

# RESEARCH TECHNIQUES AND INSTRUMENTATION: EMG

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Electromyography (EMG) is a technique especially suited to the analysis of skilled movements in general, and of speech in particular. Its particular merit is that it provides direct information about the speech gesture in its natural units. The sound spectrogram and x-ray motion picture, though valuable, give only indirect and highly encoded answers to the essential questions about speech: what muscles are contracting, and when? Moreover, since the muscular contractions reflect so directly the motor commands carried by neural impulses, EMG enables us to look upstream toward the speaker's brain for clues to the organization of the neural machinery that generates spoken language.

This paper consists of a brief account of the underlying phenomena and the means by which they can be observed instrumentally, examples of the use of electromyography in speech studies (drawn largely from the work of colleagues at Haskins Laboratories<sup>1</sup>), and comments on the special opportunities and problems associated with the use of EMG for research on speech.

## *Muscle Potentials and Their Recording.*

EMG provides graphic information about the electrical activity which accompanies muscle contraction. The basic entity in the neuro-muscular mechanism is neither the whole muscle nor the individual muscle fibre, but a structure of intermediate complexity called the motor unit. This comprises, in the small-to-medium-size voluntary muscles used for speech, a single neuron and the group of a hundred or so muscle fibres to which it is connected by its motor end plates. A neural impulse arriving at one of these end plates excites a wave of depolarization that sweeps along the muscle fibre, somewhat like a grass fire, at a few meters per second. The local activity, corresponding to the flame in the analogy, is a flow of electric current near the depolarized part of the membrane. The strength of the ionic currents decreases with the distance from the muscle fibre, though electrical effects are still detectable at several centimeters.

<sup>1</sup>More extensive accounts of this work and the names of colleagues responsible for it are indicated in the References.

Motor unit potential (a), fibrillation potential (b), positive denervation potential (c), polyphasic potential with spike potentials of short duration (d), and grouped polyphasic potential (e). (Negative is up. 1 msec. = 1/1000 of a second. 1  $\mu$ V = 1/1000000 of a Volt).

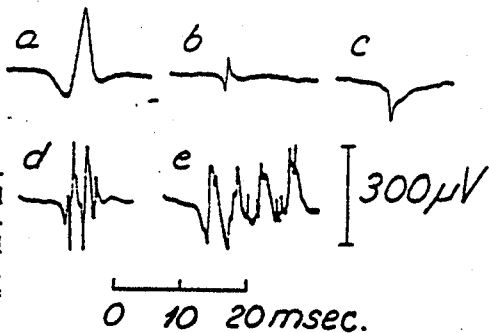


FIGURE 1. Electrical activity of muscle as recorded from a needle electrode by photographing the trace on a cathode-ray tube. (From Buchthal)

If two wires are placed with their exposed ends close to each other and to the muscle fibre, momentary differences in the electric potentials at the wires can be observed when the wave of activity sweeps past. The whole event, which takes but a few milliseconds, can be displayed on the face of a cathode-ray tube, and gives a trace similar to the one shown in Figure 1(a). The entire process of stimulation by the nerve and response by the muscle may be repeated some tens of times per second.<sup>2</sup>

Much of the extensive literature on EMG<sup>3</sup> deals with correlations between the detailed characteristics of muscle potentials and various pathological conditions of either the muscle fibre or its innervation. Some examples of atypical spike potentials are shown in Figure 1(b-e).

The effect of level of effort (Rosenfalck, 1960) in a normal muscle is illustrated by the oscillographic recordings of Figure 2. The top trace shows several muscle action potentials occurring in rapid succession, one at each activation of the particular muscle fibres near the needle electrode. The middle trace shows that a slight increase in contraction involves a second motor unit, and the bottom line, where the individual motor unit spikes are no longer distinguishable, shows the trace for a stronger contraction. Clearly, the total amount of electrical activity increases with the forcefulness of the contraction; indeed, force and electrical activity are proportional to each other, to a first approximation.

<sup>2</sup>For additional descriptions and quantitative data about conduction velocities, innervation ratios, etc., see Buchthal and Faaborg-Andersen.

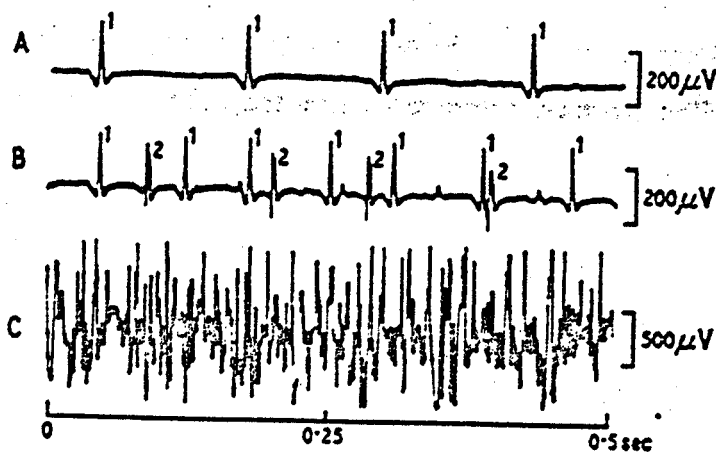
<sup>3</sup>An extensive "Bibliography on Electromyography" as of 1960, arranged by subjects and authors, has been made available by DISA Elektronik A/S Herlev, Denmark.

When the response of the muscle as a whole is of primary interest, as it usually is in research on speech, a simple indication of the total electrical activity would be preferable to much fine detail. Such an indication can be obtained by using larger electrodes that record directly from the whole muscle, rather than from the very limited zone around a needle tip. The larger electrodes may be placed on the surface of the skin if the muscle is not too deep. These surface electrodes are affected by the waves of depolarization in muscle fibres just as are needle electrodes but, since they are almost equally exposed to many fibres and to a greater length of each fibre, the electrode potential is a summation over both space and time; thus, EMG recordings from surface electrodes do not show the spike potentials characteristic of single motor units but rather a less rapid fluctuation of potential attributable to the activity of many motor units.

### *EMG and Speech Research: Needle Electrodes*

Since EMG techniques for studying muscle pathology have usually employed needle electrodes, it was to be expected that these same techniques would be used in investigating speech articulation, even though a different kind of information about muscle activity was being sought. Some of the advantages and limitations attendant upon the use of needle electrodes can be indicated by examples of such use.

Ladefoged (1962) and his colleagues at the University of Edinburgh have examined the activity of the subglottal system from the point of view of Stetson's hypothesis that rhythmic contractions of the intercostal muscles are the significant counterparts of spoken syllables. Their EMG recordings, taken during an ongoing utterance, showed a transfer of activity from the external



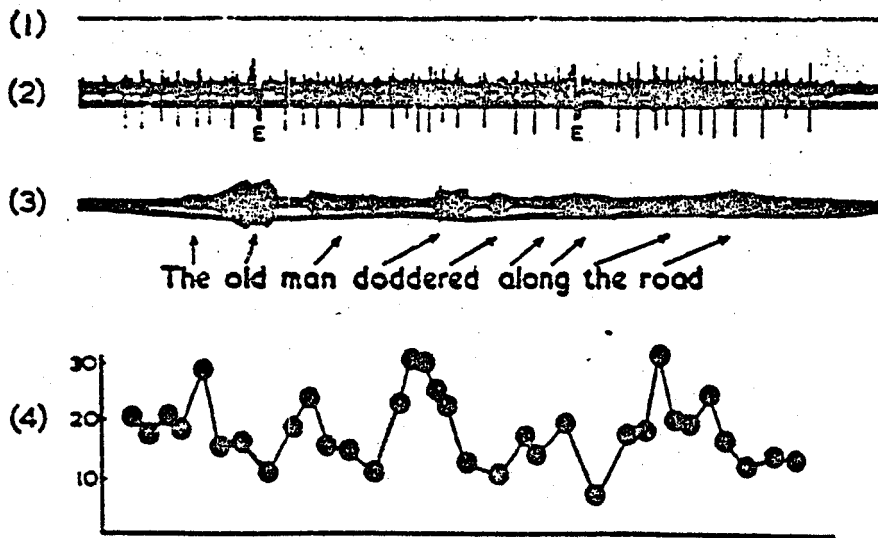
*Muscle action potentials recorded at weak effort (A and B) and strong effort (C)*

FIGURE 2. Effect of level of effort in normal muscle. (From A. Rosenfalck)

to the internal intercostals as the subglottal air pressure shifted from overpressure to underpressure. In addition, there were bursts of activity superimposed on the gradually increasing signal from the internal intercostals. Though these bursts were not correlated in a simple way with the individual syllables of the utterance, there was some correspondence with the stress pattern.

Figure 3 gives the data and their analysis for a single sentence. A needle electrode in the internal intercostals picks up mainly the activity of a single motor unit firing between 10 and 30 times per second. The derived curve at the bottom of the figure shows the instantaneous repetition rate of the motor unit spikes. The variations in rate corresponds roughly to the stress pattern of the sentence. This is an example of the detail provided by a needle electrode and of one quantitative use that can be made of it. The reduction of the experimental data is laborious, and any error in identifying or measuring the position of a single pulse would introduce a substantial perturbation in the final curve; furthermore, interpretation of the data involves the implicit assumption that all of the motor units would, if recorded, show similar variations in firing rate. A virtue of the method is, of course, that needle electrodes permit unambiguous identification of the muscle from which the data are being taken.

Another illustration is provided by the experiments of Faaborg-Andersen (1957) on the behavior of the intrinsic muscles of the larynx during phonation.



Internal intercostal activity during speech. (1) Time marker 1/10 and 1/100 seconds. (2) Internal intercostal action potentials (electrical activity associated with the action of the heart indicated by E). (3) Microphone record. (4) Instantaneous frequencies of the single motor unit recorded in (2) in impulses per second.

FIGURE 3. Electrical activity of internal intercostal muscle during speech, as recorded from a needle electrode. (From Ladefoged)

Electrical activity in the left vocal muscle during phonation with simultaneous microphone recording. A. The action potential pattern. B. The mean action potential amplitude. C. Microphone recording. Phonation: "e". Frequency 285 c.p.s. Patient no. 56, a 64 year old woman with the right vocal cord immovable in paramedian position. The left vocal cord was normally movable.

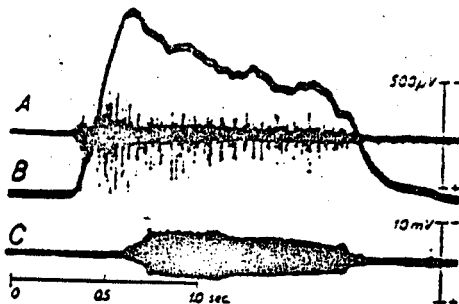


FIGURE 4. Electrical activity of an intrinsic muscle of the larynx during phonation, as recorded from a needle electrode. (From Faaborg-Andersen)

Figure 4 shows the activity in the left vocalis muscle during a brief phonation, as recorded from a small needle electrode. So many motor units are active that it is not possible to separate and count their spikes (Trace A), though the temporal course and general magnitude of the activity is evident. This aspect is made explicit in Trace B which shows a running average of the signal from the electrode. The temporal relationship between Traces A and B and Trace C are typical: muscle activity precedes the acoustic signal, in this case by some tenths of a second.

The series of studies from which this example was taken explores the coordinated activities of most of the intrinsic laryngeal muscles in respiration and in phonation at different pitches, intensities and registers. The recordings were made with needle electrodes and a DISA electromyograph, which provides three channels of photographic registration from three cathode-ray tubes. Special input amplifiers are required to avoid "loading" the electrodes, since the latter have, typically, an impedance of a few hundred thousand ohms. Careful shielding is required to avoid extraneous voltages on such high-impedance leads, though noise problems are not severe in EMG since signal levels are usually rather high. Cathode-ray tubes and photographic recording are used to obtain a high frequency response.<sup>4</sup> The recording session can be monitored by a second set of oscilloscopes and a loud speaker; even so, photographic recording is inconvenient and the limitation to three channels is restrictive. It would, of course, be possible at some further expense to have more channels and to avoid photographic processing by utilizing the ultraviolet recording papers and optical galvanometers that are now available.

### Surface Electrodes

Considerations of the kind mentioned above have led a number of investigators to use surface electrodes and penwriters, particularly when their research needs could be met by measurements of overall muscle activity. This was the case in the research undertaken at Haskins Laboratories. The initial experi-

<sup>4</sup>Buchthal recommends a frequency response good to 10 kilocycles.



FIGURE 5. Suction electrodes developed for electromyographic studies of speech.

ments employed the techniques and surface electrodes described by J. F. Davis (1952) of McGill University. Although surface EMG proved suitable, it was soon necessary to develop a special electrode system and make use of magnetic recording to store data for later analysis.

The primary aim of the work at Haskins Laboratories has been to gain an understanding of the distinctive components of speech gestures and their relationships to the linguistic units of normal speech. Thus, the chief interest has been in gross aspects of the activity, primarily in the supraglottal region and at the larynx. The obvious need for electrodes on the tongue and inside the mouth, and the desirability of simultaneous recordings from several locations, led to the development of a system using small vacuum cups as electrodes.<sup>5</sup>

Figure 5 shows a complete electrode assembly and also an electrode attached to a finger. The electrodes are silver jewelry beads about a quarter of an inch in diameter that have been cut in half and fitted with side tubes which can be inserted into small-diameter Silastic tubing. A stranded steel wire inside the tubing connects the electrode to a brass plug at the other end. This plug makes both vacuum and electrical connections to the manifold, shown in Figure 6. The manifold is connected by a vacuum line to a five-gallon jug that is pumped continuously. The electrical connections are carried from the manifold through shielded cables to the preamplifiers of a modified electroencephalograph.

These small suction electrodes have proved to be very satisfactory. They adhere well on the tongue, inside the mouth, or on the face; they show negligible movement artifact, at least as seen through 20-cycle high-pass filters; and, they offer very little hindrance to normal speech. The only preparation that is necessary for placement of the electrode on facial skin is a brief scrub-

<sup>5</sup>Harris, E.S., Rosov, R., Cooper, F.S., and Lysaught, G.F. "A Multiple Suction Electrode System." (Submitted for publication in *Electroencephalography and Clinical Neurophysiology*.)

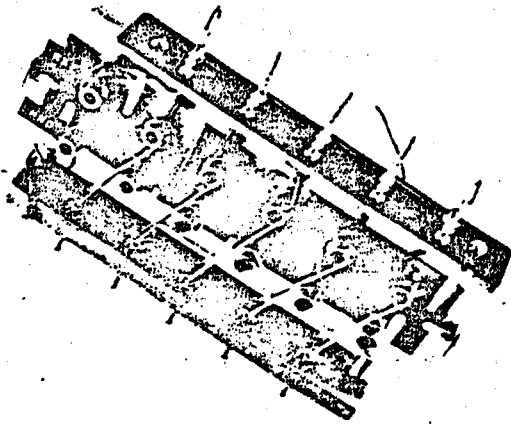


FIGURE 6. Vacuum manifold and electrical connections for suction electrodes.

bing with a gauze pad dipped in alcohol, followed by the application of a little electrode jelly; no site preparation is, of course, necessary on mucosa. The electrode resistance on either skin or mucosa is quite low, usually in the range of 1000-2000 ohms. Typical muscle potentials as picked up by these electrodes are several hundred microvolts at least, so that the subject need not be put in a shielded room even in a location that has high-level radio interference. We have used the electrodes either as bipolar pairs or singly, with a reference electrode on an ear lobe.

The EMG recordings are made with an eight-channel Edin electroencephalograph, modified to eliminate components below 20 cycles and to have a paper speed matching that of the standard sound spectrogram, namely, five inches per second. Two channels are used for each electrode position, one for the muscle potential itself and the other for an integrated trace. One channel is regularly reserved for a vibration pickup (throat microphone) located at the larynx and another is often used to record from a pressure transducer. Magnetic tape recordings are made of what the subject says, the output from the larynx microphone, and the muscle potentials from one of the electrode locations. This procedure has permitted us to experiment with integrated traces derived from various frequency bands in the myographic signal that lie above the frequency limit of the penwriter (approximately 100 cps), and also to correlate EMG traces with sound spectrograms.

The system has been quite satisfactory insofar as the individual channels were concerned, but more channels have often been needed: moreover, it would have been most helpful to have captured the raw data in a form that would have permitted detailed analysis in various ways. Hence, we are now rebuilding the system to use magnetic tape recording as the primary means of data collection. The penwriters will be used to monitor the recording session and, later, to display data from selected channels of the magnetic tape

recording. Figure 7 shows the principal components of the system. The need for automated data reduction has been thoroughly impressed on us even though we have collected and analyzed only limited amounts of data with our original system.

### *Experiments on Labial Stop and Nasal Consonants.*

The kinds of experiments for which this equipment was designed can be illustrated by early studies (Harris, Lysaught, and Schvey, 1962) of the component gestures that serve to distinguish the bilabial stop and nasal consonants /p,b,m/, as in the words "peak, beak, meek." The whole articulatory apparatus is, of course, involved in producing these sounds; however, it is the gestures at lips, velum, and glottis that are likely to be decisive in determining which of the three sounds was produced in a particular instance. It was possible to find specific electrode placements near the lips that are diagnostic, one for lip closure and the other for lip opening. These electrode positions are indicated in Figure 8 and myographic records from them are shown in Figure 9 for the stops /p,b/ in nonsense utterances. The vibrations at the larynx, as shown by the bottom trace, provide convenient timing indications for the moments of lip closure and lip opening. The electrical activity at the upper lip electrodes, presumably due principally to the Orbicularis oris muscle, starts well before lip closure but reaches a peak of activity at just about the moment the lips make contact. The activity at the lower electrodes, due presumably to the Quadratus labii inferioris, comes about 80-100 msec later in time and reaches

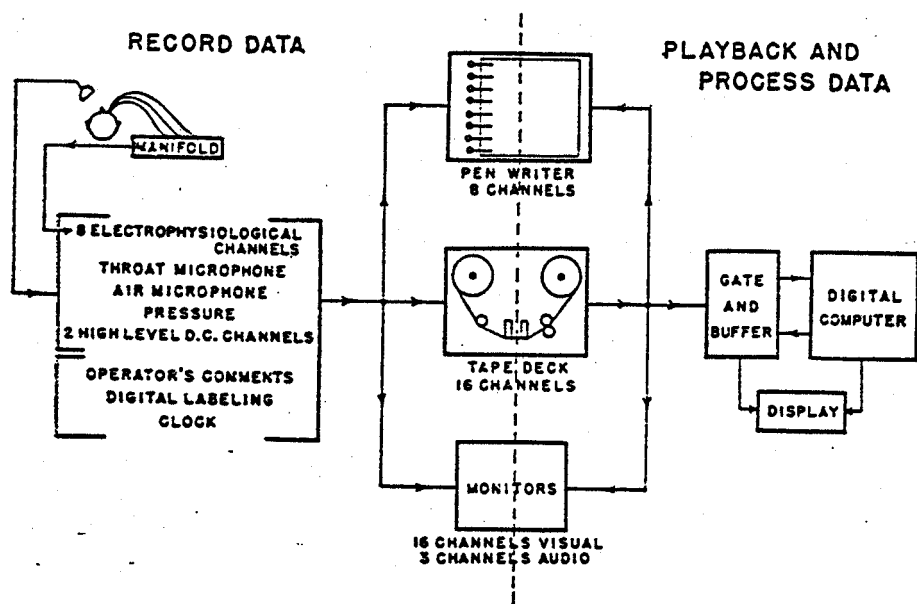


FIGURE 7. System for collecting and analyzing physiological and acoustical data about speech.



its peak at just about the moment of lip opening. This same relationship holds for both /p/ and /b/ in all four utterances.

The events at the glottis are clearly different for /b/ and /p/, as we might suppose; that is, for /b/ the vocal cord vibrations continue through most or all of the lip occlusion, while for /p/ there is an abrupt cessation of vocal cord activity at the moment of lip closure, and vibration is not resumed until appreciably after lip opening. Pressure measurements and transillumination of the glottis both indicate that for /p/ the vocal cords are drawn quickly apart and held so throughout the interval of closure at the lips.

It is, however, instructive to examine the lip gestures for /p/ and /b/ to see if there are significant differences in that location also. Figure 10 shows the relative amplitudes of the integrated myographic tracings for a total of 360 utterances produced by five subjects. There are differences of the order of 20% between /p/ and /b/; however, an examination of the spread of the amplitude distributions, shown in Figure 11, leads one to conclude that there is so much overlap that reaching a decision about any particular utterance on the basis of its magnitude alone would be extremely chancy. Hence, in a practical sense and for the quick categorical assignments so necessary in speech communication, one can say that the lip gestures are the same and the distinctive difference between /p/ and /b/ is to be found at the glottis.

What can be said about /m/? The glottal activity is the same as for /b/, and the lip gestures are very similar to those for both /p/ and /b/; however,

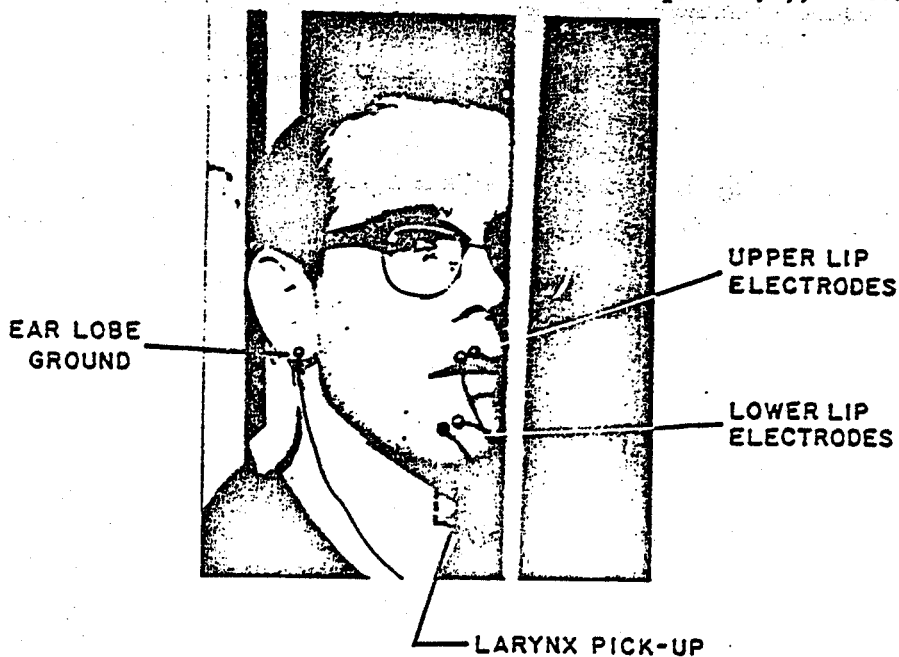


FIGURE 8. Placement of suction electrodes and larynx pick-up for experiments on lip activity in articulating the labial stop and nasal consonants.

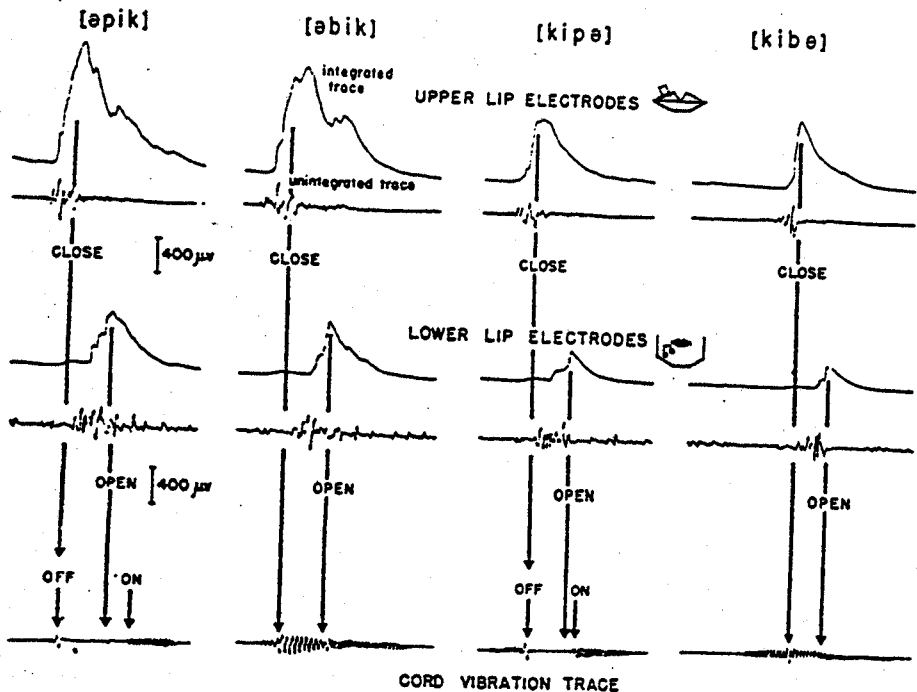


FIGURE 9. Electromyographic recordings (both direct and integrated) from the electrode locations shown in Figure 8; also, recordings of the vibrations at the larynx.

the activity at the velum is not at all similar. Figure 12 shows the various electrode placements used in searching for EMG signals that would correlate closely with velar closure. Most of the placements showed activity during speech, but only those on the posterior soft palate near the midline gave all-

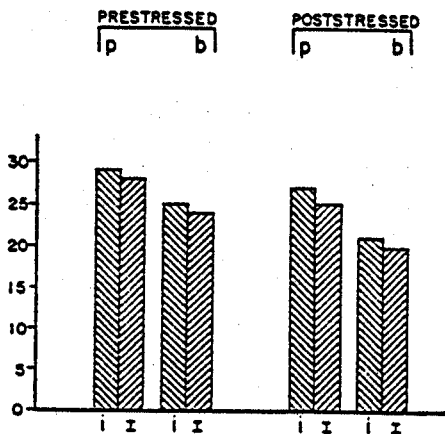


FIGURE 10. Peak amplitudes of integrated EMG traces from upper lip electrodes. The amplitudes were normalized for each subject and averaged for each utterance type.

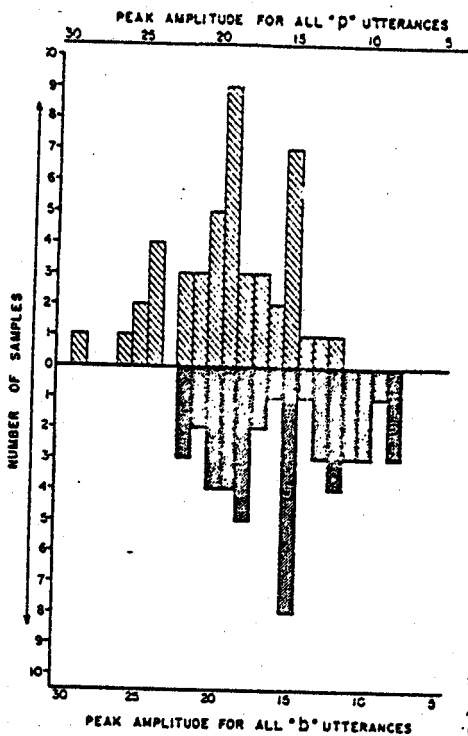


FIGURE 11. Distribution of peak amplitudes of the kind shown in Figure 10 for all /p/- and /b/-utterances for a single subject (J. B.)

or-nothing potentials that correlated with closure.<sup>6</sup>

(This would, of course, correspond to oralization in descriptive terms; none of the four subjects showed distinctive activity corresponding to nasalization.)

Two examples of activity at the velum and upper lip are shown in Figures 13 and 14. For the word "apple", there is velar activity (oralization) throughout the utterance, with an extra twitch on the velum at about the same time that the lips close for /p/; for "ample", there is rather little velar activity during the initial vowel, but then a sharp burst of activity in the middle of the closure period, signalling the shift from nasal to oral manner for the second member of the consonant cluster.

Figure 15 shows composite electromyograms for the utterances /dæpəl/ and /dæmpəl/ as recorded from electrodes on the velum and posterior pillar. For /dæpəl/, there is a surge of activity on the velar electrode to oralize the initial /d/, and it continues at a lower level throughout the utterance. For /dæmpəl/, this initial surge dies away for the /m/, but then there is a marked burst of activity for the /p/-member of the cluster. This occurs at very nearly the same moment that voicing stops, about the middle of the occlusion at the lips. The vertical line shows the offset of voicing, and was the time marker

<sup>6</sup>Fritzell, using needle electrodes in the lateral wall of the epipharynx, found electrical activity in both the tensor and levator muscles that correlated closely with the oral/nasal features of connected speech.

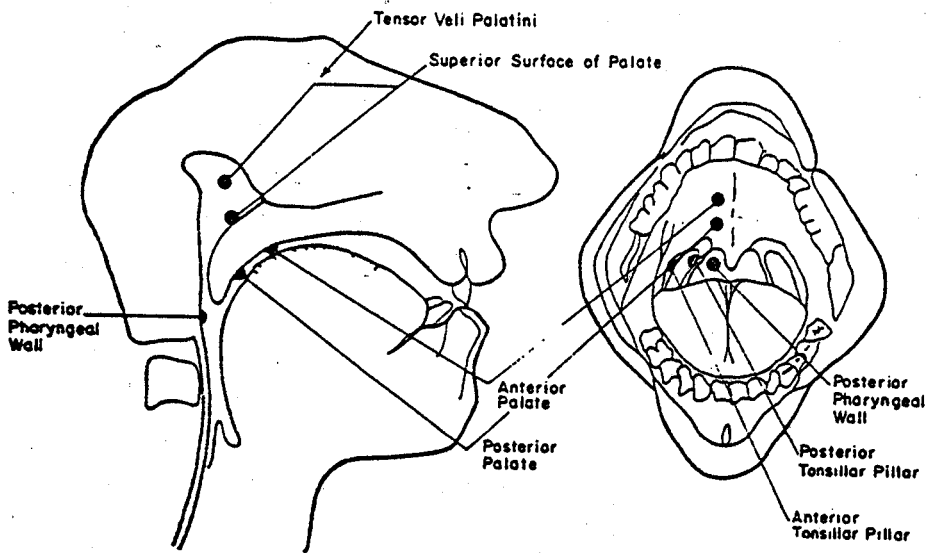
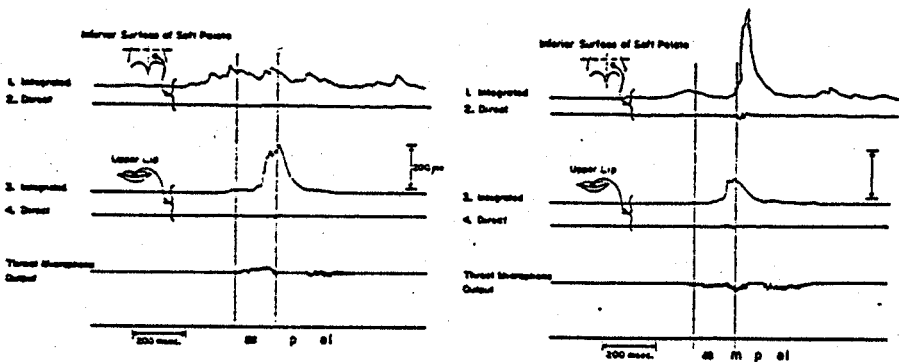


FIGURE 12. Electrode placements used in searching for electromyographic signals that correlate closely with velar closure.

used in superimposing the traces. The posterior pillar electrode shows activity that is partially, but not so closely, correlated with velopharyngeal closure. These sets of superimposed traces indicate the kind of utterance-to-utterance variability that one encounters.

The experimental results of these pilot studies can be summarized by noting the /p/, /b/, and /m/ have in common an almost identical set of gestures at the lips; that /p/ is distinguished by a devoicing gesture at the glottis; and that /p/ and /b/ are distinguished from /m/ by identical oralizing gestures at the velum. This does not differ very much from the conventional phonetic description — indeed, it would have been surprising and distressing if it had



FIGURES 13 and 14. Electromyographic recordings from soft palate and upper lip for the words "apple" and "ample." The throat microphone traces serve to identify the moments of vowel onset and lip closure.

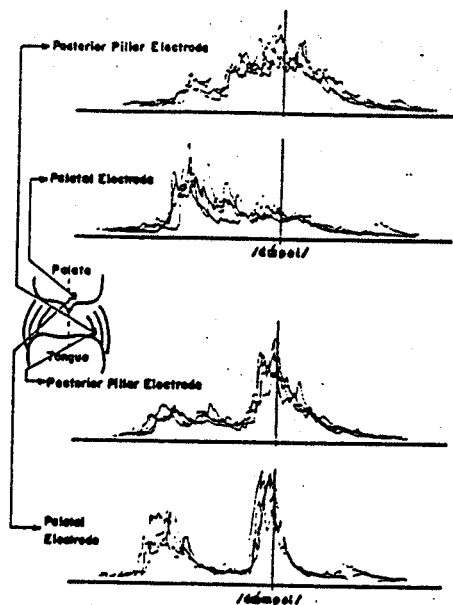


FIGURE 15. Superimposed EMG traces from electrodes on the velum and posterior pillar for the two utterances /dæpəl/ and /dæmpəl/.

—though the emphasis is different and the relationship between voiced and lax articulation is clarified. The main point is that the description is directly in terms of essentially all-or-none actions by specified parts of the articulatory apparatus. One can infer, at the neural level, an equally simple pattern of motor commands that correspond to the familiar dimensions of place and manner.

### *Working Hypothesis*

It is an open question whether or not the preceding simplified description in terms of neural motor commands to component parts of the speech apparatus can be extended to all the sounds of the language (Harris, 1963a). A study of final consonant clusters containing /f/ suggests an affirmative answer (MacNeilage, 1963b). Some recent experiments on vowels and dental consonants (MacNeilage, 1963c, d; Harris, 1963) have given distinctive electromyographic records from electrodes on the tongue; however, the results elude so simple an interpretation, either because the electrodes fail to resolve the signals from adjacent muscles or because the relevant pattern of activation is inherently complex.

The practical problem here, as in much research, is to delimit the experimental measurements to those most likely to yield a useful model of the system. A most promising basis for such a model appears to lie in the motor command aspects of speech production (Liberman, Cooper, Harris, and MacNeilage, 1962; Cooper, Liberman, Harris, and Grub, 1958; Lisker, Cooper, and Liberman, 1962). The research of the Haskins group is aimed primarily at finding out how far it is possible to go in finding simple, direct correlations between the component gestures and the phonemic units of normal speech. We hope and

believe that this kind of normative data, and the techniques for getting it, will be relevant also to investigations of defective speech.

The special relevance of EMG as a technique for the study of speech, mentioned at the beginning of this report, has its basis, therefore, not only in the fact that EMG provides a direct measure of muscle activity, but also in the probability that the spoken language is so organized that it is produced by putting together simple combinations of component gestures, and that some of these component gestures, like the ones that distinguish /p/, /b/, and /m/, are themselves quite simple.

In short, EMG as a tool is matched to its task — but even a suitable tool needs guidance. An important part of that guidance can come from a knowledge of the acoustic cues that carry the main load of letting the listener know what sounds were intended by the speaker (Liberman, 1957 and 1959). Both the sounds of speech and the gestures for producing it contain much that is irrelevant for the listener, and private to the speaker. Speech is, for each of us, a very private affair — no one else cares how it is made, or heard, anymore than he cares whether personal savings are invested in real estate or stocks or yachts; the only requirement is that external transactions be conducted in the common currency. This currency consists of the acoustic cues carried in the speech waveform; however, it can be specified not only in terms of these acoustic cues but also of their counterparts in the spectrogram, in the x-ray movie, or in the EMG. There is no requirement that the total acoustic signal, or its counterparts, should be the same for all normal speakers — indeed, wide variations are to be expected — but only that all speakers should use the same cues. Moreover, the cues should be essentially the same in cleft palate speech and in normal speech, though again their counterparts may differ markedly, or be hidden by irrelevant differences.

The working hypotheses sketched above may be put briefly as the set of assumptions (a) that a useful model for speech can be based on the role of motor commands in articulation, (b) that EMG is an especially appropriate tool for finding correlations between component gestures and phonemic units, (c) that knowledge of the acoustic cues can guide the experimentation and keep it within practical limits, (d) that normal and cleft palate speech must have much in common at the level of acoustic cues if cleft palate speech is to be intelligible, and (e) that information about normal speech, and the research techniques used to obtain that information, will be directly relevant to the problems of cleft palate speech.

#### *EMG Techniques: Prospects and Conclusion*

Various EMG techniques used in speech research have been described in terms that might seem to imply no complications and no remaining problems. Not so; for even if all phones could be characterized as simply as those that have been discussed, many of the component gestures have yet to be isolated and measured. There are technical problems as well. Several parts of the speech apparatus, notably the tongue, have a number of overlapping muscles

and this poses the question of how to allocate measured potentials to the proper muscles. There may be ways to arrive at an answer: for one thing, a pair of electrodes gives maximum response for those muscle fibres that are parallel to the line through the electrodes; for another, the muscles nearest the electrodes will typically give the largest potentials and the highest frequency components; and, for a third, multiple electrodes and correlation techniques should help to sort out the potentials from adjacent muscles. In many locations, needle electrodes can also be used either to identify the active muscle or to confirm inferred assignments; likewise, a combination of electrical stimulation and EMG recording may be useful in making these assignments.

Finally, it should be said that we are not recommending EMG as an exclusive tool: the objective in research on speech, as in all research, is to learn about the phenomenon by any means. The trained ear, reinforced by the sound spectrograph, can be extremely useful in identifying the key elements in a speech event; x-ray motion pictures and direct photography of the vocal cords both yield valuable insights in a very literal sense; and, pressure, flow, and vibration measurements can also provide essential information. We are employing most of these techniques and find them useful. Even so, we feel that EMG holds the principal place as a tool with special relevance for the study of speech.

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