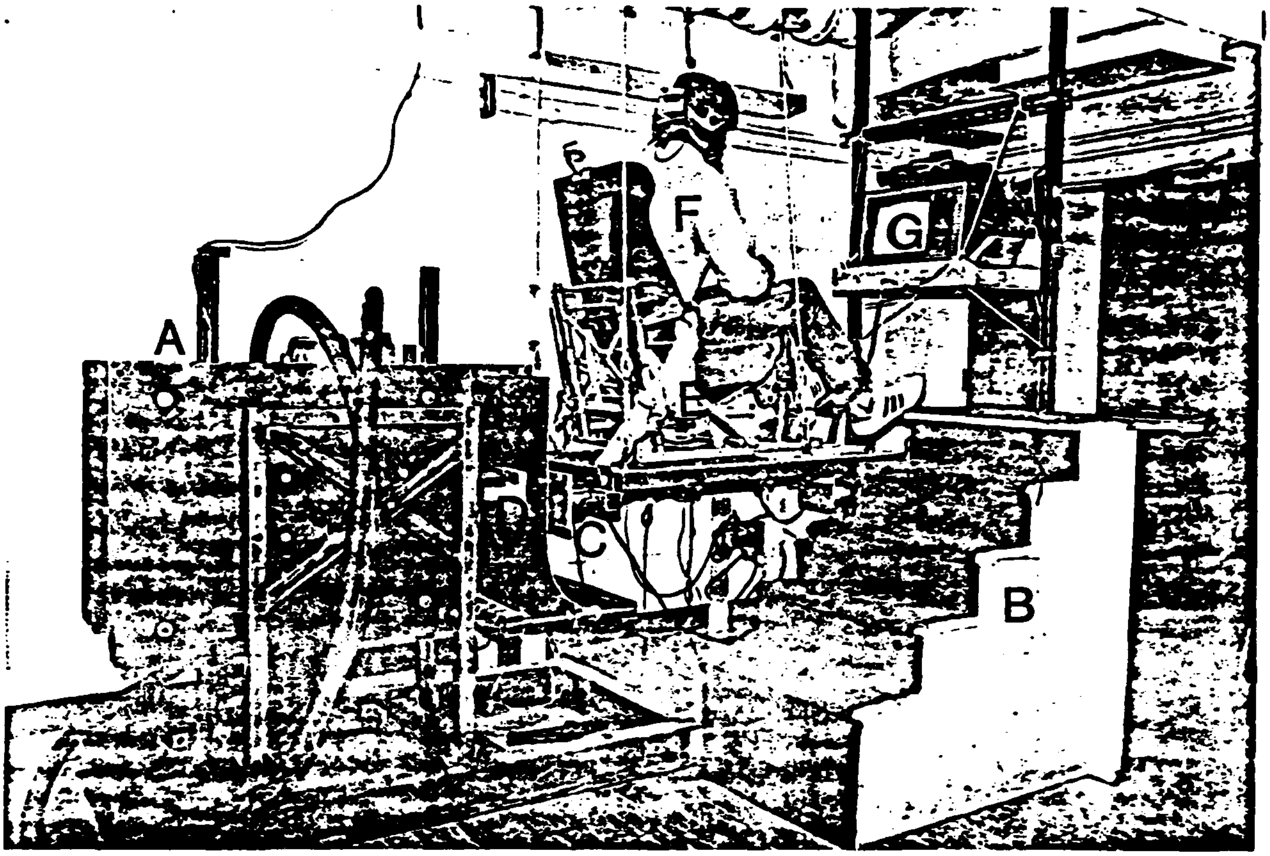


Fig. 3.

Overall view of simulated UH-1-H vibration/cockpit environment.

A. Vibration simulator base: capable of rotation to other orientations.
B. Steps up to simulator.
C. Reaction force sensing load cells.
D. Acceleration sensor.
E. UH-1-H seat in place on simulator.
F. Subject oriented in a manner similar to pilots.
G. Atari™ video game (controlled by cyclic).

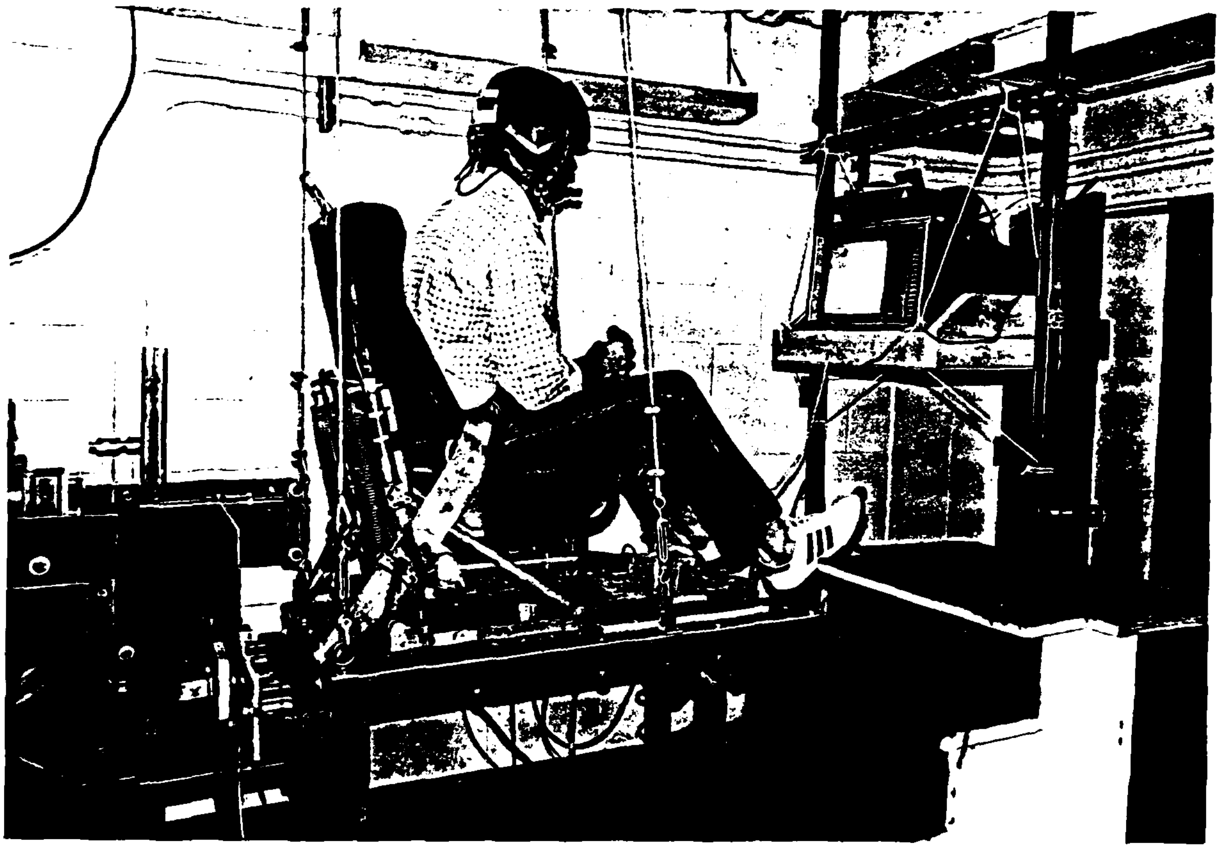


Fig. 4.

Close-up of simulated UH-1-H vibration/cockpit environment.

Fig. 5.

Placement of EMG electrodes over palpated bellies of erector spinae musculature.

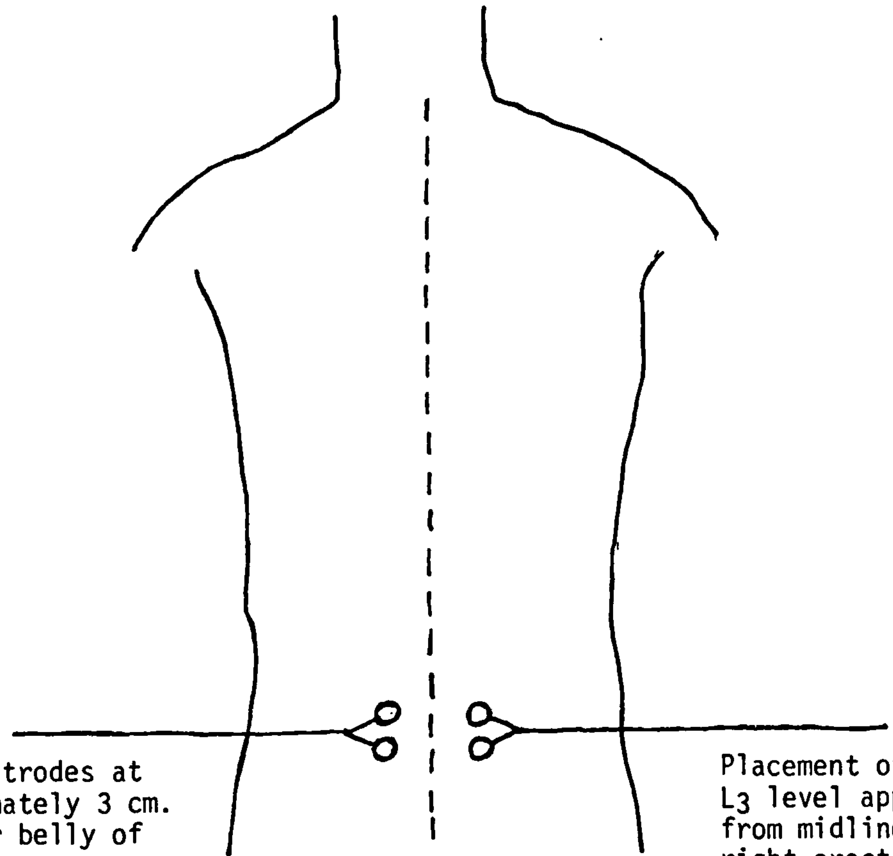
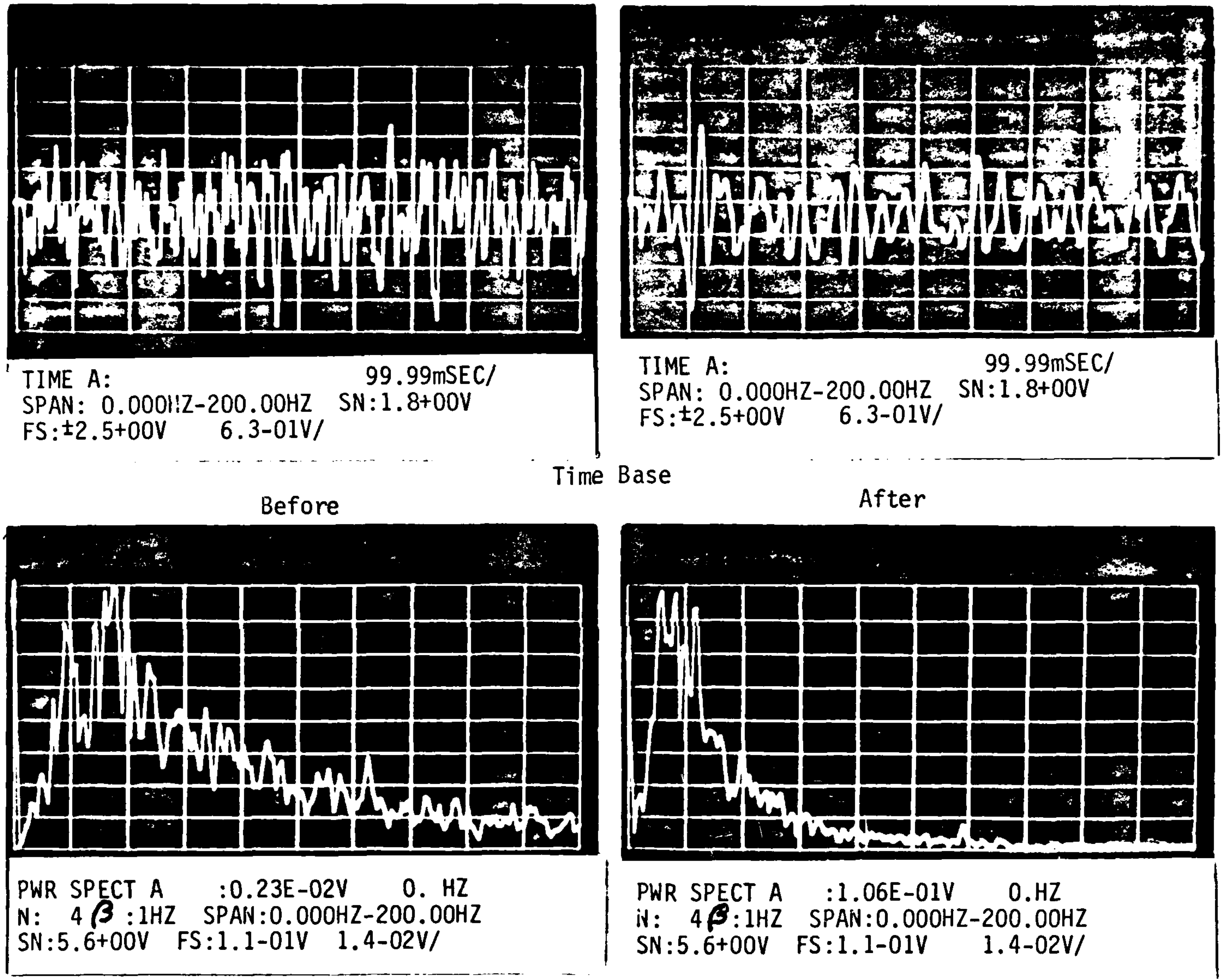


Fig. 6.

Representative EMG Data

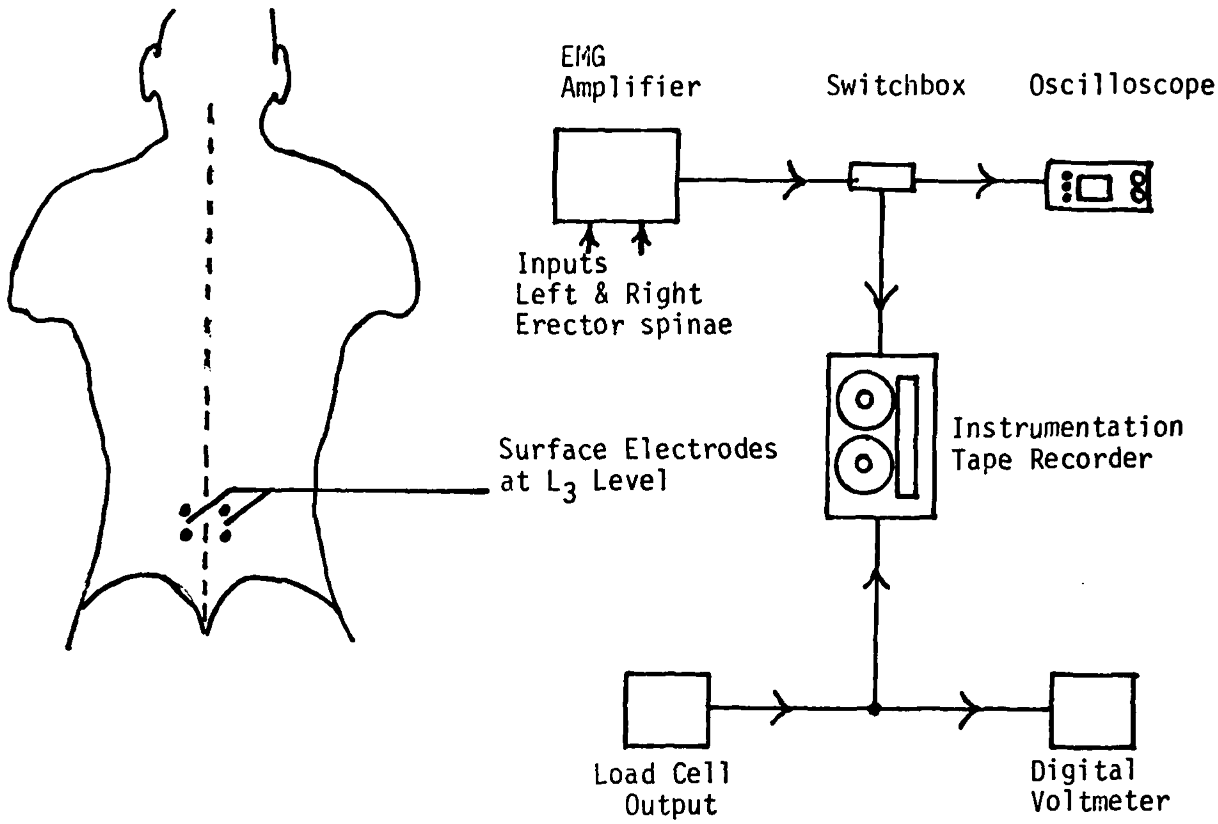


Power Spectrum

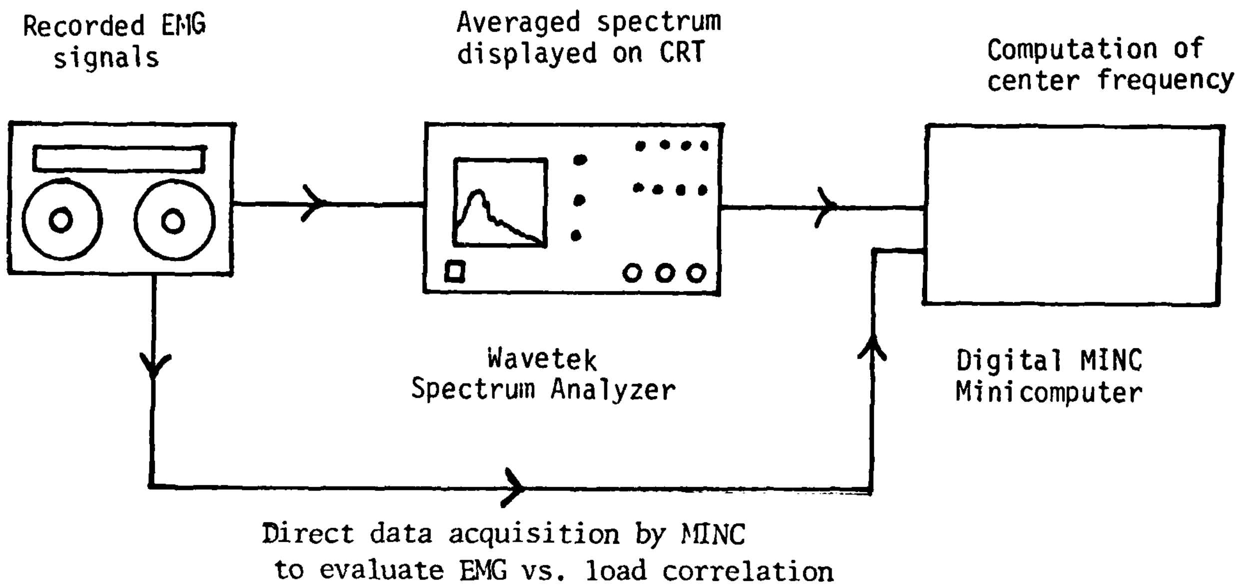
Before After

Fig. 7.

Data Acquisition



Data Analysis



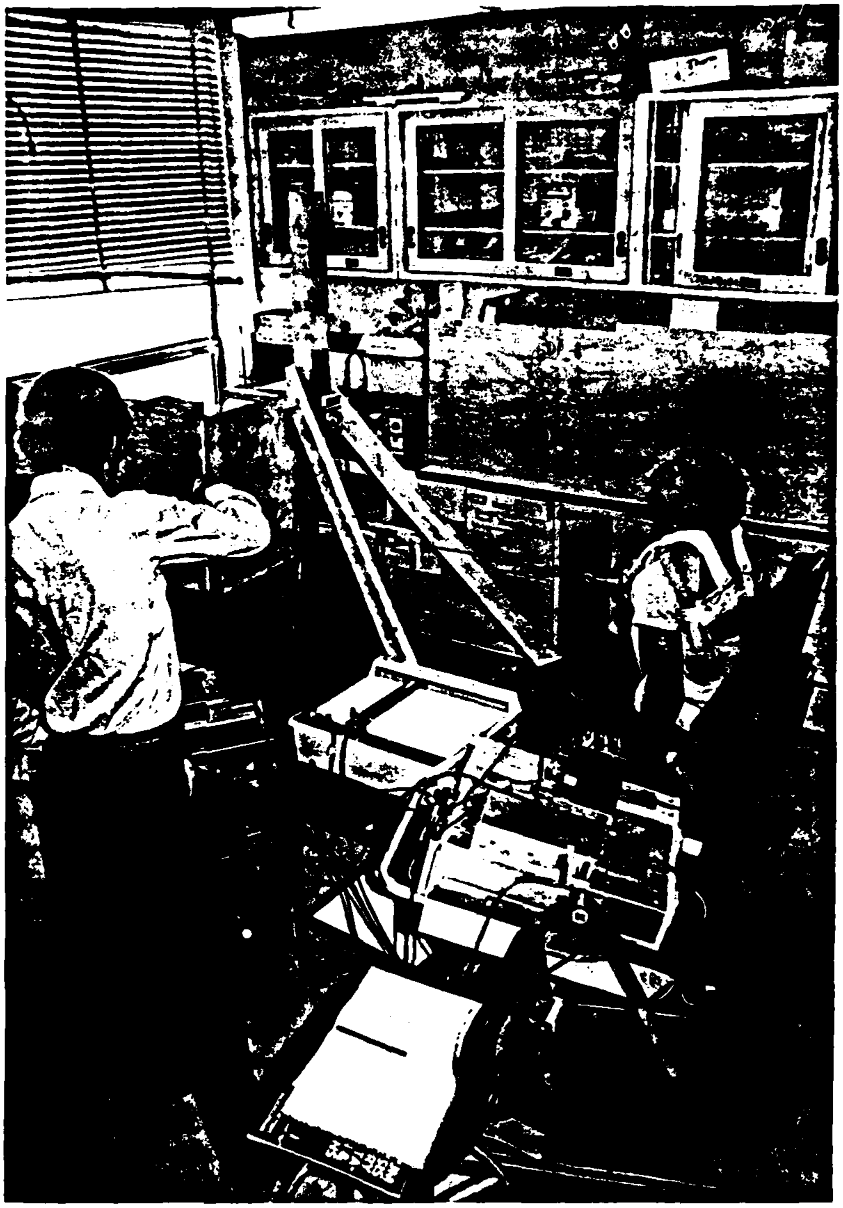


Fig. 8.

Overall view of "set-up" to determine EMG vs. force relationship.

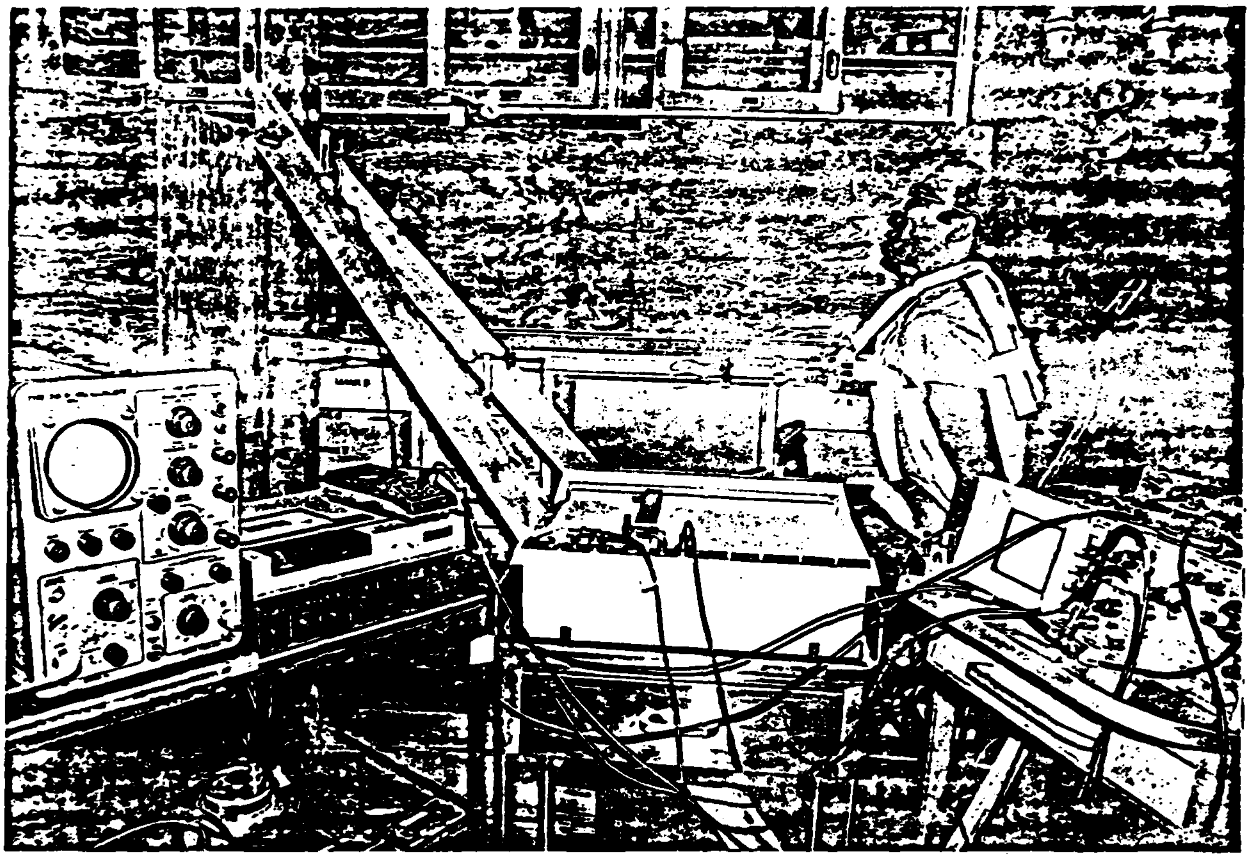
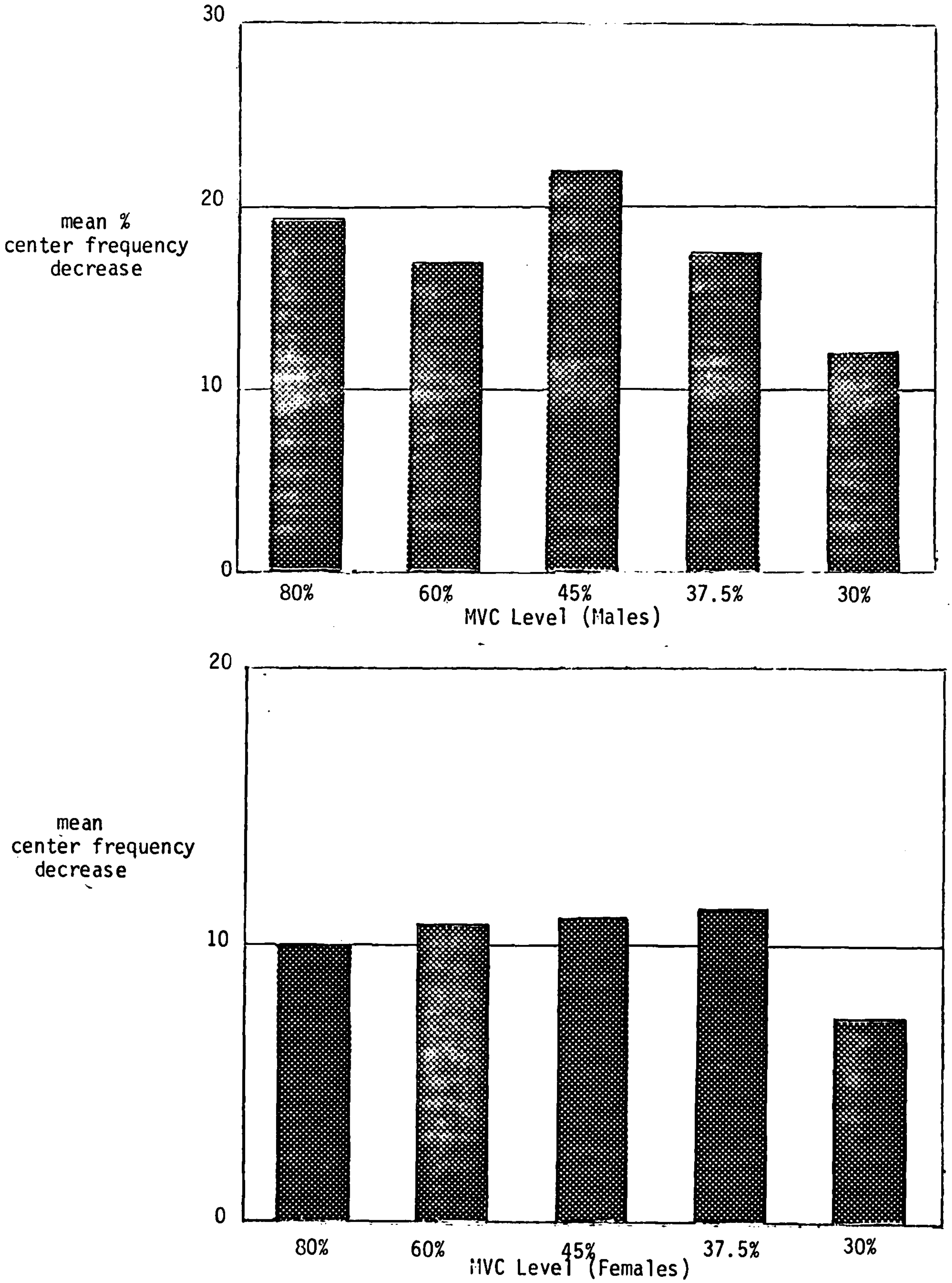


Fig. 9.

Close-up of "set-up" to determine EMG vs. force relationship.

Fig. 10.

Mean & Center Frequency of Decrease of Left Erector Spinae Muscle Activity



Appendix I

Acquisition of three-dimensional vibration data in the UH-1-H helicopter.

UVM-USAARL
VIBRATION DATA COLLECTION 7-15-82
DOCUMENTATION

Dennis Donnermeyer
University of Vermont
Burlington, Vermont

1. Vibration data for contract 0752-81 was recorded on 15 July 1982. I used your TEAC R70-A 4-channel FM recorder. I used ENDEVCO model 2730 charge maplifiers and an ENDEVCO model 2223D tri-axial accelerometer.

2. Equipment was set up as in Figure 1 of this letter. The output of the charge amplifiers was fed into the 4-channel recorder, and a multichannel oscilloscope in order to monitor the vibration signals. 120 in. transducer cables (ENDEVCO, microdot) fed from the accelerometer to the amplifiers. The accelerometer was mounted on the rear outer seat rail of left seat as shown in figure 2.

3. Calibration procedures were as follows:

   a. An ENDEVCO model 4815A accelerometer simulator was used to calibrate the charge amps. The simulator was first set so that the peak-to-peak value for the simulator for a 100 Hz signal in the 10 v/g full-scale range was 10 mv (7.07 mv rms).

   b. The simulator was then adjusted to the sensitivity of the particular axis being measured (pk/g).

   c. A 100 Hz signal, at the particular sensitivity of each accelerometer direction, of an equivalent 1 g signal was fed into the respective charge amplifier the output of the amplifier was adjusted, with the same type of vornier calibration pot as on the simulator, so that the amplifier output was 10v pk to pk (7.07 rms).

   d. The output to the charge amplifier was fed into the tape recorder and each channel was adjusted to the metered "100% range" with the level adjust potentiometers. The anticipated vibration signals were 0.1 g rms.

   e. 1.0 volt pk 100 Hz cal signals were annotated on each channel tape 0-30. Because I did not modify the microphone, I kept track of the tape counter and annotated the tape on return to the lab.

4. Events on the tape are as follows:

Tape	Comment, ch 4,	X,1	Y,1	Y,2	Z,3	(file no.)
0-30	Explanation	100 Hz, 1v pk (±0.5v) cal signal				
40-55	Ground, engine running				(1)	
55-75	Hover				(2)	
75-85	20 Kts, 1000 ft				(3)	
85-95	40 Kts, 1000 ft				(4)	
95-105	60 Kts, 1000 ft				(5)	
105-115	80 Kts, 1000 ft				(6)	
115-EOT	100 Kts, 1000 ft	(10)	(9)		(7)	

5. As there is a (10) step down on playing back through the tape recorder, the playback values are 1v/g. Therefore the conversion factor for driving with this tape is 1v=1 g.

6. I completed spectral analyses 19 July of the vibration data. My plotter fell victim to Deep South-itis (95% humidity) but I will have the spectra when we meet on 1 August.

Signed: John Wells

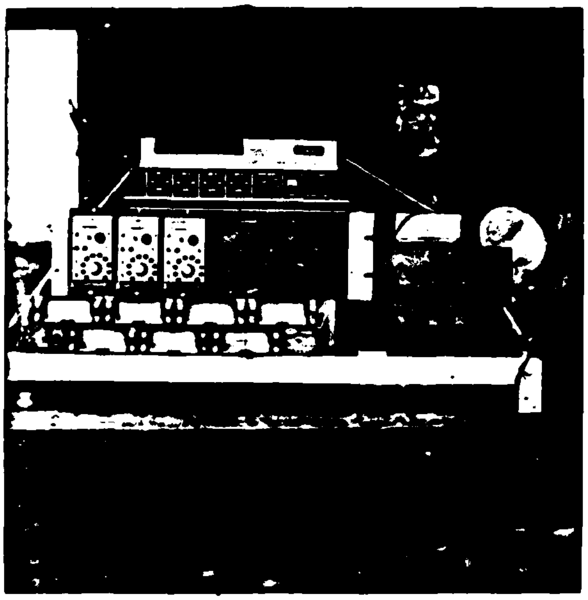


Figure I.1. Univ. of Vt. Teac Fm Casette Data Recorder with other instruments in UH-1-H

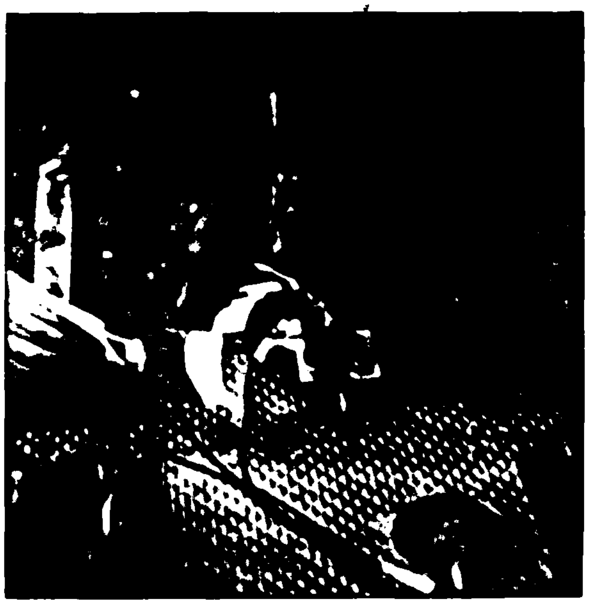


Figure I.2. Endevco triaxial accelerometer on rear outer seat rain of left seat in UH-1-H.

Appendix II

Specifications and schematic of EMG amplifier circuit

DEPARTMENT OF THE ARMY
U S ARMY AEROMEDICAL RESEARCH LABORATORY
FORT RUCKER, ALABAMA 36362

1LT Wells/bbk/AUTOVON
558-6883

SGRD-UAD-IV

5-24845
US DAMD17820-2153
COPE 6/30/83

21 September 1982

Dave Wilder
Department of Orthopaedics
Given Bldg., University of Vermont
Burlington, VT 05405

Dear David:

Attached as inclosure 1 is the FFT Algorithm Documentation. Also attached as inclosure 2 is the software used in our FFT using Hewlett Packard equipment.

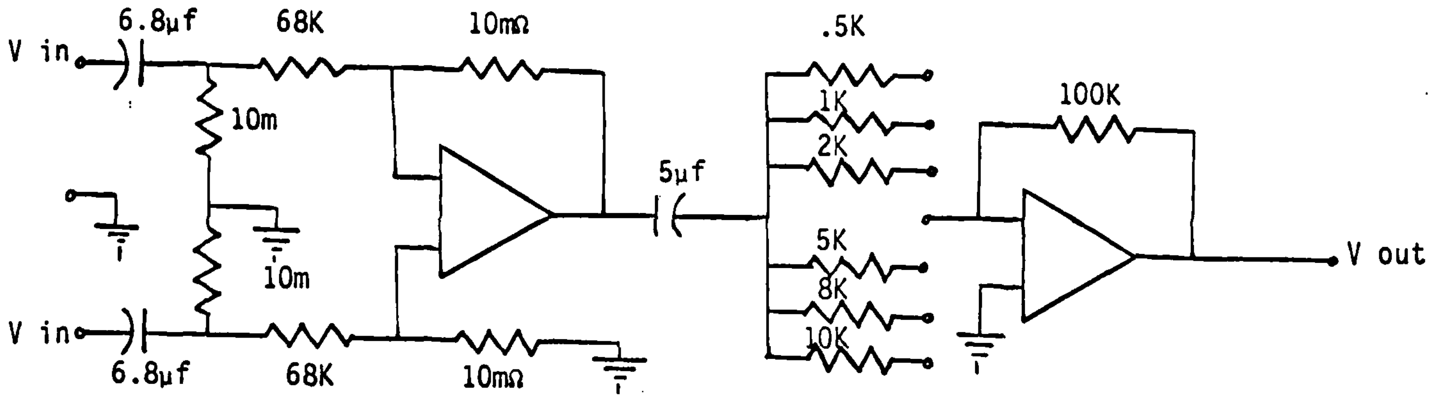
As regards the EMG amplifier, the following characteristics apply:

Impedance	2 megohms
Filtering	after the amplifier, low pass at 10 kHz (3 db drop point)
Frequency Response	DC to 70 kHz (3 db drop point)
Gain: ratio of	feedback resistor / input resistor
Additional	pre-amplification

Sincerely,

JOHN H. WELLS
1LT, MS
Contracting Officer's
Technical Representative

2 Incl
As stated



EMG Amplifier

Appendix III

Algorithm and program for determining center

frequency from EMG signals

PROCESSING OF EMG SIGNALS BY

SPECTRUM ANALYZER/MINICOMPUTER SYSTEM

The EMG signals recorded on tape are input to Wavetek/Rockland model 5820A spectrum analyzer using fast fourier analysis. The time signals are frequency analyzed in the range 0 - 200 Hz, with a resolution of 1 Hz. Operation of the analyzer is controlled by a DEC (MINC) 1123 laboratory minicomputer.

A special purpose program written for the MINC enables the minicomputer to perform the following two major functions:

1. Set-up of spectrum analyzer front panel. Software control of the spectrum analyzer results in faster data analysis. The panel controls are set as follows:

   a. Vertical scale linear, horizontal scale linear.

   b. Hanning window

   c. Number of samples average = 4

   d. Trigger - Transient mode

   e. Pulse

2. Read power spectrum and compute center frequency.

After the averaged spectrum is displayed on the spectrum analyzer screen, it is read by the minicomputer. The transfer of data takes place in ASCII format, which is then converted to a numerical value for each frequency.

The center frequency k is found by the equation

$$\sum_{i=1}^{k} A_i = (1/2)\left[\sum_{i=1}^{200} A_i\right]$$

where A_i is the power spectrum amplitude at frequency i.

```
 TYP CF4.BAS
10 REM CENTER FREQUENCY FROM WAVETEK
20 IEEE_BUS_CLEAR \ ALL_INSTR_CLEAR
30 DIM S(201)
40 SET_TERMINATORS(10)
50 SEND("SET FR R",20)
60 SEND("SET SC SP",20)
70 SEND("SET TR FR",20)
80 SEND("SET N 4",20)
90 SEND("SET W H",20)
100 SEND("SAMP INT",20)
110 SEND("SET VERT LIN",20)
120 SEND("SET FR L',20)
130 STOP
140 SEND("SET FR R",20)
150 SEND("READ SP A",20)
160 FOR I=1 TO 7
170 RECEIVE(R$,,20)
180 IF I=1 THEN S$=R$
190 IF I=2 THEN T$=R$
200 IF I=3 THEN U$=R$
210 IF I=4 THEN V$=R$
220 IF I=5 THEN W$=R$
230 IF I=6 THEN X$=R$
240 IF I=7 THEN Y$=R$
250 NEXT I
260 SEND("SET FR L",20)
270 REM S$
280 C=-7 \ D=-1
290 FOR J=1 TO 28
300 C=C+9 \ D=D+1
310 S(D)=VAL(SEG$(S$,C,C+7))
320 NEXT J
330 S(28)=VAL(SEG$(S$,254,255)+SEG$(T$,1,6))
340 REM T$
350 C=-1 \ D=28
360 FOR J=1 TO 27
370 C=C+9 \ D=D+1
380 S(D)=VAL(SEG$(T$,C,C+7))
390 NEXT J
400 S(56)=VAL(SEG$(T$,251,255)+SEG$(U$,1,3))
410 REM U$
420 C=-4 \ D=56
430 FOR J=1 TO 28
440 C=C+9 \ D=D+1
450 S(D)=VAL(SEG$(U$,C,C+7))
460 NEXT J
470 REM V$
480 C=-7 \ D=84
490 FOR J=1 TO 28
500 C=C+9 \ D=D+1
510 S(D)=VAL(SEG$(V$,C,C+7))
520 NEXT J
530 S(113)=VAL(SEG$(V$,254,255)+SEG$(W$,1,6))
540 REM W$
550 C=-1 \ D=113
560 FOR J=1 TO 27
570 C=C+9 \ D=D+1
580 S(D)=VAL(SEG$(W$,C,C+7))
590 NEXT J
600 S(141)=VAL(SEG$(W$,251,255)+SEG$(X$,1,3))
610 REM X$
620 C=-4 \ D=141
```

```
630 FOR J=1 TO 28
640 C=C+9 \ D=D+1
650 S(D)=VAL(SEG$(X$,C,C+7))
660 NEXT J
670 REM Y$
680 C=-7 \ D=169
690 FOR J=1 TO 28
700 C=C+9 \ D=D+1
710 S(D)=VAL(SEG$(Y$,C,C+7))
720 NEXT J
730 S(60)=S(59) \ S(61)=S(62)
740 S(120)=S(119) \ S(121)=S(122)
750 REM CENTER FREQUENCY
760 S1=0
770 FOR I=2 TO 195
780 S1=S1+S(I)
790 NEXT I
800 S2=S1/2
810 PRINT \ PRINT
820 S1=0
830 FOR I=2 TO 195
840 S1=S1+S(I)
850 IF S1>S2 THEN 870
860 NEXT I
870 PRINT "CENTER FREQUENCY = ";I;"  HZ"
880 PRINT \ PRINT
890 STOP \ END
```

Appendix IV

Program for force and EMG data acquisition

and analysis

```
TYP SY1:EMGLOD.BAS
10 PRINT  \ PRINT "Chan 0: Load cell;   Chan 1: EMG signal"
20 PRINT "Clock: St1: VAR/full CW,+slope;  St2: TTL,-slope,Switch closure on 'St2 out'"
30 PRINT "A/D: Do not exceed -25 or +20 volts on inputs"
50 DIM A%(1023,1) \ PRINT "Calibration: "
60 PRINT "Chan 0: Load cell (lbs/volt)  (C0=0:default): "; \ INPUT C0
70 IF C0=0 THEN 130
80 PRINT "Chan 1: EMG activity (millivolts/volt): "; \ INPUT C1
130 REM Set calibrations to default conditions
140 IF C0=0 THEN C1=.411 \ C0=160.8
160 REM  D:datalength  F:sweeps per second  C:1st channel  N:# of channels
170 D=2048 \ F=1024 \ C=0 \ N=2 \ P=1/F \ PRINT "Ready for data"
180 AIN('ST2,FAST',A%(),D,1/F,C,N)
190 A2=0 \ A3=0 \ P0=0 \ K0=0
230 FOR I=0 TO ((D/2)-1) \ A2=(ABS(A%(I,0)*C0*P*2.5E-3))+A2
235 A5=(ABS(A%(I,1)*C1*P*2.5E-3)) \ A3=A5+A3 \ P0=A5^2+P0 \ NEXT I
240 P0=SQR(P0/P)
244 REM Where P0=EMG(rms for 1 sec) and A3=EMG(time integrated for 1 sec)
246 REM   and A2=Force(time integrated for 1 sec)
250 FOR I=2 TO ((D/2)-2)
260 IF P0<ABS(A%(I,1)*C1*2.5E-3) THEN GO TO 280
270 GO TO 310
280 IF ABS(A%(I-1,1))<ABS(A%(I,1)) THEN GO TO 300
290 GO TO 310
300 IF ABS(A%(I+1,1))<ABS(A%(I,1)) THEN K0=K0+1
310 NEXT I
320 PRINT  \ PRINT "Integrated force: "; A2 \ PRINT "Integrated EMG: "; A3
325 PRINT "RMS value of EMG signal over 1 second: "; P0
330 PRINT "Full-wave rectified peaks above RMS of EMG signal: "; K0
335 PRINT
340 GO TO 10
350 END

READY
```

Appendix V

MINITAB statistics package: Regression package

documentation

Minitab

Reference Manual

by

Thomas A. Ryan, Jr.
Brian L. Joiner
Barbara F. Ryan

1/15/81

Minitab is a very easy to use, flexible, and powerful statistical computing system. It is machine compatible, and runs interactively or in batch. For information on availability, questions, or corrections, please contact:

Minitab Project
Statistics Department
215 Pond Laboratory
The Pennsylvania State Univ.
University Park, Pa. 16802

Phone: (814) 865-1595

This Reference Manual is a companion to the Minitab Student Handbook, published by Duxbury Press, 20 Providence Street, Boston MA 02116 (Telephone 617/482-8957)

13. REGRESSION

The regression command was written with extensive help from Prof. Webb C. Miller of the University of California Santa Barbara.

The regression command has a number of optional arguments The basic regression command is:

```
REGRESS y in C using K predictors in C,...,C
```

Note that the number of columns of predictor variables must be specified.

Most careful regression analyses require further analysis of residuals and residual plots. These are made possible by the optional storage columns. If one storage column is specified, the (standardized) residuals are stored; if two storage columns are specified, the predicted values are stored as well. A third storage column can be specified for storage of the regression coefficients. A fourth argument, a matrix, is for storage of (X'X)-inverse.

```
REGRESS y in C using K predictors in C,...,C, [store st.
                   residuals in C [pred. y in C [coef. in C
                          [ (X-prime)*X-inverse into M]]]]
```

Weighted fits may be done by specifying a column of weights following the column of y values:

```
REGRESS y in C, weights in C, using K predictors in C,...,C,
      [store st. resid. in C [pred. y in C [coef. in C]]]
```

In all cases, the command finds the least squares linear equation for predicting Y from k predictors X1, X2, ... Xk. This equation (also called the regression equation) is of the form

$$Y = b0 + (b1)X1 + (b2)X2 + \ldots + (bk)Xk.$$

The values b0, b1, ... bk are found by Minitab, and are called regression coefficients.

```
Example:  READ Y INTO C1 AND X INTO C2
            2.1  4.1
            1.5  2.2
            1.7  2.7
            2.5  6.0
            3.0 8.5
            2.1  4.1
            3.2  9
            2.8 8.0
            2.5 7.5
          REGRESS Y IN C1 ON 1 PRED. IN C2
```

If the command NOCONSTANT is in effect, the b0 term is not fitted in the equation. Therefore Minitab fits

Y = (b1)X1 + (b2)X2 + ... + (bk)Xk

Use of the regression command

By multiplying a column of X's by itself to create a column of X-squares, curves such as

Y = b0 + (b1)X + (b2)X-squared

can be fitted. By using Minitab functions such as SQRT and LOGE, equations such as

Y = b0 + (b1)ln(X)

can be fitted. Analysis of variance and analysis of covariance can be done by creating the appropriate dummy variables. The INDICATOR command may be useful. To fit models without a constant (b0) term, use the command NOCONSTANT (described in this Section.)

Further analysis usually follows the REGRESS command. The most important part of this analysis is usually the plotting of residuals. If the residuals and predicted values have been stored, the usual plots of the residuals versus the predicted values and the residuals versus each X variable are easily done by the PLOT command. If the order in which the observations were taken is known, the residuals should be plotted against time order. A histogram or normal probability plot of residuals is also recommended.

Examples

The output from a simple regression and output from a multiple regression are below. This is the "full" output, given when the command NOBRIEF is in effect. (See BRIEF and NOBRIEF below for other forms of the output. Additional output is possible using the BRIEF 6 command.) The use of the optional storage columns does not affect the output.

```
-- REGRESS Y IN C1 ON 1 PRED. IN C2

THE REGRESSION EQUATION IS
Y =     1.12 + 0.218 X1
                                               ST. DEV.      T-RATIO =
        COLUMN      COEFFICIENT                OF COEF.      COEF/S.D.
        --               1.1177                 0.1093           10.23
X1      C2               0.21767                0.01740          12.51

THE ST. DEV. OF Y ABOUT REGRESSION LINE IS
S = 0.1274
WITH (   9- 2) =    7 DEGREES OF FREEDOM

R-SQUARED = 95.7 PERCENT
R-SQUARED = 95.1 PERCENT, ADJUSTED FOR D.F.

ANALYSIS OF VARIANCE

 DUE TO      DF            SS        MS=SS/DF
REGRESSION    1       2.54192         2.54192
RESIDUAL      7       0.11365         0.01624
TOTAL         8       2.65557

            X1          Y     PRED. Y    ST.DEV.
ROW         C2         C1      VALUE     PRED. Y    RESIDUAL     ST.RES.
  1       4.10     2.1000     2.0101     0.0516      0.0898       0.77
  2       2.20     1.5000     1.5966     0.0755     -0.0966      -0.94
  3       2.70     1.7000     1.7054     0.0685     -0.0054      -0.05
  4       6.00     2.5000     2.4237     0.0426      0.0763       0.64
  5       8.50     3.0000     2.9679     0.0635      0.0321       0.29
  6       4.10     2.1000     2.0101     0.0516      0.0898       0.77
  7       9.00     3.2000     3.0767     0.0702      0.1233       1.16
  8       8.00     2.8000     2.8591     0.0573     -0.0591      -0.52
  9       7.50     2.5000     2.7502     0.0519     -0.2502      -2.15R
R DENOTES AN OBS. WITH A LARGE ST. RES.

DURBIN-WATSON STATISTIC = 1.11

(X-PRIME X)INVERSE

                0            1
   0     0.735748
   1    -0.107903     0.018640
```

Multiple regression

```
Example:  READ INTO C1    C2    C3    C4
                    20     1     1     2
                    25     4     2     3
                    10     3     4     1
                    12     6     8     2
                     4     4     8     1
                    24     4     4     2
          REGRESS Y IN C1 ON 3 PRED. IN C2, C3, C4
```

```
-- REGRESS Y IN C1 ON 3 PRED. IN C2, C3, C4

THE REGRESSION EQUATION IS
Y =     11.7 +  2.01 X1 -  2.45 X2
    +  4.25 X3
                                              ST. DEV.      T-RATIO =
        COLUMN       COEFFICIENT              OF COEF.      COEF/S.D.
        --                11.662                9.904          1.18
X1      C2                 2.014                3.424          0.59
X2      C3                -2.445                2.169         -1.13
X3      C4                 4.250                5.680          0.75

THE ST. DEV. OF Y ABOUT REGRESSION LINE IS
S = 4.638
WITH (   6- 4) =   2 DEGREES OF FREEDOM

R-SQUARED = 87.9 PERCENT
R-SQUARED = 69.9 PERCENT, ADJUSTED FOR D.F.

ANALYSIS OF VARIANCE

 DUE TO       DF          SS       MS=SS/DF
REGRESSION     3      313.81         104.60
RESIDUAL       2       43.02          21.51
TOTAL          5      356.83

FURTHER ANALYSIS OF VARIANCE
SS EXPLAINED BY EACH VARIABLE WHEN ENTERED IN THE ORDER GIVEN

 DUE TO       DF          SS
REGRESSION     3      313.81
C2             1       15.41
C3             1      286.36
C4             1       12.04

          X1          Y     PRED. Y    ST.DEV.
ROW       C2         C1       VALUE    PRED. Y    RESIDUAL    ST.RES.
  1     1.00      20.00       19.73       4.32        0.27       0.16
  2     4.00      25.00       27.58       3.80       -2.58      -0.97
  3     3.00      10.00       12.17       4.34       -2.17      -1.32
  4     6.00      12.00       12.68       3.66       -0.68      -0.24
  5     4.00       4.00        4.40       3.88       -0.40      -0.16
  6     4.00      24.00       18.44       2.38        5.56       1.40

DURBIN-WATSON STATISTIC = 1.07

(X-PRIME X)INVERSE

                  0             1             2             3
  0       4.56056
  1       0.81836       0.54492
  2      -0.72657      -0.32031       0.21875
  3      -2.25001      -0.75000       0.50000       1.50000
```

Glossary of regression terms

The terms used on the output and in this Reference Manual are as follows:

adjusted for d.f. See R-squared adjusted for d.f..

analysis of variance. The analysis of variance table gives the following sums of squares (SS). Let n = number of observations. The TOTAL SS = SUM((Y-Ybar)-squared), and has n-1 degrees of freedom. The SS DUE TO REGRESSION is SUM((Yhat-Ybar)-squared) where Yhat is the predicted value of Y. The SS RESIDUAL is SUM((Y-Yhat)-squared). The last column gives the mean squares which are useful for various F-tests.

BRIEF. Command which controls the amount of output of the regression command. See the description of BRIEF below.

coefficients. These are the constants b0, b1, ... found by Minitab, and are the coefficients in the regression equation.

covariance of the coefficients. Since the coefficients are determined by the data, they are random variables. The estimated covariance matrix of these random variables is printed out if the command BRIEF 6 is in effect.

confidence intervals. To use the information on the output to form confidence intervals for the coefficients, regression line, etc., see any standard regression text or the Minitab Student Handbook.

D.F. Degrees of freedom.

degrees of freedom. The number of degrees of freedom for the sum of squared residuals is the number of observations minus the number of coefficients in the regression equation. This degrees of freedom is used in t-tests and confidence intervals and in F-tests. Each regression coefficient has 1 degree of freedom associated with it.

dependent variable. The dependent variable, or y variable, is the variable which is predicted by the independent, or x, variable(s).

Durbin-Watson statistic. Used to test for autocorrelation in the data. Note: all the (non-missing) residuals are used in the calculations.

F-tests. F-tests for the significance of regression, etc, are easily carried out using the MS values in the analysis of variance and further analysis of variance tables.

further analysis of variance. The first line in the FURTHER ANALYSIS OF VARIANCE table is exactly the same as in the ANALYSIS OF VARIANCE table. The next line gives SS(b1/b0), i.e. the further reduction in the sum of squares due to fitting the b1 term (or equivalently using X1 as a predictor), assuming that you've already fit the b0 or constant term. The next line gives SS(b2/b0,b1), i.e. the further reduction in the sum of squares due to fitting the b2 term, assuming that you've already fit the terms b0 and b1. The next line (if any) is SS(b3/b0,b1,b2), and so on. If you want something like SS(b2/b0,b3), then you have to use the REGRESS command again, entering the variables in an appropriate order, such as REGRESS C1, 3 PRED. C4, C3, C2.

least squares. The criterion for fitting equations used by the REGRESS command is to find the equation which minimizes the sum of squared (vertical) distances from the equation to the observation. This minimum is SS(residual).

mean square. Sum of squares divided by its degrees of freedom.

MS. Mean square.

predicted y-value. The value produced by substituting the x-value(s) into the fitted regression equation.

prediction interval. A prediction interval for a future observation is easily found using information on the output. See any standard regression text or the Minitab Student Handbook.

predictor. An x-variable (independent variable).

R. If an observation has a standardized residual greater than 2 in absolute value, the letter R is printed next to it.

R-matrix. Under BRIEF 6, the R-matrix is printed. R is an upper triangular matrix such that X = QR, with QQ' = I.

regression equation. The equation found by the REGRESS command which fits the data best, according to the least squares criterion.

residual. The difference between the observed and predicted y value, i.e., y - (b0 + b1 X1 + ...). This difference is also called the error or deviation.

R-squared. A measure of how well the regression equation fits the data, with 100% indicating a perfect fit. Defined by 100(SS due to regression)/(SS total). It is alsc equal to the correlation between the observed and predicted y values.

R-squared adjusted for degrees of freedom. If more variables are used to form an equation, R-SQUARED will get larger, even if the added variable is of no real value. To compensate for this, Minitab also prints R-SQUARED ADJUSTED FOR DEGREES OF FREEDOM. This is an approximately unbiased estimate of the population R-SQUARED, and is calculated by the formula

R-squared (adj) =
1 - (SS(residual)/(n-p))/(SS(total)/(n-1))

and then is converted to percent, where p is the number of coefficients fit in the regression equation. In the same notation, the usual R-squared is

R-squared =
1 - ((SS(residual)/(n-1))/(SS(total)/(n-1))

References for R-squared adjusted include Ezekial and Fox: Methods of Correlation and Regression Analysis (1959) and Neter and Wasserman: Applied Linear Models.

s. Standard deviation of y about the regression line.

SS. Sum of squares.

standard deviation of coefficent. Since the coefficients are determined by the data, they are random variables. The estimate of their standard deviation is printed in the table of coefficients. This estimate is useful for confidence intervals and tests concerning the coefficients.

standard deviation of predicted y values. Since the fitted regression equation is determined by the data, the predicted values are random variables. The estimated standard deviation of these is printed out as an indication of uncertainty and for use in forming prediction and confidence intervals.

standard deviation of y about regression line. This is an estimate of sigma (see Assumptions, below). It is defined by s = sqrt(MS(error)). The degrees of freedom associated with s is the same as for SS(error), that is, n-p, where p is the number of coefficients in the equation.

st.dev. Standard deviation.

st. res. Standardized residual.

standardized residual. The residual divided by the estimated standard deviation of that residual. The that residual. The covariance matrix of the residuals = (s-squared)(I-H) where H = X((X'X)-inverse)X'. The variances of the residuals appears on the diagonal of the covariance matrix. For further information, see Hoaglin and Welsch (1978). Note: some books and some regression programs use the term standardized residuals for the residual divided by s; this gives less information about the influence of residuals at extreme x-values.

total. The total sum of squares on the output is adjusted for the mean. That is, SS(total) = SUM((Y-Ybar)-squared).

tests. Tests of significance of the coefficients are based on the t-ratio in the table of coefficients. F-tests for the significance of regression, etc., can be done easily by using the MS values in the analysis of variance and further analysis of variance tables.

t-ratio. The ratio coefficient/(est. st. dev. of coef.) is used as a test statistic for testing the hypothesis that the true (population) coefficient is 0. The degrees of freedom for the test is the same as the degrees of freedom for s or SS(residual).

weights. An n by n matrix W is formed, with the column of weights as its diagonal and zeros elsewhere. The coefficients are estimated by INV(X'WX)*(X'WY). Note, W is the inverse of the covariance martix of Y.

X. Observations with unusual x-values. That is, observations for which the i-th diagonal element of X((X'X)-inverse)X' is larger than 2p/n. These are indicated by printing the letter X next to their standardized residuals. Here p = number of coefficients and n = number of observations. These points have unusual values of their predictors, values which are "far" from the majority of the predictor values. These points therefore have a great influence in determining the regression coefficients. If these points are correct, they are very useful in getting a good estimate of the coefficients; if they are incorrect, they may cause serious errors in the estimates of the coefficients. If the predictors have a multivariate normal distribution, then about 5% of the observations, on the average, will have unusual values, and will be given an X. For further information, see Hoaglin and Welsch (1978).

X-matrix. Matrix formed with the first column a column of 1's (unless NOCONSTANT is in effect), and the other columns the columns of x-variable(s) used in the regression.

x-variable. One of the independent variables (predictors) used in the regression.

X1, X2, ... The names of the x variables used in the regression. X1 corresponds to the first column of x variables, X2 to the second, etc.

X'X matrix. Matrix product of the transpose of the X matrix with the X matrix.

y. The dependent variable in the regression.

Missing data.

All observations which contain one or more missing values (either on the dependent or one or more of the independent variables) are not used in calculating the regression equation.

Assumptions.

The basic assumptions of regression are that the data are of the form Y= B0 + (B1)X1 + (B2)X2 +...+ E, where the B0, B1, ... are unknown "true" coefficients (to be estimated by b0, b1, ...), the E's are independent normal errors with mean 0 and standard deviation sigma (estimated by s). You can use residual plots, etc., to check whether some of these assumptions are reasonable. (See the Minitab Student Handbook for further details.)

Ill-Conditioned Data.

Predictor variables can have two types of problems. Each of these can cause both statistical and computational difficulties.

The first problem is "multicollinearity". That is, some predictors are highly correlated with other predictors. If this correlation is moderately high, the message

```
NOTE - THE FOLLOWING VARIABLES ARE HIGHLY
CORRELATED WITH OTHER PREDICTOR VARIABLES.
```

is printed (with a list of columns), and computation continues. The predicted values and residuals will be computed with high statistical and numerical accuracy. The coefficients, however, will be affected statistically (their standard deviations will be very large) and may be affected somewhat in numerical accuracy.

If the correlation of a predictor with other predictors is very high, it is eliminated from the equation, and a message such as the following is printed (where C5 is the correlated predictor):

```
C5    IS HIGHLY CORRELATED WITH OTHER PREDICTOR VARIABLES.
C5    HAS BEEN OMITTED FROM THE EQUATION.
```

The correlation structure of the predictor variables can be examined by using the CORRELATION command and by regressing each suspicious predictor on the other predictor variables.

Some possible solutions to the problem of multicollinearity of predictor variables are: (1) Eliminate predictor variables from the equation, especially if deleting them has little effect on R-squared; (2) Change predictor variables by taking linear combinations of predictor variables (e.g. principal components); (3) If polynomials are being fit, subtract a value near the mean of a predictor before squaring it.

The second problem occurs when a predictor variable has a small coefficient of variation. These predictors are "nearly constant", such as the variable YEAR which has values from 1970 to 1975. This can cause numerical problems, since all the information is contained in the fourth digit. The problem is compounded if the variable is squared. The solution is to subtract a constant from the data (e.g replace YEAR by YEARS SINCE 1970, which has the values from 0 to 5).

If the coefficient of variation is moderately small, the answers from Minitab should be reasonably accurate numerically, but some loss of statistical accuracy will occur. In this case, the message

```
WARNING - THE FOLLOWING PREDICTOR VARIABLES ARE NEARLY
CONSTANT. (ST. DEV./MEAN  IS NEAR ZERO.)
```

will be printed. If the coefficient of variation is very small, the variable is eliminated from the equation, a message such as the following is printed (where C5 has a small coefficient of variation):

```
C5    IS (ESSENTIALLY) CONSTANT.
      THAT IS, ST. DEV./MEAN IS (ESSENTIALLY) ZERO.
C5    HAS BEEN OMITTED FROM THE EQUATION.
```

If the command NOCONSTANT is in effect, the "correlations" are calculated without correcting for the mean (e.g., for two variables, "R-squared" = (SUM(X1*X2))/(SUM(X1-squared)*SUM(X2-squared)).

The checks for ill-conditioned data have been heavily influenced by Velleman et al. (1977).

Method

The computational method used is Givens transformations without square roots (fast Givens method) as described by Gentleman (1973). This method has very high accuracy (which allows Minitab to do the computations in single precision, yet obtain accuracy comparable to, or better than, using double precision in methods which solve the normal equations). The method is quite fast, and gives good diagnostics for ill-conditioned problems.

The method for determining points with high influence due to their position in X-space is from Hoaglin and Welsch (1977).

Other useful references concerning the computational methods used are Gentleman (1974), Golub (1969), and Stewart (1973).

The answers produced are essentially always the correct answer for data which differs from the original data by no more than the imprecision of single precision storage. The biggest limitation or accuracy for most data sets is arithmetic and transformations carried out in Minitab before the regression is called; thus some care should be exercised by the user. For example, if a quadratic equation is to be fit using the year (1960-1970) and year-squared, it is highly desirable to subtract 1960 from the year before doing the squaring.

The number of places printed out is determined as follows: Most quantities are printed to 2, 3, or 4 significant digits in their standard deviation, but to at most 7 or 8 digits. This means that digits which are statistically and numerically meaningful are printed, but as few "garbage" digits as possible are printed. The analysis of variance table is printed so that SS(residual) is printed to 3 significant digits (unless other SS are very large). This means that any F-ratios can be calculated to 3 significant digits, unless the F-ratio is very large or less than 1.

Notes:
(1) Large or small numbers may be printed out in scientific notation. That is, a number may be printed as 0.23E-09. This is equal to 0.23 times 10 to the power -9, or 0.00000000023.

(2) If a number does not fit in the space that the program allows, the space for that number will be filled with *'s on most computers. Also if a t-ratio doesn't make sense, it will be printed as a *.

(3) Cases which contain missing y or a missing x are not used in calculating the regression equation. The residual and predicted values for these cases are stored as missing and are printed as *'s.

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