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TECHNICAL NOTE

A METHOD FOR QUANTIFYING ELECTROMYOGRAMS*

INTRODUCTION

When the motor end plate of a motor neuron transmits a signal to its muscle fibers, it induces local voltage changes that reflect the functional utilization of the muscle. Electromyography (EMG) is a technique for recording these localized voltage changes either from the surface of the entire muscle or within the muscle by the insertion of needles or pairs of fine wires (Guha and Amend, 1979). The voltage changes at the electrode tips are amplified, displayed on a chart recorder or oscilloscope screen, and also stored on magnetic tape for subsequent analysis.

EMG is now used extensively in a variety of biological and biomedical applications. It is also being used in zoological studies to report on muscular activity during feeding, locomotion, breathing, and display behavior in fishes, amphibians, reptiles, birds and mammals. With relatively few exceptions, the descriptions for the records obtained are qualitative. Start and stop of activity may be determined from chart records or films taken from an oscilloscope screen. However, the magnitude of these signals and the changes with time (coincident with physical events) are often sorted only into general categories of 'high', 'medium' and 'low' firing intensity. Such descriptors permit only limited correlation with the physical effects induced by muscular activity.

The literature contains numerous proposals for computer-generated spectral analysis of EMG signals (Basmajian *et al.*, 1975; Desmedt, 1973; Eberstein and Goodgold, 1978). However, these approaches have not found their way into most studies on functional morphology, either because of the cost and complexity of the equipment concerned or because correlation with mechanical events has not been obvious.

The present paper describes a simple system that simultaneously analyzes up to seven channels of electromyograms. (1) It can utilize data stored on any analog or commercial FM tape system, so that the results of several experimental laboratories may be analyzed in a single central facility. (2) It provides a data matrix directly from the analog signal without intervening manual steps. Each channel of the EMG record is subdivided automatically into sampling intervals (bins). For each of these, the resulting data matrix lists the number of spikes and their mean height. The matrix is machine readable and may be transformed into bar graphs and otherwise analyzed by an intelligent graphics system. (3) It permits compensation for variable levels of baseline noise during analysis. (4) It incorporates the capacity for analysis of other physical factors, such as displacement or pressure. (5) It provides easy adjustment of the bin width, for instance, matching it to the framing rate of cine or television films.

The number of spikes, their height and the product of spike and amplitude have proven to correlate well and individually with various mechanical events (Gorniak *et al.*, 1979; Gorniak and Gans, 1980). They are repeatable in the same muscle group from animal to animal (Gans and Gorniak, 1980). In some cases, fiber diameters correlate positively with spike amplitudes and negatively with their frequency. Isometric tetanic tension is correlated with the product of spike frequency and amplitude in the manner of the integrated EMG. Histological and physiological characteristics of muscle have thus been correlated with muscular activity using these simple EMG descriptors. We here describe the system because it is applicable to the results of many laboratories and potentially permits tests of the reality of hypotheses in biomechanical theory (Guha and Amend, 1979).

DESCRIPTION OF THE SYSTEM

The system may acquire EMG and other physiological signals immediately (on line). More commonly, these are stored first on magnetic tape and later processed by the Hewlett-Packard (HP) 21MX minicomputer (32K words of core memory) that is configured as a data acquisition system and data processor (Fig. 1). The minicomputer is connected with a teletype keyboard and printer (modified ASR-33TZ), high-speed paper tape reader (Addmaster), digital cassette tape recorder (Computer Aid), a baud-rate selecting control and a Tektronix 4051 terminal. The cassette recorder stores programs on relatively inexpensive commercial tape cassettes. The teletype and the Tektronix 4051 will respond to program variables and list processed data. The paper tape reader allows the developing and loading of programs. This system provides the data matrix that may be printed out by the teletype or transmitted to a graphics system for transformation into graphs allowing visual comparison and further statistical analyses (Figs 2 and 3).

While many of our results are based on data recorded on a fourteen-channel tape system, the Honeywell 5600, we have often obtained equivalent results for fewer channels by recording the EMGs on commercial quadrophonic tape recorders, such as the Sony TC-788-4 and the Dokorder 1140. Simultaneous analysis of more than four channels requires play-back at a slower speed. Each EMG signal is passed through an a.c.-coupled preamplifier (Grass P15) set at a gain of one. These preamplifiers are included to balance the d.c. levels between the tape recorders and the computer, and to

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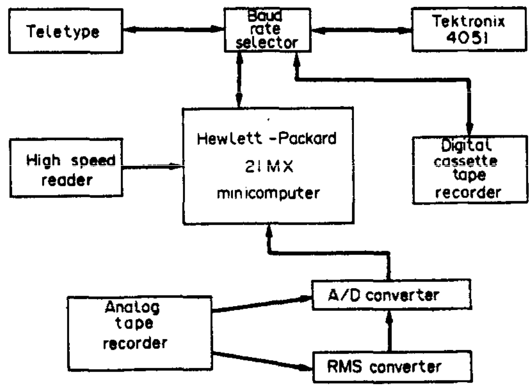

Fig. 1. Block diagram of the system used to obtain and plot numerical descriptors of electromyograms. The arrows show the directions in which the flow of information passes among components. A/D, analog to digital; RMS, root mean square.

provide a stable baseline for reference of EMG signals. The a.c. coupling in the 30–10 Hz pass band provides a constant baseline from which spike amplitudes can be measured. The filtering has little effect on spike amplitude or duration. Signals from the preamplifiers are passed on to a multiplexed analog to digital converter and routinely monitored on a Tektronix 565 oscilloscope. The rapid baseline variation is used to set spike detection thresholds (noise margins) for each channel.

A ten-bit, eight-channel analog to digital (A/D) conversion system was designed around a Hybrid Device (model ADC 550-10-S) A/D modular converter mounted on a Hewlett-Packard general purpose interface board (kit 12620A). A sample and hold amplifier is used to buffer the modest 30 μs conversion time with the rate of change of the EMG. Signals entering the A/D system can be amplified at either unit gain or 5 × to utilize the full range of the A/D converter.

The basic algorithm used in this implementation is described in the flow diagram of Fig. 4. The main parameter entry and control program allows the user to select or adjust sampling variables before each series is analyzed. These vari-

CAT MAST 7 74 R1
NMS: 5 5 5 5

NB: 180 BW: 0 K1: 1 K2: 180

CHS: 1 2 3 4

Frame Number		Channel One S	Channel One A	Channel Two S	Channel Two A	Channel Three S	Channel Three A	Channel Four S	Channel Four A
1	0	2	1	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	2	1	0	0	0	0	0	0
4	0	10	4	0	0	0	0	0	0
5	0	11	5	0	0	0	0	3	4
6	0	2	2	0	0	0	0	8	9
7	0	5	2	0	0	0	0	12	14
8	0	4	3	0	0	1	4	4	4
9	0	0	0	0	0	1	4	0	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	1	1
13	0	7	4	6	2	0	0	0	0
14	0	13	15	7	6	0	0	12	27
15	0	14	10	9	7	2	34	18	23
16	0	12	36	14	23	8	37	15	24
17	0	10	77	9	70	14	85	16	57
18	0	12	81	8	81	14	78	18	54
19	0	25	22	7	42	0	0	1	1
20	0	20	5	8	17	0	0	0	0
21	0	7	1	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0
26	0	4	1	1	4	0	0	0	0
27	0	0	0	0	0	0	0	0	0
28	0	6	25	3	5	0	0	9	30
29	0	9	18	5	5	2	8	11	13
30	0	14	40	14	24	5	23	20	40
31	0	9	64	14	58	10	53	21	63
32	0	17	9	15	76	0	0	19	6
33	0	14	2	6	12	0	0	5	1
34	0	3	3	0	0	0	0	0	0
35	0	1	1	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0
39	0	3	2	0	0	0	0	1	7
40	0	13	12	0	0	0	0	12	19
41	0	16	20	10	19	1	5	18	35
42	0	11	51	12	29	5	11	23	45

43	0	1	11	1	122	1	10	1	122
44	0	11	52	15	53	6	59	16	65
45	0	1	1	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0
48	0	1	1	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0
50	0	0	0	2	2	0	0	0	0
51	0	1	1	0	0	0	0	0	0
52	0	5	10	0	0	0	0	4	20
53	0	11	31	3	11	0	0	15	19
54	0	11	32	11	39	2	4	18	43
55	0	5	32	8	60	4	25	14	43
56	0	3	3	5	32	1	24	8	40
57	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0
62	0	2	3	0	0	0	0	0	0
63	0	10	34	1	10	0	0	7	19
64	0	13	27	13	33	0	0	17	34
65	0	10	36	13	38	1	4	20	41
66	0	7	23	8	103	5	42	12	58
67	0	3	47	10	42	2	88	11	55
68	0	0	0	9	23	0	0	0	0
⋮									⋮
180	0	0	0	0	0	0	0	0	0

Fig. 2. Sample teletype printout of the frame number and the number of spikes (S) and their mean amplitude (A) for each of four channels (1–4) of EMGs. At the top of the figure, the first line is the title; the second gives the noise margins (NMS) for each channel; the third gives the number of bins (NB), the bin width (BW), the frame number at which analysis starts (K1), and the number of sequential frames sampled (K2); and the fourth line gives the number of EMG channels (CHS). These instructions are typed by the operator. Frames 69–179 have been omitted from the table. The second column of the table may be used to acquire the absolute magnitude of an analog signal (i.e. pulmonary pressure). In this sample, EMGs were recorded when a cat was chewing a piece of raw beef. Channel 1 = activity from the right medial pterygoid; Channel 2 = activity from the left medial pterygoid; Channel 3 = activity from the right deep temporalis; Channel 4 = activity from the left deep temporalis.

ables include the spike detection threshold (noise margins), the number of EMG channels being sampled, number of bins for that series, and a title.

The sampling intervals can be triggered from signals produced by a camera or a photocell; thus, EMG activities can easily be matched to simultaneous mechanical or physiological events on cine and television records. When a photocell output (measuring a camera shutter-coupled stroboscopic flash) is used to define bins, the system scans the photocell output, identifies the start of a frame and then samples the EMG until the next photocell signal is perceived. Signals from a stimulator also can be used to set and change sampling intervals. In a second implementation of this system, an internal clock built around the MOSTEK 5009R time-base generator provides intervals variable from 10 to 200 ms. If the signals marking each frame of synchronized movie or TV records are used to define the bins, analysis can start on any specified bin and continue for up to 1000 intervals thereafter. The series of bins defined by the interval clock is triggered by voltage changes from a transducer.

Up to seven EMG channels can be interdigitated during each bin. An EMG channel is sampled every 115 μs, providing channel throughput rates of 8.9 kHz (890 points/100 ms interval) when one channel is used and 2.2 kHz (220 points/100 ms interval) when four channels are multiplexed. When more than four channels are sampled simultaneously, sampling rates are insufficient for real time analysis; the data must be recorded on tape and played back at a slowed-down rate.

For each channel, the total number of peaks (wavelets included) per interval and their summed amplitudes are stored. Either or both polarities of the EMG may be scanned. The peak detection algorithm of Fig. 5 keeps track of the polarity of the slope of EMG wavelets for each channel and recognizes peaks above the noise margin on the basis of slope reversals. Amplitudes of the peaks are measured from baseline to the sampled value nearest the true EMG peak, as shown in Fig. 6.

The eight most significant bits of the digitized EMG provide an accurate representation of the level of activity if the gain is set to exploit the range of the A/D converter; less than one per cent of full scale can be resolved with an eight-bit representation. Mean spike heights are calculated in FORTRAN by dividing the accumulated amplitude for each sampling interval by the spike count for that interval after an entire series has been scanned. The eight-bit representation allows averaging without overflow of the amplitudes for each of 1000 sequential intervals, each containing up to 200 full scale spikes. Root mean square (RMS) values may also be digitized by first converting the raw EMGs stored on tape to RMS values using a four channel RMS converter (Analog Devices AD536AKD) and then passing them to the A/D converter for processing by the minicomputer.

Programs designed to obtain these numerical descriptors of muscular activity were developed using the Hewlett-Packard Basic Control System. The primary program modules include a main parameter entry and control program (HP FORTRAN II), a high-speed data acquisition and analysis subroutine (HP 2100 ASSEMBLER), and a teletype and cassette data transfer subroutine (HP FORTRAN II).

CONCLUSION

The simple numerical descriptors here utilized have al-

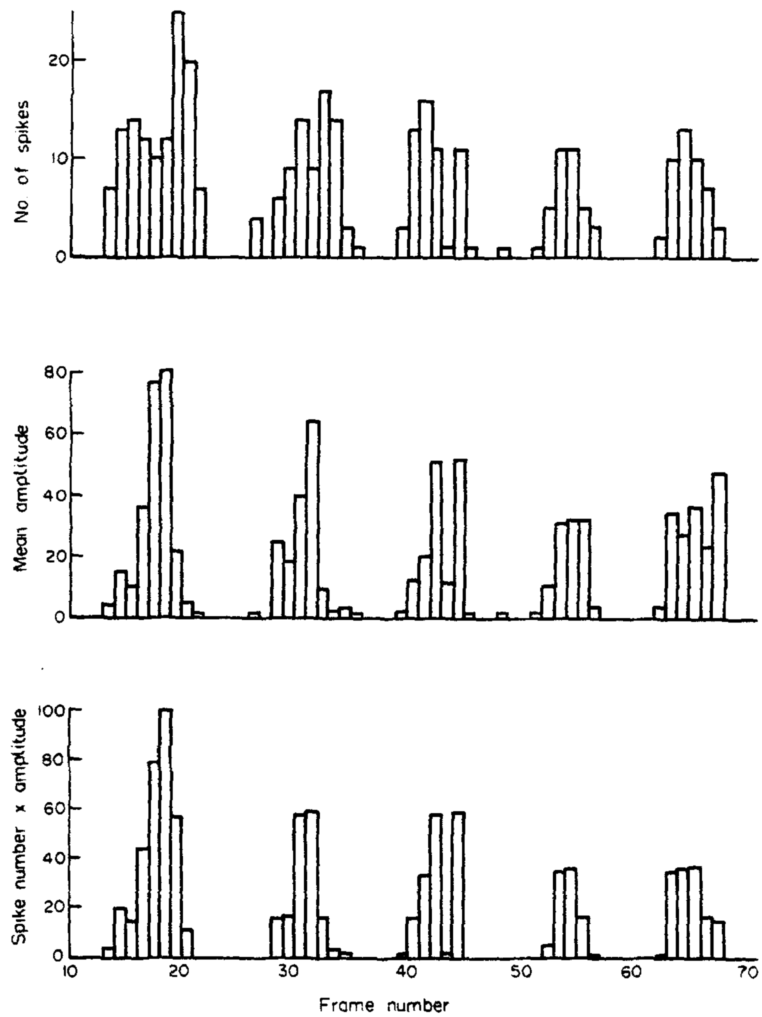

Fig. 3. Bar graphs of the number of spikes, mean amplitude, and the product of the spike number times the amplitude taken from a record of the activity pattern of the right medial pterygoid (channel 1, frames 10–70 in Fig. 2) for five successive bites. The product is given as a percentage of the maximum value per bin for that sequence.

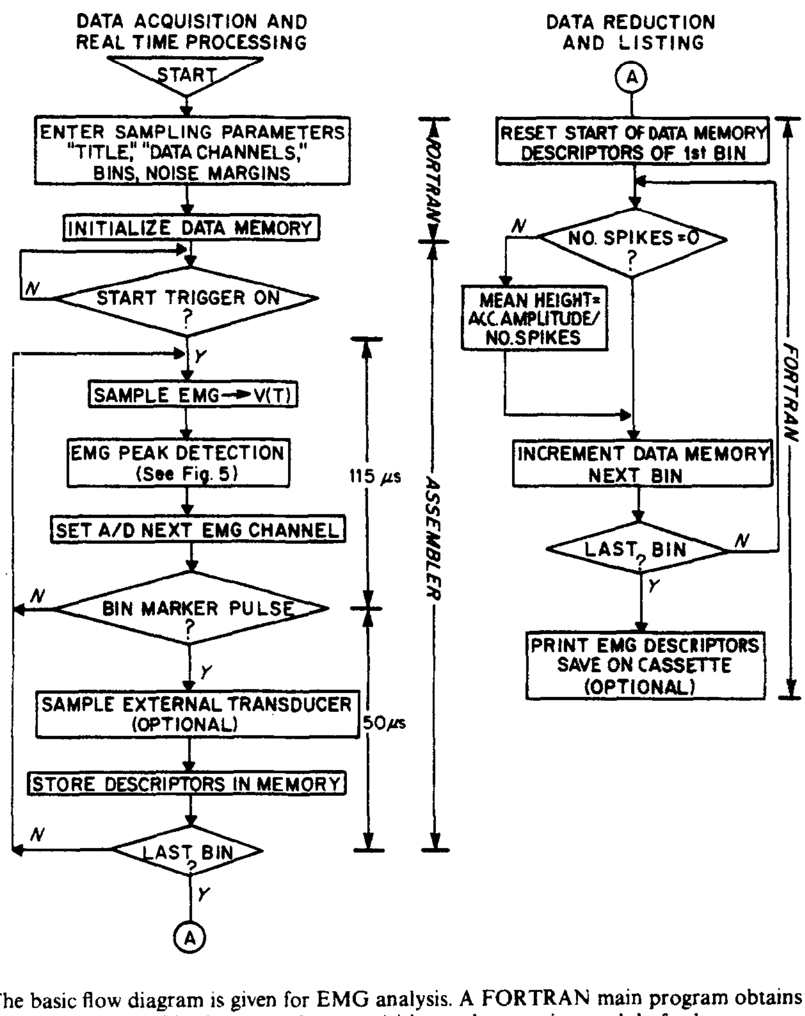

Fig. 4. The basic flow diagram is given for EMG analysis. A FORTRAN main program obtains sampling parameters, initiates a machine language data acquisition and processing module, further processes the data into EMG descriptors which may be listed or saved on cassettes. The start trigger represents alternatively a camera shutter coupled pulse which also serves as bin marker pulse, or a pulse derived from a transducer when bins are marked with the clock system.

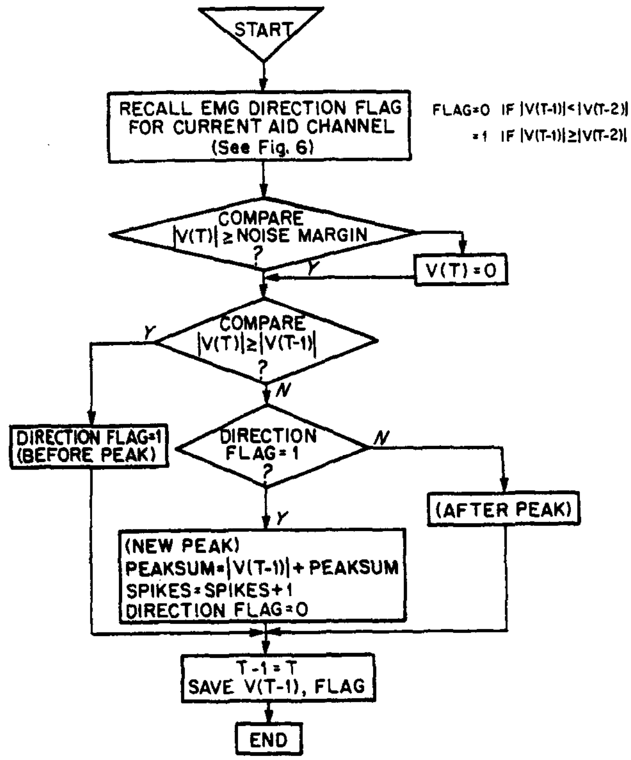

Fig. 5. The algorithm used for bipolar peak detection is described. The slopes of EMG waveforms prior to resampling each channel are maintained in direction flags (1: slope polarity = EMG polarity, 0: slope polarity = $-$EMG polarity). $V(t-1)$, $V(t)$ etc. represent successive samples of the same channel. Peaks are indicated when the direction flag and current difference in samples are of opposite sign. Samples within the noise margin are numerically zeroed. This algorithm is incorporated into the machine language module of Fig. 4 and modifies spike count and accumulated amplitudes only on passes which encounter peaks.

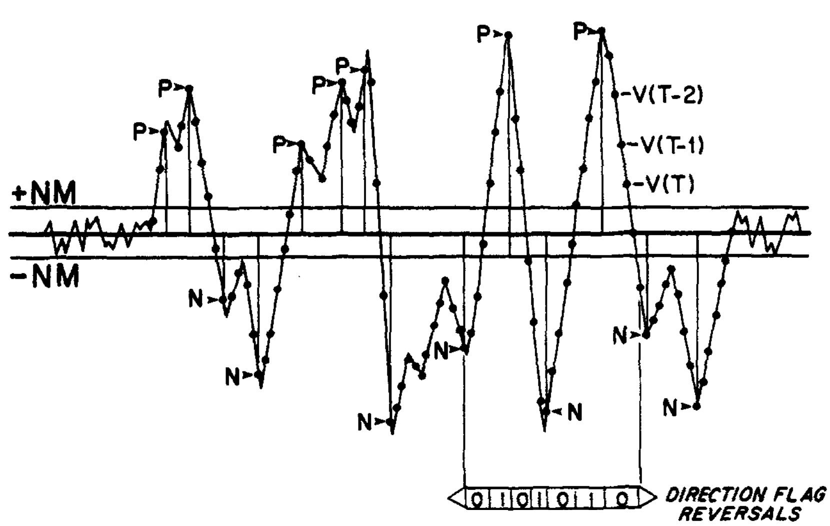

Fig. 6. An example of an EMG waveform showing the sampling process used for determining the number of spikes and their mean amplitude. The dots indicate the points $V(t)$ sampled. Points within the noise margins (+NM and $-$NM) are ignored. Those outside the noise margins and nearest the peak of a wave or a wavelet are counted and their amplitude calculated from baseline ground. N = negative peaks; P = positive peaks.

lowed correlation of muscular activity with certain histological and physiological characteristics of the muscle (Gorniak *et al.*, 1979). They also provide a simple approach for comparison of activity among muscles, among animals and when an animal is performing different actions. The method presented here seems to provide a potentially useful and time-saving approach for comparison of muscular activity with the forces and movements it produces.

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