METHODS & DESIGNS

EMG waveform duration: A validation method for the surface electromyogram¹

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The electromyogram (EMG) recorded with surface electrodes was examined using a triggered oscilloscope technique. When all but the high-amplitude waveforms in a given segment of activity were excluded from analysis, it was found that the duration of the remaining waveforms was specific to the muscle that produced them. That is, waveforms of a given duration were recorded whenever conventional indices—observable contraction, joint movement, needle recordings—showed activity in a specific muscle. This led to the suggestion that waveform duration might be used to validate the surface EMG. The suggestion, which is limited by the need to control posture and electrode placement, both of which may influence waveform duration, was illustrated in application to psychological research.

Although it is relatively simple to record the electromyogram (EMG) with surface electrodes, the results may be quite rewarding: under certain, well-defined conditions the area under the curve of the surface EMG is linearly related to the force of voluntary muscular contraction (cf. Lippold, 1967). Nevertheless, the results from day to day and from one laboratory to another are often ambiguous or contradictory. In some cases the problem appears to be one of inadequate technique (Grossman & Weiner, 1966); in others, the problem may be traced to the nature of surface recording. Since the activity transduced with surface electrodes may originate well away from the site of electrode placement, the surface EMG may display action potentials from muscles both relevant and irrelevant to the measurement at hand (Basmajian, 1967, p. 25; Lippold, 1967; Norris, 1963, p. 62).

At present the only check on the validity of a surface EMG comes from correlating the surface-recorded activity with other indices of muscular contraction. Palpation, or visual inspection of a muscle or of the joint it moves, has sometimes

provided an index of activity, but direct observation is not always possible, nor is it usually sensitive to small-scale contractions. Intramuscular recordings from needle or wire electrodes have also been used to establish an activity index for a given muscle, but the method is not completely satisfactory; the exact location of depth electrodes is not easy to determine, and they do not always sample a sufficiently large volume of muscle tissue (cf. Campbell, 1958). In short, each of the available indicators of muscular activity has its own limitations, and each fails to span the range from minimal to maximal contraction.

Our purpose here is to describe a solution to the problem of EMG validity that is based on the finding that the EMG taken with surface electrodes during sustained isometric contraction includes waveforms that are readily distinguished on the basis of peak-to-peak duration. Since waveforms of a given duration are recorded whenever conventional indices show activity in a specific muscle—high-amplitude waveforms appear both during observable contraction of the muscle and during movement of the appropriate joint, and low-amplitude waveforms occur synchronously with needle-recorded single motor unit activity—our suggestion is that waveform duration may be used to identify the activity of a muscle at all levels of contraction.

The present report describes our observations on waveform duration, some of the factors limiting our findings, and several applications of the waveform technique to psychological research.

WAVEFORM TECHNIQUE

Our method of waveform analysis is illustrated in Fig. 1. The "raw" data of the method are displayed in the top portion of the figure, where the EMGs taken during weak (C), moderate (B), and strong (A) contraction are depicted as they appear in conventional recordings. The "typical electromyograms" show the activity photographed from the face of an oscilloscope during a single slow sweep of the beam from left to right. With increasing degrees of contraction, the single motor unit pattern shown in C gives way first to the mixed pattern, B, in which individual

units may still be recognized, and then to the high-voltage interference pattern obtained when many different units have been called into play, A. Let's examine the single motor unit pattern of C more closely. The "hypothetical electromyogram," in the middle portion of the figure, shows how this pattern would appear if the sweep speed were increased about 10 times. To save space, the records of several single sweeps have been placed side by side, with the "quiet" segments deleted. What remains are three biphasic roughly sinusoidal waveforms of relatively constant duration and amplitude. The waveforms are sufficiently similar to allow the "paste-and-scissors" method of

TYPICAL ELECTROMYOGRAMS

HYPOTHETICAL ELECTROMYOGRAM

SUPERIMPOSED OSCILLOSCOPIC DISPLAY

Fig. 1. A comparison of the EMG displays obtained when the oscilloscope beam is free-running [top, after Buchthal (1957) and middle] and when it is triggered (bottom). See text for details.

Fig. 2. Electrode placement used to record the EMG associated with adduction and abduction of the little finger.

waveform comparison to be replaced by electronic means. The dotted lines illustrate the process. The EMG is fed in parallel to the vertical deflection circuits of an oscilloscope and to its joint slope and voltage detector (trigger) circuits. The latter are adjusted so that the initial component of each waveform crosses the "trigger level" in a negative-going direction at the point indicated by the left-hand dotted line in each vertical pair. A trigger pulse derived at this point initiates a single brief sweep of the beam timed to end at the right-hand line, at about the point when the second or positive component of the waveform returns to the "baseline" voltage level. Since the sweep circuits are inhibited except after receipt of a trigger pulse, a film exposed to the face of the oscilloscope long enough to record multiple instead of single sweeps will superimpose photographically only the portions of the electromyogram that fall between the dotted vertical lines. The resulting "superimposed oscilloscopic display" is represented in the bottom portion of the figure; a similar display may be observed visually on oscilloscopes equipped with medium to long persistence phosphors. In addition, an "average" waveform display may be obtained by using the trigger pulse that started the sweep to initiate the storage cycle of a summing computer. In this case the cycle length, like the sweep duration, is timed to include a single EMG waveform. Although the method of waveform extraction has been described with reference to the single motor unit pattern, it is also applicable to the more complex mixed and interference patterns. For these, the trigger level is set well away from the baseline so that the final display excludes all but the high-amplitude waveforms in a given sample of activity.

TYPICAL RECORDING ARRANGEMENTS

Figure 2 illustrates an electrode placement that gives convenient waveform data. We have used this placement extensively because of its accessibility, because of the relative isolation of the muscles of interest, and because the limb movements produced by these muscles lend themselves to definition by conventional switch-closure methods. As shown in the figure, the recording electrode is centered on the belly of the hypothenar eminence, a muscle group formed by the three short muscles of the little finger: abductor digiti minimi, opponens digiti minimi, and flexor digiti minimi brevis (Brash, 1951, pp. 504-507). The indifferent electrode is seated at the base of the little finger, and the ground electrode, not shown in Fig. 2, is clipped to the lobe of the ipsilateral ear. The recording and indifferent electrodes were silver-silver chloride pellets encapsulated in plastic (Beckman 650437 W), while the ground electrode was a silver disk housed in a spring-loaded nylon assembly (Grass E34S). The electrodes were filled with jelly (Beckman) and applied after the skin had been scrubbed with acetone and then abraded with emery cloth. They were reapplied when pairwise resistances, measured with a battery-operated multimeter, differed by more than 10% or were greater than 3,000 ohms. In some cases, the skin beneath the electrodes was pricked with a pin to lower contact resistance.

As shown schematically in Fig. 3, a cable running between the S's shielded booth and the adjoining control room connected the electrodes directly to cascaded low-level preamplifiers (Tektronix 122). Signals appearing between the recording and indifferent electrodes were differentially amplified and then filtered to attenuate frequency components below 8 and above 1,000 Hz. An analog voltmeter (Ballantine 320) and a master oscilloscope (Tektronix 565), provided with triggered sweep circuits, displayed the amplified signals, while an FM tape system (Technical Instruments 700) recorded them continuously. Outputs from the master oscilloscope were available to drive a slave oscilloscope (Tektronix 561), providing visual feedback to the S. On-line or playback analysis was performed using an average response computer (Technical Instruments CAT 1000) or a triggered oscilloscope and camera system (Tektronix 532 and Tektronix C-12 with polaroid back).

CORRELATION WITH INSTRUCTED MOVEMENT

A simple demonstration will serve to illustrate our basic waveform findings. The S was tested in a reclining chair with the right hand resting palm down on a padded board holding two microswitches (keys). The tip of his little finger was placed between the keys, as shown in Fig. 2, and he was instructed to close one or the other key—each operated at a static pressure of about 25 g—and to hold it closed by

Fig. 3. Equipment configuration used in our waveform experiments.

Fig. 4. Waveforms extracted from the EMG taken at the hypothenar eminence during sustained adductive and abductive pressures of the little finger. Each horizontal division shows 3.1 msec of activity. With negativity downward, the peak-to-peak amplitudes are 50 μ V/div for adduction, 100 μ V/div for abduction. Fifty waveforms make up each computer-averaged (A, B, E, F) and each photographically superimposed (C, D) display.

pressing against it lightly for about 30 sec. The EMG taken from the hypothenar eminence under this procedure typically included waveforms of short and long durations. These are characterized in three ways in Fig. 4. The upper panels, taken by computer summation, indicate the central tendency of the waveforms; the middle panels, taken by multiple-sweep photography, represent, by the dispersion and intensity of the traces, the variability about the mean for the same data. The lower panels were made with a tape-recorder technique in which the trigger pulse derived from the waveforms was, in effect, moved back in time so that the full waveforms were included in the computer average. The left-hand panels show the waveforms taken as the S maintained an adductive pressure just sufficient to keep the key closed. The peak-to-peak duration of the waveforms is about 2.5 msec. In comparison, the duration of the waveforms associated with the minimal abductive pressure necessary for key closure is about 6 msec, as shown in the right-hand panels.

The apparent correspondence of short and long waveforms to adductive and abductive pressures was further examined

by requiring the Ss in the keypressing procedure to work at various levels of effort. An oscilloscope placed in front of the S displayed a vertical line whose length was controlled both by the amplitude of the EMG waveforms and by the magnification of the amplifier used to display them. The S was asked to keep the line at the same predetermined length throughout each trial. On successive 30-sec trials, the magnification of the S's display was gradually reduced, so that progressively higher amplitude waveforms were needed to produce the required length. When the S could no longer maintain a criterion display, a maximum amplitude waveform was recorded. The display magnification was then increased, so that progressively lower amplitude waveforms were required. When the S was no longer closing the key, he was told to "move as if to close the key," and to maintain the criterion display on each trial. After a minimum amplitude waveform had been recorded using one key, a set of trials using the one that operated in the other direction was begun. Both sets rarely required more than two 30-min sessions.

The waveforms presented in Fig. 5 are characteristic of those obtained under the variable pressure procedure. The top and bottom rows show, respectively, the minimum and maximum amplitude waveforms recorded for an individual S; representative waveforms taken from the same S at intermediate pressures are displayed in the two middle rows. The correspondence of short (3 msec) and long (8 msec) waveforms to adductive and abductive pressures is unmistakable: although the shapes of the averaged waveforms change slightly with amplitude—in part this reflects the increasing variability associated with increasing waveform amplitude—the peak-to-peak duration remains relatively constant. In general, short waveforms (1.5-3 msec) were recorded over the range of amplitudes from 20 to 600 μ V, and these were associated with adductive pressures of the little finger. Long waveforms (5-8 msec) were recorded from 80 to over 2,000 μ V, and these occurred during sustained abductive pressures. Although the waveforms extracted from the EMG differed in other respects (discharge rate, amplitude, long-term variability), it was the different durations that consistently related the waveforms to the directions of movements of the little finger.³

Of course, the hypothenar placement of Fig. 2 is not the only one that yields clear-cut relations between waveform duration and instructed movement or contraction. For example, the EMG taken

from the base of the thumb (thenar eminence) also includes long and short waveforms which occur, respectively, during abduction and adduction of the thumb. In fact, similar relations, some of which are described in later sections of this paper, may be found throughout the body.

CORRELATION WITH NEEDLE-RECORDED ACTIVITY

The finding that waveforms of a particular duration occur during the performance of an instructed movement suggests that the waveforms originate in the muscle known, on other grounds, to be active during the movement. For example, since anatomical and electromyographic evidence both indicate that different muscles are active during abduction and adduction of the little finger (cf. Basmajian, 1967, pp. 187-204; Hollinshead, 1960, pp. 189-196), the implication is that the long and short waveforms taken during instructed abduction and adduction originate in different muscles—the long presumably from the hypothenar muscles, the short from the third palmar interosseous.

To test the implication, we had to determine whether needle electrodes placed internally to the muscles would show activity when surface electrodes recorded long waveforms. To do this we designed an experiment similar to that of Harrison and Mortensen (1962), who used

Fig. 5. Computer-averaged waveforms taken at four adductive and four abductive levels of pressure. Amplitudes are peak-to-peak measures based on the average of 50 waveforms. Horizontal calibration is 31.2 msec.

Fig. 6. Multiple-sweep photographs of two abductive motor unit waveforms (1 and 2) recorded simultaneously from bipolar surface electrodes (S) and from three concentric needle electrodes (K, L, M). With negativity downward for surface waveforms and upward for needle, the p-p amplitudes are $19 \mu\text{V}/\text{div}$ for surface, and 94, 19, and $94 \mu\text{V}/\text{div}$ for waveforms from Needles K, L, and M, respectively. The horizontal calibration is 1.6 msec/div. Each panel gives the photographic superimposition of about 100 waveform repetitions (10-sec exposure $\times$ 10/sec repetition rate). The photographs were made with the 'scope beam intensity adjusted so that a single waveform produced a barely visible trace.

visual and/or auditory feedback of the surface and/or the needle EMG to train Ss to recruit, contract, and control one or more individual motor units in the tibialis anterior muscle. They found that (1) each motor unit could be identified in the surface, as in the needle records, by its unique waveform characteristics, and (2) each unit produced synchronous surface and needle activity—that is, there was a one-to-one correspondence between surface- and needle-recorded motor unit waveforms. Their results suggested that we could use oscilloscopic feedback of the surface EMG to train Ss to control one or more low amplitude variants of the long surface waveform (i.e., one or more motor units) and that this would produce synchronous activity in needle recordings taken from the hypothenar muscles—if in fact long waveforms have their source in these muscles.

In our experiment concurrent surface and needle recordings were taken from the hypothenar eminence of the right hand. The surface electrodes were arrayed much like those in Fig. 2: the recording electrode was placed slightly dorsal to the center of the hypothenar eminence; the indifferent

electrode was placed at the distal end of the eminence, at the base of the little finger. Three concentric needle electrodes (Adrian & Bronk, 1929), inserted to a depth of 1.2 cm, were placed 1.3 cm from each other and from the recording electrode. With the recording electrode, they formed a diamond-shaped configuration centered on the hypothenar eminence. The needle electrodes, constructed from 25-ga hypodermic needles, were designated "K," "L," and "M" in proximal to distal order.

After the electrodes had been placed, the S was seated in a shielded booth with his forearms pronated on the arms of a reclining chair. His right hand and wrist extended past the arm of the chair, leaving his hand hanging and flexed comfortably at the wrist. A feedback oscilloscope, mounted in front of the S, provided triggered displays of the EMG recorded with surface electrodes, but did not feed back needle activity. The long waveform and its corresponding abductive movement were described to the S, and he was asked to produce the waveform at amplitudes that do not generate observable movement of the little finger. With the display magnification at nearly 10^6 , low-amplitude waveforms (60 to $180 \mu\text{V}$ peak to peak) were quickly obtained. Typically, from two to six waveforms were found, all of which occurred with durations characteristic of the waveforms previously collected during abductive movements (5-8 msec peak to peak) but which could be distinguished from each other on the basis of variations in shape, amplitude, and duration. Two of the long surface waveforms were pointed out to the S—"That's it; good"—and he was encouraged to make them and to learn to produce one variant of the long waveform and then the other on command (cf. Basmajian, 1963; Harrison & Mortensen, 1962). About 30 min of training was typically sufficient to bring both variants under the control of the E's instructions to begin, sustain, and stop waveform emission. Several Ss were given additional training until they could produce on request one, the other, or both variants concurrently.

Figure 6 shows the surface and needle waveforms collected from one of the Ss given additional training. Each panel in Fig. 6 was made by exposing film to the face of a single-beam dual-trace oscilloscope whose sweep circuits were triggered on the waveform in the lower trace. Each sweep of the beam thus displayed the triggering waveform in the lower trace and, in the upper trace, displayed whatever activity happened to be occurring during the triggering waveform.

One trace in each panel, designated "S," shows a surface waveform; the other, designated "K," "L," or "M" according to the needle in use, shows the activity recorded between the tip of a needle and its cannula. In each panel the numbers 1 and 2 in the trace designations refer to the first and second variants of the long surface waveform. For example, Trace S1 in Panels A-D shows the first variant of the surface waveform, Trace S2 in Panels E-G shows the second, and Trace S12 in H-J shows both variants occurring concurrently.

Since both traces in each panel of Fig. 6 were triggered on the waveform displayed in the lower trace, the presence of coherent waveforms in each of the upper traces indicates that the surface and needle waveforms occurred synchronously in time. For example, the upper traces in Panels A, B, C, G, H, I, and J show the synchronous needle potentials found when both traces were triggered on the surface waveforms, while the upper traces in D, E, and F show the synchronous surface waveforms found when triggering on activity in a needle channel. As suggested by comparing Panel C to D, it made no difference which channel of EMG, surface or needle, was chosen for triggering. For the same needle placement and for the same surface variant, triggering on either channel displayed the same two synchronous waveforms. (The panels look slightly different because in C only the later waveform components are shown, while in D both waveforms are displayed in their entirety.) That either surface or needle triggering resulted in the same display suggests that under the conditions of the present study, a one-to-one correspondence existed between the long surface-recorded waveforms and needle activity in the hypothenar muscles. We can presume, then, that these are the muscles of origin for the long waveforms.

The panels of Fig. 6 bear information not only about the origin of the long waveforms, but also about their nature. In this regard two results are pertinent. Although the first has not been made explicit in order to save space, it can be inferred from the figure that the three needle waveforms corresponding to each surface variant were synchronous, not only with the surface waveform, but also with each other. For example, both traces in Panels A, B, and C were triggered on repetitions of the surface variant displayed in Trace S1, so that the needle waveforms in Traces K1, L1, and M1, because they are synchronous with the surface variant, are also synchronous with each other. The second result is made clear by a comparison of Needle Traces K1, L1, and

M1 in Panels A, B, and C with the traces for the same needle placements in Panels E, F, and G. The comparison shows that the waveform recorded at each needle during instances of the first surface variant (Panels A-C) is markedly different from the waveform taken from the same needle during the second surface variant (Panels E-G). The contrast in needle waveforms is even more clearly displayed when both surface variants occur concurrently, as in Panels H-J. These results, taken together with those previously described, indicate that each variant of the long surface waveform occurred in a one-to-one correspondence with a unique set of synchronous needle waveforms.

Since the needle waveforms in Fig. 6 meet the criteria for recordings of single motor unit activity (cf. Buchthal, 1957), it seems reasonable to assume that each set of needle waveforms, and in turn each correspondent surface variant, represents the activity of either (1) a cluster of motor units firing synchronously or, more simply, (2) an individual motor unit. In fact, both interpretations are possible (cf. Buchthal, Guld, & Rosenfalck, 1957; Buchthal & Madsen, 1950), but for the present purposes there is no need to choose between them. The points to be made are that the surface waveforms dealt with here apparently correspond to motor unit activity and that different surface waveforms apparently signify the activity of different units or of different clusters of motor units.

Our results, then, confirm those of Harrison and Mortensen (1962)—surface electrodes can be used to identify and control single motor unit activity—and so serve both to generalize the reliability of the surface EMG and to provide evidence indicating that long waveforms originate in the hypothenar muscles.

Our picture would now be complete if we could also report that the short waveforms taken during instructed adduction originate in the third palmar interosseous as expected. Unfortunately, we cannot. The necessary experiment has not been attempted, since we are not equipped to make accurate needle placements in deep-lying muscle. We can report, however, that short waveforms appear to be generated by a source not contained in the hypothenar eminence. In Ss trained to make low-amplitude short surface waveforms, we have not obtained synchronous activity from needles placed in the hypothenar muscles, except when volume recordings were made across the tips of two needles or between a needle and a surface electrode. In this case the surface and "needle" waveforms occurred

simultaneously and were of identical shape, although sometimes of different amplitude.

Up to this point, we have demonstrated (1) that long surface waveforms are obtained from the hypothenar EMG during virtually all degrees of instructed isometric abduction and (2) that, at the single motor unit level, long waveforms occur synchronously with the activity recorded from concentric needle electrodes placed in the hypothenar muscles. It would seem, then, that the presence of long waveforms in the surface EMG may be used to identify the activity of the hypothenar muscles at all levels of effort. For the short hypothenar waveform, however, our conclusion is weaker, although not necessarily without interest. Since short waveforms occur during instructed adduction, their presence in the hypothenar EMG may be used to identify adductive movements, provided that the identification is not taken to imply a physiological rather than a strictly operational relationship between the waveforms and the behavior.

In general, for superficial muscles, such as the hypothenar muscles studied here or the tibialis anterior studied by Harrison and Mortensen, waveform duration is readily correlated with other indices of muscular activity—observable contraction, movement of the appropriate joint or limb, needle activity in the muscle—and may then be used to validate the surface EMG with respect to the muscle of origin. Although we presume that waveform duration may also be used to validate the EMG volume-conducted to surface electrodes from deep-lying muscles, we have no data on this point and must counsel great caution in interpreting records thought to be taken from other than superficial muscles (cf. Basmajian, 1967, p. 26; O'Connell & Gardner, 1963).

DISCUSSION

Our suggestion that waveform duration may be used to validate the surface EMG must be evaluated in light of the factors that determine this waveform characteristic. At present, three factors appear to act in combination. Two of these, electrode placement and the posture of nearby joints, will be dealt with in later sections of this paper. A treatment of the third factor, the physical parameters of the muscle of origin (cf. Buchthal, Guld, & Rosenfalck, 1954), lies beyond the scope of the present paper. Nevertheless, we can note its effect on the surface-recorded waveforms, namely that different muscles characteristically produce surface waveforms of different durations, and compare this effect to those obtained when other measures of a muscle's electrical

Fig. 7. Spontaneous variation in the shape of an abductive waveform recorded with surface electrodes from the hypothenar eminence. The figure is the composite of 12 multiple-sweep tracings—each showing the photographic superimposition of about 100 waveforms (negativity downward)—stacked from top to bottom in chronological order. The tracings were taken on Trials 1, 3, 4, 5, 6, 9, 11, 12, 15, 16, 17, and 35 of a 40-trial session. Trials were 10 sec long and were presented at 2-min intervals. The S's task was to produce the waveform with oscilloscopic feedback.

activity are studied. In this regard the frequency spectra of surface and needle potentials and the duration of needle waveforms are of particular interest. At question is whether these measures, like the duration of surface waveforms, differ from muscle to muscle and, if they do, whether they are stable for a given muscle under different degrees of voluntary contraction.

In general, each of the measures does, in fact, take on different values according to the muscle of origin. For example, the mean durations of both the needle and the surface waveforms taken from the biceps brachii are consistently longer than the durations measured for the small muscles

Fig. 8. Computer averages of the abductive surface-recorded waveforms taken at the hypothenar eminence under four different voluntary postures of the wrist. Each average includes 100 waveforms. With negativity downward, the vertical calibration is 20 $\mu\text{V}/\text{div}$; the horizontal calibration is 1.5 msec/div. A tape-recorder technique was used to display the full waveforms.

of the face (Bruno & Camp, unpublished data; Buchthal, 1957; Kaiser & Petersen, 1963; Petersen & Kugelberg, 1949).⁴ Similarly, the frequency spectra taken both with needle and with surface electrodes are relatively broad when recording from the biceps but are narrow when taken for the facial muscles (Hayes, 1960; Kaiser & Petersen, 1963, 1965). Of course, the measures are necessarily interdependent: the frequency spectra are determined in part by waveform duration (cf. Kaiser & Petersen, 1963); the surface measurements represent a complex summation of the energy recorded intramuscularly by needle electrodes. That the measures covary, then, tends to substantiate our finding that different muscles produce surface waveforms of different duration.

While each of the measures appears to vary according to the muscle of origin, only the measures taken with surface electrodes appear to be stable for a given muscle at weak and strong effort. Under different loadings, the biceps, for instance, gives surface waveforms of different amplitudes and surface-recorded frequency spectra of different absolute energies, but the duration of the waveforms and the shape of the frequency spectra are not greatly affected by the degree of loading (Bruno & Camp, unpublished data; Hayes, 1960). In contrast, both the mean duration of needle waveforms and the shape of the needle frequency spectra change with the degree of contraction of the biceps brachii (Kaiser & Petersen, 1963, 1965), presumably because the needle waveforms tend to have longer durations as the

activity of individual motor units becomes electrically superposed at higher contractile strengths.⁵

In practical terms, then, the waveform duration emerges as a suitable validator of the surface EMG. Like other measures, it varies with the muscle of origin. In common with the surface-derived frequency spectra, it does not vary with contractile strength. Unlike any of the other measures, it is immediately available without further data processing and so can provide a continuous validator. It remains now to see how this measure behaves when the other factors which determine waveform duration—posture and electrode placement—are deliberately varied.

EFFECT OF POSTURE

As a validator of the surface EMG, waveform duration is useful only to the extent that it is reliable, viz, to the extent that repeated measurements for the same muscle produce the same duration value. Of course, there is no reason to expect that waveform duration, or any other physiological measure, will exhibit identical values on each measurement occasion. Rather, variance or dispersion about the central tendency waveform is to be expected. Our experience, and here we must rely for the present on the evidence gathered by multiple-sweep photography (e.g., Panels C and D in Fig. 4), is that the longest and shortest waveforms collected from the same muscle, under apparently constant conditions, span approximately a twofold range.

In general, the range is greatest when near-maximal tensions are required or when the session is long, that is, under those conditions that make it difficult to maintain a constant posture. Figure 7, for example, illustrates the changes in waveform shape and the consequent changes in peak-to-peak duration, which took place during a single 90-min session. The S, provided with oscilloscopic feedback of the surface waveforms recorded from the hypothenar eminence, was simply required to reproduce the same long waveform on each of 40 10-sec trials given at 2-min intervals. Although needle data from three placements indicated that the S had succeeded in reactivating the same motor unit or cluster of units on each trial, the surface waveforms show progressive changes in the region of the positive peak. On this occasion, time was the only variable correlated with the changes in the surface waveform, so we are obliged to describe the changes as "spontaneous." In other cases, however, similar modifications in shape and duration have been observed when posture was deliberately varied.

Two simple demonstrations will serve to illustrate the effect of posture on the surface-recorded waveforms. For the first, electrodes were placed on the hypothenar eminence of the right hand, as shown in Fig. 2. The S sat with his hand resting palm-down on the arm of a reclining chair. He was provided with oscilloscopic feedback of the hypothenar waveforms and was asked to maintain a steady rate of abductive waveforms. While continuously producing the waveforms shown in the computer average of Fig. 8A, the S slowly bent his wrist sideways as far as it could go in the direction of the thumb (radial abduction of the wrist). The waveform duration increased to the maximum shown in Fig. 8B. When the wrist was bent forwards as far as it could go (extended), the duration became shorter, as in Fig. 8C; it became shorter still, as shown in Fig. 8D, when the wrist was bent sideways in the direction of the little finger (ulnar abduction). From the longest waveform (8B) to the shortest (8D), peak-to-peak duration changed by a factor just less than two.

Postural modifications similar to those just described have been found during shoulder movements when recording from the trapezius and in the second demonstration study during forearm flexion when recording from the biceps brachii. Here the recording electrode was centered transversely on the biceps at about the point where the two heads merge. The indifferent electrode, also centered transversely, was placed 3.8 cm distal to the recording electrode, and the ground electrode was placed on the anterior side of the wrist. The S was again

Fig. 9. Computer-averaged waveforms recorded from the surface of the biceps brachii with the forearm extended (A), partially flexed (B), and completely flexed (C). With negativity downward, each average includes 100 waveforms. The horizontal calibration is 21.9 msec.

Fig. 10. The electrode placements used to record muscular activity during extension and flexion of the middle finger. Adapted from Lippold, 1967.

given waveform feedback and asked to maintain a steady rate of waveform discharge. With the forearm extended in an approximately horizontal position (palm upward), a long (12-msec) waveform was recorded, as shown in Fig. 9A. When the arm was slowly flexed and the waveform maintained, the duration of the waveform gradually shortened, as indicated in Fig. 9B (6-msec duration), until, as shown in Fig. 9C, a waveform of about 3-msec duration was recorded during complete flexion. Here postural modifications were responsible for a fourfold change in waveform duration.

The point of our demonstration studies is obvious: Posture affects the duration of the surface waveforms taken from the same muscle during voluntary contraction. Although the finding appears to apply only to those muscles whose length can be altered by movements of a proximal joint, the mechanism of the effect is not yet clear.⁶ Nevertheless, its implication is straightforward, namely that posture must be controlled in order to use waveform duration as a validator of the surface EMG. Alternatively, it may be possible to allow posture to vary so that changes in waveform duration may be used to specify changes in response topography. This possibility, which might have value in experiments on response generalization or differentiation or in experiments on postural set, is now being studied.

EFFECT OF ELECTRODE PLACEMENT

That the interpretation of a surface-recorded potential may depend crucially upon a knowledge of electrode placement is by now a well established principle in the field of electrophysiology. In fact, in some areas of application, e.g., electroencephalography, elaborate systems have been devised in order to standardize

placements from one session to the next and from one laboratory to another (cf. Jasper, 1957). The problem, of course, is that the parameters of volume-conducted potentials, such as the EMG waveforms recorded from the surface of the skin, vary both with the distance from the potential source and with the nature of the media through which the potentials pass. In order to focus on this problem, we have performed two demonstration studies to show how waveform duration may vary with electrode placement.

In the first, two sets of electrodes were placed on the S's forearm, one set over the muscle active during flexion of the middle finger and the other over the muscle active during extension of the finger. The electrode placements were those used by Lippold (1967) and are shown in Fig. 10. In the figure the indifferent electrode in each set is designated "A," and the recording electrode designated "B"; the ground electrode, not shown in the figure, was clipped to the lobe of the ear.⁷ The S's hand was placed palm-down on the broad arm of a reclining chair. Surgical tape was used to hold the middle finger firmly against the arm of the chair. The S was asked to extend the middle finger and thus to press upward against the tape (1) at a comfortable effort level, (2) less than that, (3) more than that, and (4) with as much effort as possible. After training both to relax and to maintain steady pressures, the S produced the waveforms displayed in Fig. 11. The upper trace in each panel shows the waveforms recorded during extension of the middle finger at the extension placement. These waveforms were used to trigger the oscilloscope. The waveforms in the lower trace in each panel were also recorded during extension of the middle finger. Although derived from the flexion placement, they occurred

synchronously with those from the extension placement. The panels in Fig. 11 show that over the range from slight (A) to maximal (D) effort, extension of the middle finger is correlated with a long-duration waveform at the extension placement and with a lower-amplitude, short-duration waveform at the flexion placement.⁸

The data point up the fact that the waveforms associated with a movement may be recorded at sites quite distant from the presumed source of activity, in this case at a seemingly inappropriate site, and indicate that the duration of a movement-correlated waveform may vary according to the site of electrode placement.

In our second demonstration study, four sets of electrodes were placed on the S's forearm, as shown in Fig. 12, and a ground electrode was clipped to the lobe of the ear. The extension placement shown in Fig. 10 was used to determine the location of the set of electrodes designated "4" in Fig. 12. The locations of Sets 1, 2, and 3 were then determined by measurement from the placement of Set 4. The S was asked to sustain first flexion and then extension movements of each of the fingers of the right hand. The four channels of the EMG were scanned during finger movements for coherent waveforms.

The computer-averaged waveforms displayed in Fig. 12 were obtained during

Fig. 11. Multiple-sweep photographs of the waveforms recorded during extension of the middle finger at the extension placement (upper traces in each panel) and at the flexion placement (lower traces) during slight (A), moderate (B), strong (C), and extreme (D) efforts. Each horizontal division represents 2 msec. With negativity downward, voltages per vertical division for the upper traces are 100 (A), 200 (B), 500 (C), and 1,000 (D) μ V. For the lower traces, voltages are smaller in each case by a factor of 10. In D the upper waveform overloaded the amplifier, causing the initial portion to appear flattened out.

Fig. 12. Electrode placements used to study the durations of the waveforms associated with flexion of the ring finger. With negativity downward, the tracings represent the simultaneous computer averages of 300 waveforms. The averages were triggered on the waveforms from Placement 1.

forceful flexion of the ring finger, which produced palpable movement under the electrodes of Set 1. The waveforms recorded from this set were used to trigger each of the four averages simultaneously. Waveforms of similar duration and shape, but of differing amplitudes, were recorded from Sets 1 and 2. Synchronous waveforms were also found in the derivations of Sets 3 and 4, but these differed from the triggering waveform of Set 1, not only in amplitude, but also in shape and in duration. The waveform of Set 3 appears longer and more complex than that of Set 1, while the Set 4 waveform appears to be considerably shorter than those of the other three sets.

It should be noted that the waveforms derived from Sets 2, 3, and 4 are of low amplitude and that without computer averaging, they would not ordinarily be visible in the EMG. Our primary point in presenting these waveforms is not that synchronous activity may be recorded over a wide area of the forearm, but rather that

the shape, and more importantly, the duration of the movement-correlated waveforms may vary greatly with electrode placement.⁹

Our demonstration studies dealing with electrode placement lead to two conclusions. The first is that electrode placement, like posture, must be specified and controlled in order to use waveform duration as a validator of the surface EMG. The second is that electrode placement, because it influences waveform duration, may be used to deliberately shorten the duration of one muscle's waveforms when these might otherwise be confused with the waveforms generated by another muscle. Of course, a similar conclusion may be drawn from the studies dealing with the influence of posture. In other words, electrode placement and posture, while they must be controlled, also provide the means for extending the usefulness of waveform duration as a validation method; within limits, we can choose to hold constant that placement and that posture

which combine to make the duration of a particular muscle's waveforms distinguishably different from those originating in other muscles. The limits are determined in the case of placement by the amount of amplitude attenuation that is acceptable and in the case of posture by the comfort of the S.

PSYCHOLOGICAL APPLICATION

Throughout the present paper we have described waveform duration as a validator of the surface EMG since we expect that this will be its most common application. We have, for example, used the waveform technique to validate the EMG taken during studies of the evoked myogenic response (Bruno & Camp, unpublished data) and during psychophysical studies of muscular tension (Bruno, Hefferline, & Suslowitz, 1970). In these experiments, on-line measurements of waveform duration permitted us to repeat those trials during which the EMG was contaminated by potentials originating in muscles other than the one under study. Validation, however, is not the only application of the waveform technique: it can also be used via feedback displays to train the activity of a specific muscle or to train a waveform-correlated movement. In this application, we have used the technique to establish covert, prestimulus tensions during reaction-time, generalization, and threshold experiments in order to determine the extent to which covert tensions bias an overt perceptual response (Hefferline & Bruno, 1970). Waveform feedback can also be used to generate a full-scale performance through development of its miniature counterpart. For example, by training Ss with oscilloscopic feedback to make increasingly higher amplitude versions of the adductive and abductive waveforms taken from the hypothenar eminence, we were able to teach them to make overt movements of the fifth finger, in some cases without their observation of the response (Hefferline, Bruno, & Davidowitz, 1970). This result points up, we think, the potential usefulness of the waveform technique both in physical therapy and in the treatment of psychoneuroses and functional psychoses.

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4. It is worthwhile to note that the durations of needle and surface waveforms are not strictly comparable measures: (1) the duration of needle waveforms, which are often polyphasic (cf. Fig. 6), is typically measured from baseline to baseline rather than from peak to peak as we have done for the biphasic surface waveforms; (2) although the mean duration of needle waveforms does differ from muscle to muscle, it must be determined from at least 20 different locations, since the individual durations from placements within the same muscle may differ by a factor of five or more (Buchthal, 1957).
5. Buchthal (1957) reports that needle "potentials are of the same duration during weak and strong effort [p. 16]." We presume that his report is based on findings made with electrodes whose pick-up area was either (1) very restricted, so that interference pattern EMGs were not obtained, even under near-maximal contractions, or (2) quite widespread, giving records comparable to those obtained with surface electrodes.
6. As will be demonstrated elsewhere (Davidowitz & Bruno, in preparation), posture also modifies both the duration of surface waveforms evoked by cutaneous stimuli and the temporal relations among synchronous needle waveforms recorded from different sites within the same muscle.
7. The distances in Fig. 10 and in Fig. 12 are given, as they were measured, in inches. They may be converted to centimeters by multiplying by 2.54.
8. It should be noted that the waveforms recorded at the flexion placement for flexion of the finger were of longer duration and of different polarity than those described here as corresponding to extension of the middle finger.
9. The waveforms dealt with in both of the studies presented in this section have been described as "movement-correlated" because the needle data needed to establish their source were not taken. However, since the different waveforms in each study occurred in synchrony with each other and in correlation with the same finger movement, a common muscular origin was presumed in each case. Knowledge of the particular muscle of origin was not necessary to make our point.

NOTES

1. This report represents an extension and evaluation of the findings originally made in our laboratory by J. Davidowitz. Portions of this material were previously presented at the 1965 meetings of the Eastern Psychological Association and in a paper delivered at the Joint C.A.S.D.S.-Ciba study group on "Mechanisms of Motor Skill Development," London, November 1968 (Hefferline, Bruno, & Davidowitz, 1970). The work presented here was supported by NIMH Grants M-2961 and MH-13890, by Columbia University grants from the Higgins Fund and from the Institutional Scientific Research Pool, and by PHS postdoctoral Fellowship MH-17827 to J. Davidowitz.

2. Now in the Department of Ophthalmology, New York University Medical Center.

3. It should be noted that two additional waveforms appeared—quite infrequently—during abductive pressures. One was about twice the duration and of the same polarity as the common "long" waveform. The other was shorter and smoother in shape, but of opposite polarity.