METHODS & DESIGNS

Variability in commercial electromyographic biofeedback devices

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The purpose of this study was to evaluate the functional characteristics of a sample of commercial electromyographic feedback devices for the purpose of determining variability between instruments. Seventeen physical and functional characteristics (such as input impedance, filter bandwidth, and sensitivity) were evaluated on a sample of 11 instruments. Wide variability was found in several important functional characteristics. Input impedance, for example, was found to vary from 13K to more than 1 megohm and filter bandwidths ranged from 55 Hz to 2,600 Hz. Such variability makes the comparison of data from studies using different instruments quite difficult; it also suggests the need to develop equipment standards and common calibration procedures.

Instruments of varying degrees of sophistication have been used in the experimental analysis of behavior for decades. The devices have ranged from relatively well-tested devices (e.g., the Mowrer bed pad for enuretics) to inventions of a very speculative nature (e.g., brain polarization devices for depressed persons; cf. Schwitzgebel & Schwitzgebel, 1973). Recent popular interest in biofeedback has prompted the development of a sizeable number of commercial instruments. One published list of biofeedback device suppliers included 39 companies supplying over 100 different devices (Rugh & Schwitzgebel, 1975).

The use of any particular device potentially involves some variability in application and results. For example, the same device may be used in different ways by different practitioners (e.g., placement of electrodes, procedures of skin preparation), or the apparatus itself may generate artifacts. To date, there have been relatively few efforts directed at evaluating the sources and magnitude of error which may be expected from poorly designed instruments or from improper use of well-designed instruments. Replicability of laboratory and clinical studies using such devices cannot be expected without some consistency in the application of instrumentation. The purpose of the present investigation is to evaluate variability in the functional characteristics of a sample of commercially available electromyographic (EMG) biofeedback instruments.

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METHOD

Apparatus

Eleven EMG feedback devices were obtained through a loan or purchase arrangement from 11 of 17 companies contacted during 1974 and 1975. Manufacturers were informed of the testing procedure and were provided an opportunity to question the test results obtained from their apparatus. Each device was subjected to a routine series of 17 tests developed to evaluate the physical and functional characteristics of the devices.

Procedure

The instrument variables measured included input impedances, sensitivity, filter bandwidth, center frequency, 60-Hz suppression, type of input, type of feedback signal, battery life, and common mode rejection ratio. Retail price and warranty period data were provided by the manufacturer. Weight and size measurements were made with the batteries included.

The device's input impedance was measured at the center frequency of each device's filter by determining the series resistance in one active input which would reduce an output signal level by one-half. Although amplifier noise and sensitivity characteristics are normally specified in terms of a "noise figure," we chose to evaluate the total system noise and sensitivity by determining the minimal input signal which could be detected by the instrument at the device's most sensitive frequency. A sine-wave battery-powered signal generator provided the input test signal. The input signal was increased until a noticeable change could be observed in the instrument's output above the noise level. Instruments with adjustable time constants were tested at the shortest time constant setting.

The modality of feedback signal varied between instruments. Some employed meters, some used an FM tone, while others provided the raw EMG signal. When multiple feedback modes were provided, the mode that provided the best reading was used. Although this measure is somewhat subjective, two technicians making the measure consistently reported readings within .3 microV of each other.

Filter bandwidth, center frequency, and 60-Hz suppression figures were obtained from a plot of the device's input-output characteristics as a function of frequency. The input-output function was measured at 27 different frequencies, with a range of 10 Hz to 5,000 Hz. The filter bandwidth was defined as those

points where the output signal was attenuated by 3 dB. The 60-Hz suppression figure was calculated by subtracting the instrument's gain (decibel) at 60 Hz from the gain at its most sensitive frequency. The nature of the input configuration—single ended or differential (i.e., two active inputs and one common input)—was determined by examining the input circuitry. Simple visual examination of the device's signal-processing methods indicated the presence of signal (EMG) gain controls, feedback volume controls, and potted circuitry (i.e., components encapsulated in plastic).

The mode and nature of feedback provided by each device was determined by observation and analysis of output signals. A code was used to indicate six different types of feedback; several instruments provided more than one mode of feedback and were thus assigned multiple codes (see Table 1). Expected battery life was calculated for a cutoff point of 1.2 V for a 1.5-V cell or 7.2 V for a 9-V battery. The battery life figure was calculated for continuous usage with a constant feedback signal at a temperature of 22°C. Under normal intermittent use, battery life would be longer than that indicated. Common mode rejection figures were calculated from measurements of the differential and common mode gain at 60 Hz. The common mode rejection ratio (CMRR) was defined as:

$$20 \log \frac{\text{Differential Gain}}{\text{Common Mode Gain}}$$

Since the CMRR is a characteristic of the input amplifier, measurements for this calculation were made at the output of the first differential amplifier stage prior to extensive filtering.

The test results of each instrument were supplied to the respective manufacturer for comment. Manufacturers were provided a 30- to 60-day period in which to challenge the test results. Four conflicts with manufacturers concerning the results were resolved by evaluating differences in test procedures or by retesting of specific parameters.

RESULTS

Comparative test results are provided in Table 1. Wide variability was found in several characteristics: Input impedance ranged from 13 kohms to over 1 megohm, minimal detectable signal levels varied from .15 microV to 4.0 microV peak to peak, expected battery life ranged from 15 h to 500 h. All differential input instruments had common mode rejection figures better than 60 dB. All devices provided an FM mode of audio feedback, although the nature of the tones varied widely. Most devices provided a meter display of EMG amplitude, but no consistency was found in meter calibration. Ten of the 11 instruments provided an EMG gain control and a differential input configuration.

Filter characteristics, such as bandwidth, center frequency, and 60-Hz suppression, were highly variable. Bandwidth ranged from 55 to 2,600 Hz. Center frequency was found to vary from 60 Hz to a high of 800 Hz; 60-Hz suppression capability varied from 0 to 70 dB. Differences in instrument filter characteristics are further illustrated in Figure 1, which indicates the gain of each instrument as a function of input frequency. Superimposed upon the individual plots in Figure 1 is the power spectrum of a typical EMG signal as detected by 25-mm surface electrodes from the right bicep during a strong contraction (Hayes, 1960).

DISCUSSION

Although the devices were designed to perform essentially the same function, little consistency was found in 7 of 17 important functional characteristics. The variability is generally not the result of poor manufacturing practices or carelessness in design, but rather a result of insufficient knowledge or technical agreement about optimal instrument characteristics. Parametric studies have not been conducted to specify instrument characteristics which provide the best diagnostic and therapeutic results; thus, it is impossible to rate the devices with respect to acceptability. When ideal characteristics are known, our experience suggests that manufacturers usually incorporate these standards in their design. For example, it is generally agreed that input impedance should be at least 10 times greater than source impedance in order to minimize error due to variation in electrode-scalp impedance and to provide accurate amplitude information (Geddes, 1972; Roman & Lamb, 1962). All but one of the instruments examined in this study were found to have a 10 to 1 ratio.

The question repeatedly arises, "What is the best instrument to purchase?" This question cannot be answered without detailed knowledge of the intended applications. No one instrument is ideal for all applications. Each device has unique characteristics which may make it desirable for some applications but possibly useless in others. Small size may be desirable when portability is required. Long battery life may be necessary when extended periods of use are anticipated. Differential amplifiers with high common mode rejection figures (80-120 dB) and good 60-Hz rejection (> 30 dB) will obviously be required in electrically noisy environments but be unnecessary where subjects are to be tested in a shielded room. Rugh (1975) has recently discussed the relative advantages and disadvantages of these and other instrument characteristics.

Optimal value of instrument characteristics such as integration period and the nature of the feedback signal have not been agreed upon. For example, learning by means of biofeedback appears to involve a shaping procedure in which the subject is reinforced for emitting responses in the direction of the desired result. The nature of the feedback signal and the degree of integration could be a critical factor in the process. Presumably, the feedback signal should indicate relatively small changes in the response being shaped. Steps that are too small (i.e., insufficient integration of signals) could lead to extinction or erratic responding. The instruments tested varied widely in the degree to which the EMG signal was integrated before being converted into an audible tone or displayed on a meter. Additionally, some instruments provided a tone which increased in frequency as the EMG signal increased in frequency; in other devices the tone frequency increased with an increase in amplitude. Parametric studies need

Table 1
Comparative Test Data on 11 EMG Feedback Devices

Supplier	Device/Price	Weight (g)	Size (cm)	Input Impedance (ohm)	Minimal Detectable Signal (μ V p-p)	Filter Bandwidth (3 dB, Hz)	Center Frequency (Hz)	60-Hz Suppression (dB)
(a) Aquarius	300A/\$300	3000	19 x 21 x 8	900K	1.0	110	210	44
(b) Autogenic	1500/\$595	2600	11 x 32 x 14	> 1M	.15	70	120	70
(c) Behavioral Instruments	HP94/\$150	556	8 x 15 x 10	> 1M	2.5	550	350	26
(d) Biofeedback Technology	BFT401/\$575	4300	32 x 21 x 13	> 1M	1.5	550	120	19
(e) Biofeedback Research Institute	502/\$450	1120	12 x 25 x 8	700K	1.0	305	200	16
(f) EMPS Labs	EMPS200/\$450	1120	17 x 13 x 8	> 1M	4.0	55	60	0
(g) Cyborg	P433/\$675	?	30 x 13 x 25	> 1M	1.5	820	250	27
(h) Electro Lab	TBS-3/\$695	560	15 x 11 x 6	13K	.9	2.6K	800	23
(i) Extended Digital Concepts	PE-22/\$49	360	13 x 6 x 6	100K	2.0	590	375	31
(j) Med Associates	2000/\$685	2500	30 x 11 x 28	> 1M	.5	750	350	33
(k) Self-Control Systems	220/\$545	1700	7 x 28 x 18	> 1M	2.5	272	150	32

Type of Feedback	Ex-pected Volume Control	Battery Life (h)	Potted Circuit	CMRR at 60 Hz (dB)	Raw EMG Feedback	Auxiliary Equipment Output Jack	Warranty (Years)	Special Features
(a) 1,2,3,4	Yes	100	No	65	Yes	Yes	5	Calibrated threshold and meter, external audio input jack, built-in speaker, squelch control, optional accessories.
(b) 2,3,5	Yes	87	Some	77	Yes	Yes	5	Optional bandpass, seven modes of feedback, five auxiliary outputs, logarithmic meter, variable time constant, battery test, derivative feedback.
(c) 1	No	43	No	74	No	No	1/4	Small size, built-in speaker, simple operation.
(d) 1,4	Yes	Re-chargeable	No	106	No	Yes	5	Low-frequency rejection filter, battery test, numerous auxiliary outputs, electrode test function, optional bandpass.
(e) 1,3,4	Yes	25	No	112	Yes	Yes	1	Multiple electrode input jacks, built-in speaker, built-in storage compartment, battery test.
(f) 1,6	Yes	30	No	89	No	Yes	1	Small size, zero centering meter.
(g) 2,5	Yes	34	No	90	No	No	1	Logarithmic meter, battery test.
(h) 3,6	Yes	Re-chargeable	Yes	n.a.	Yes	Yes	1/2	Unit is designed to detect motor unit action potentials; device includes temperature and GSR feedback modes, built-in speaker, acupuncture sensor.
(i) 2,6	No	15	No	80	No	No	?	Kit, small size, variable time constant.
(j) 1,4	Yes	Re-chargeable	Some	66	No	Optional	1	ECG filter option, variable time constant, battery test, four options.
(k) 1,6	Yes	500	No	76	No	Yes	1/4	Battery test function, very long battery life, variable time constant.

Note—Addresses of manufacturers are available from Rugh and Schwitzgebel (1975). Abbreviations are: p-p = peak to peak, dB = decibel, CMRR = common mode rejection ratio. Type of feedback codes: (1) FM-audio, (2) FM-pulse repetition rate, (3) raw EMG signal, (4) calibrated meter reading in microvolts, (5) calibrated logarithmic meter reading in microvolts, (6) calibrated meter reading in arbitrary units. Top part of table: Input was differential except for h, which was single ended. All but a had EMG gain control. Although precaution has been taken to assure the accuracy of the data, performance can vary from unit to unit. No warranty for safety, effectiveness, or performance of listed devices is implied, or liability assumed, by the National Institute of Mental Health or the testing facility.

to be conducted to determine which instrument characteristics are most clinically effective.

One of the most important results of this investigation was the variability found in the instrument filter characteristics. Some units had very broad filters, while others were very narrow. The data in Figure 1 indicate that each unit is sampling a different portion of the actual muscle signal. This presents a problem because

signal amplitudes cannot be accurately measured, nor can one compare the amplitude readings of one instrument to that of another instrument. Although it is known that as bandwidth is decreased the noise level of the instrument can be reduced, a narrow bandwidth permits only a small portion of the EMG signal to be detected. Johansson, Larsson, and Ortengren (1970) have presented evidence which indicates that the EMG

Figure 1. Input-output characteristics of 11 electromyographic units (solid line) indicating differences in filter characteristics. The dotted line indicates the power spectrum of a muscle signal. Letters a through k refer to instruments identified in Table 1.

power spectrum is changed following strong muscular contraction. When a narrow band filter is used, a shift in the EMG power spectrum may result in an inaccurate amplitude reading. Also, it has yet to be demonstrated that the EMG power spectrum does not vary significantly between individuals. Such variance would negate accurate comparison of amplitude measurements between subjects when using an instrument with a very narrow bandwidth.

Lack of agreement on the method and the units of measurement to specify EMG amplitudes poses another problem in the development of standardized instrumentation. The 11 instruments evaluated were calibrated by a variety of methods. None provided the same reading to a tape-recorded muscle signal of 100 microV (RMS). Instrument readings ranged from 82 to

340 microV. This range of difference makes it almost impossible to compare results of investigators employing different instruments. At the present time, meter readings are useful only as relative measures and should not be interpreted as absolute values.

The results of this evaluation suggest the need for experimentally determined standards for moderately priced EMG instrumentation. Until standards for device manufacturing are developed, clinical and research EMG studies should clearly indicate the functional characteristics of the particular apparatus used.

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