PHYSIOLOGICAL MEASURES OF SPEECH MOVEMENTS: EMG AND FIBEROPTIC STUDIES

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Since the topics discussed in this *Report* are divided in a fashion which is reasonable from the point of view of labor-sharing, but not from the point of view of orderly theoretical exposition, I shall begin by making a distinction between the nature of the data obtained from fiberoptic and transillumination studies, on the one hand, and electromyographic studies, on the other. Although both these techniques are useful in discussions of the orofacial functioning other than speech, the speech area is the one that I know best, and, consequently, I shall make no attempt to review the extensive literature on the use of electromyography in the study of chewing, for example.

Detailed studies of speech articulation have suffered in the past from the general inacessibility of the speech mechanism to direct viewing. A number of techniques have been developed with vastly different technologies, which share the same object—that is, the observation of the movement of the articulator in space and time. Although the technologies are different, the end result will be the same, except for differences due to distortions or incompleteness of the view given. For example, we find Lindblom (1968) and MacNeilage (1969) using light monitors to describe the position of the lip and jaw. Other workers, Houde (1969), for example, have used x ray for essentially the same purpose.

One of the techniques I shall discuss, fiberoptics, is one of the group of techniques for viewing the movement of articulators—in this case, the larynx and its associated structures. Other techniques, such as x ray, indirect laryngoscopy, and observations of patients who have had massive surgical removals in the orofacial area may supply the same information. Electromyography, the second technique to be discussed, monitors an entirely different level of function, that is, the signals which accompany muscle contraction and lead to the movement of the articulators.

This review will be divided into three parts: first, current techniques in fiberscopy and transillumination; second, the status of the electromyographic technique; and third, the circumstances in which EMG seems particularly useful. Findings from each technique will not be reviewed; the primary purpose of the paper is to indicate where the techniques might be employed usefully.

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FIBEROPTIC OBSERVATION OF THE LARYNX

In this section, I will rely heavily on the work of my colleague, Masayuki Sawashima, now visiting the Haskins Laboratories from the Institute of Logopedics and Phoniatrics of Tokyo University. Fiberoptic techniques appear to have been used in speech research only for observation of the larynx although there is no reason in theory why modifications of this technique could not be used for other purposes, such as observations of velopharyngeal closure.

Several techniques have been used in the past for observation of the larynx. Indirect laryngoscopy has been in use since the 19th century. Under ideal circumstances, excellent movies can be made of the opening and closing of the larynx during production of sustained vowels. (See Lieberman, 1961, for example, or Timcke, von Leden, and Moore, 1958.) The difficulties with the method are, however, that good mirror viewing requires suitable anatomy and a low gag reflex in the subject. A more serious objection is that observation of the larynx is not possible during running speech. The Taub panendoscope (1966) is essentially a useful modification of classic technique, and suffers from the same limitations.

Techniques have been developed which overcome this limitation of observation. Transillumination of the larynx has been used by various investigators, including Sonesson (1960), Moore,[1] and Lisker, Abramson, Cooper, and Schvey (1969). The principle involved is to put a light source on one side of the larynx, and a photocell on the other. The light transmitted will be roughly proportional to the glottal area. Since the light source can be made less bulky than the mirrors used in classic indirect laryngoscopy, it is possible to insert the light through the nasopharynx and obtain a record of the overall size of the laryngeal opening in running speech. Its disadvantage is that it does not record the shape of the glottal opening, but merely the area. Consequently, one cannot make good inferences about the precise detail of the opening and closing mechanism.

With the development of fiberoptic systems, it has been possible to combine the true image properties of indirect laryngoscopy with the continuous viewing advantage of transillumination. The fiberscope depends for its operation on the fact that a long cylinder of glass can transmit light from one end to the other. If the light-transmitting cylinder is bent into a curve, there will be only moderate leakage, which can be minimized by coating the fibers. Modern technology has made it possible to produce extremely thin filaments of glass, of diameters of only a few microns. In such sizes, glass fibers are extremely flexible. Consequently, it becames possible to use bundles of such fibers to transmit an optical image over a tortuous pathway, such as that from the larynx out the nasal passage.

Optic bundles have been used widely in various medical applications, such as a flexible gastroscope. Sawashima has developed a practical working fiberscope for laryngoscopic use (Sawashima et al., 1968). This device now is avail-

[1]Moore, P., personal communication (1969).

able commercially.[2] The fiberscope consists of a hard tip, a flexible optical cable, an optical connector, a light source, and a camera. The tip of the fiberscope is approximately 6 mm in diameter, and consequently can be inserted easily through the nasal cavity of most subjects without discomfort. We do, however, anesthetize the nasal fossa and epipharynx with a 4% Xylocaine (lidocaine) solution.

Excellent still photographs or movie sequences can be made with an appropriate camera tied in to this device. The only problems that arise seem to be rather minor. The first, and more important, is that the larynx moves not only open and closed, but also up and down and in some more complex rotational patterns, while the fiberscope moves simultaneously. Consequently, the relationship of the fiberscope tip and the glottal chink cannot be fixed.

The image of the glottal chink occasionally moves out of the viewing field or varies in how well it is focussed. Also, since the distance varies, the size of the image is not in constant proportion to the size of the opening, nor is it always in focus. Later models of the fiberscope have an external repositioning device which sometimes is helpful in keeping the image in the field, but doesn't help with the other movement artifacts. A second problem is that the image is not as bright as would be desirable for all purposes. The light source, however, probably can be improved.

This device should have wide experimental and clinical application. It has already been a useful source of information in studying the opening and closing of the glottis for stop consonants (Lisker et al., 1969). It probably can be used as a routine tool for clinical laryngeal examination. As was suggested earlier, it probably could be used with slight modification for observing velopharyngeal closure; an extremely similar bronchoscope already has been manufactured.

ELECTROMYOGRAPHIC RECORDING

In this section, I shall rely heavily on two earlier reports on the technology of electromyographic recording—an earlier one by Cooper (1965) and a later one by Gay and Harris (in press). In this section, reemphasis will be placed on the two technical problems most troublesome to investigators in this area—the probe used for picking up potentials, and the type of analysis used in processing them. Other problems generally have been solved adequately in ordinary commercial EMG installations.

Electromyography is a technique for providing graphic information about the time course of the electrical activity which accompanies muscle contraction. All muscles consist of large numbers of fibers arranged usually in parallel inside a sheath. Groups of fibers within the muscle are connected to a single neuron, and contract when signalled by that nerve fiber. The size of the ratio between the muscle fibers and the nerve fiber varies among the skeletal muscles, with the

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[2]Inquiries may be addressed to The Olympus Corporation of America, Medical Instrument Division, 2 Nevada Drive, New Hyde Park, New York.

ratio relatively small for the muscles of skilled movement, such as those for speech. When a neural impulse arrives at the motor end plate, the region of connection between muscle and nerve, a wave of depolarization sweeps along the associated muscle fibers, and accompanies their contraction. If two wires are placed with their exposed ends close to each other and to the muscle fiber, momentary differences in the electrical potential at the wires can be observed when the muscle contracts; their magnitude will depend on the distance of the wires from the site of activity. As the strength of contraction increases, there will be recordings from more units in a fixed time interval. The details of the appearance of the electromyographic record under various clinical conditions are summarized in standard texts on the subject.

The electromyographic system, then, will consist of some sort of probe for picking up the potentials, amplifying equipment, recording equipment, and an ultimate graphic display, which may have more or less signal processing equipment incorporated. I shall discuss some problems connected with the type of probe, and with the ultimate display.

In speech research, three types of probe have most generally been used—surface suction electrodes (Harris et al., 1964), conventional needle electrodes (Buchthal, 1957), and so-called "hook" electrodes (Shipp, Deatsch, and Robertson, 1968; Hirano and Ohala, 1969). All three electrodes record essentially the same information; the differences between them depend simply on the distance between the probe and the site of activity, and the size of the probe. Generally, the larger the probe, the more units it will record from. The further the probe from the activity, the more units it sums, and the smaller the activity. (Distance probably will also affect the frequency characteristics of the signal, but no use has been made of these properties thus far.)

The choice among probe types seems to be largely a matter of convenience for the problem at hand. Useful work has been done with all three. The surface suction electrode we use at Haskins Laboratories has been described exhaustively in the reference just cited. It is useful when the articulatory movement of interest is caused by a muscle close to an orofacial surface. For example, a number of investigators have used it to investigate lip closure in labial consonant formation (Harris, Lysaught, and Schvey, 1965; Fromkin, 1966; Tatham and Morton, 1969), and levator palatini action in velopharyngeal closure (Harris, Schvey, and Lysaught, 1962; Lubker, 1967). In both cases, the gesture studied is rather unambiguously related to a single muscle. A second advantage of the surface electrode is that it is a less drastic procedure than inserting a hook or a needle; it can be used by speech researchers without medical help, or in clinical circumstances, such as the office examination of a small child, where minimum trauma is desirable. The disadvantage is that many speech events take place in muscles far from an appropriate electrode site.

The needle electrode can be inserted into virtually any articulatory muscle. Most of the early work on the laryngeal muscles was done with needle electrodes (Faaborg-Anderson, 1957, for example). The particular advantage of the needle electrode is that it is available commercially, and has a long history of use in a large clinical literature. Its disadvantage in speech research is that many of the articulators are small and change shape rapidly. Therefore, the electrode is dislodged easily during a long recording session, and may be quite painful.

These disadvantages are overcome by the use of hooked wire electrodes, now in use by several groups (Shipp, Deatsch, and Robertson, 1968; Hirano and Ohala, 1969; Fritzell, 1969). Apparently, Basmajian and Stecko(1962) first developed the technique. The electrode consists of a thin wire threaded through the cannula of a hypodermic needle. The exposed end of the wire is bent back over the needle to form a hook. The needle is used only to carry the wire electrode to the desired location, after which it is withdrawn. Upon withdrawal of the needle, the hooked portion of the wire becomes anchored in the muscle.

The disadvantages of the hooked wire procedures are two: first, small adjustments in the electrode position cannot be made once the needle is inserted; second, as hooks are presently constructed, the distance between the two hooks is variable and not under the experimenter's control. We are presently investigating the possibility of using an insulated double-stranded wire instead of the present two separate strands.

No matter what the electrode type, it may be worth pointing out that it is almost impossible for a researcher to be entirely satisfied on either of two fundamental points—first, that he is in fact recording from a given, "named" muscle, identified by reference to an anatomy text; second, that the amount of activity recorded is directly proportional to the contraction of that muscle. There are several reasons for this. As to muscle name, it is well known that human anatomy is quite variable. Certain muscles, such as the facial fibers, may differ considerably in their arrangement from one individual to another. In view of such peculiarities, it is not always clear what fibers are picked up if an electrode is inserted carefully according to a formula.

The only solution to this problem seems to lie in more extensive anatomical studies of the entire orofacial region, particularly of muscle and nerve structures, to accompany the work on skeletal structures described by Hixon in this *Report*. At the present, one is frequently in the position, in electromyographic research, of localizing a given muscle by its apparent function, and then, in turn, describing the function as if the localization were made independently. It is not clear, either, what the orientation of the firing fibers will be relative to the electrode. Hence, a demonstration such as Rosenfalck's (1960)—that the relationship between measured activity and muscular contraction may not be generalizable to any particular situation; that is, more measured activity will probably result in more movement, but the relationship is not necessarily linear.

Furthermore, there is a conflict between the choice of electrodes for minimum crosstalk and appropriate sampling size. As Dedo and Hall (1969) recently have pointed out, the type of unipolar concentric needle electrodes often used in the past in laryngeal research will pick up significant amounts of firing from muscles adjacent to the intended signal source. They suggest the use of bipolar concentric needle electrodes, or "paired" platinum wire electrodes for laryngeal work. However, this advantage is bought at the expense of making a very small sample of the firing units in the muscle, which carries its own disadvantages, as I shall show. Probably there should be an adjustment of probe size to muscle size and geometry, but here, again, there is serious need of better anatomical work for the entire region.

In this discussion, we will leave aside the more general problems of amplifying and recording equipment, which are adequately discussed in more general texts, and pass on to the general problem of processing EMG data for display. The simplest display is some sort of direct representation of the amplified and recorded muscle signal against a representation of the acoustic speech signal. Such displays have been used effectively for qualitative arguments, but are not easily quantified; individual samples of a given utterance are quite variable. There are three obvious reasons for this. First, the display represents a signal from many individual unit spike potentials, which are random in phase. Consequently, one expects random fluctuations in size. Second, a given electrode picks up only a small sample of the firing units in a given muscle, and the smaller the electrode, the smaller the sample, and presumably, the larger the sampling error from purely statistical considerations. Third, there are fortuitous differences in the articulatory movement for a given speech sample. All these three considerations suggest that observations should be averaged by some means.

The steps in this process used at Haskins are described by Cooper (1965), and Gay and Harris (in press). Here I shall make only general remarks about the procedure. First, the signal is full-wave rectified. (Otherwise, positive and negative fluctuations of the signal could cancel each other out.) Then it is sent through an integrating circuit, and a number of tokens of the same utterance are averaged. The smoothness of the resulting averaged utterance depends both on the time constant of the integrating circuit and on the number of the included tokens. In our experiments, we usually average about 20 tokens, and choose about a 20-msec time constant for the integrating circuit.

This choice of a 20-msec time constant means that an instantaneous decrease in activity will take 20 msec to decrease to 67% of previous value. If the time constant is made longer, there will be increased probability that rapid changes in the signal will be time-smeared in the output data; if the subject is kept repeating the same utterance too long, he may change his articulatory mode.

A final variable to be discussed is the lineup of different utterances for averaging. At present, an acoustic reference point such as the onset or offset of voicing is chosen arbitrarily, and averaging is performed at time samples anchored to that point. The trouble with this procedure is that if articulatory rate varies from sample to sample, there will be a tendency for events distant to the lineup point to be time-smeared; a preferable system would be to anchor at several acoustic events, and to time-normalize between.

Ohman (1966) has suggested such a procedure. He also has made use of a more complex procedure in which the EMG traces of each sample utterance, after rectification and integration, are matched visually for all prominent humps and dips, and averaging is performed with respect to these points. This technique seems theoretically impeccable, but does involve a large amount of experimenter intervention.

Several other research groups are working with setups similar to our own. The Tokyo group (Hirose, Kiritani, and Shibata, 1968) uses a similar recording setup, a 10-msec time constant, and averages with a PDP-9 computer. The University of California group (Harshman and Ladefoged, 1967) uses a somewhat different procedure. Utterances are lined up with respect to a single point, the "triggering point," apparently usually in some fixed time relationship to the onset of voicing in the utterance. The analogue signal is digitized, rectified, and applied to an integrator, which discharges at fixed intervals. Analogous time points are added appropriately to a running average. The output curve then is smoothed by repeated averaging of adjacent points. More of the time-smearing thus occurs in the smoothing, rather than in processing the original signal. It is hard to know what the effects of this procedure are, compared to those in our own program. The details of the programming scheme of the Exeter group (Tatham and his coworkers) have not been published yet.

The purpose of this whole section on the technology of EMG is not to enable anyone to build a system, but simply to indicate the extent to which the data in the literature at present have been conditioned by some choices of the experimenters, without any particular standardization, and frequently without any theoretically compelling reasons for making one choice over another.

THE USES OF ELECTROMYOGRAPHIC DATA IN SPEECH RESEARCH

In the introduction, I tried to indicate the ways in which electromyographic signals represented a level of functioning different from that shown by direct observation techniques, like x-ray studies and fiberoptic or acoustic studies. Ultimately, perhaps it may be taken as a matter of faith that speech is so important that all knowledge about the transformation of the speech signal from the cortex of the speaker to the cortex of the listener is important. This is, however, too general an article of faith to be helpful in deciding which problems to tackle now. There are some cases where it doesn't matter; information is needed about the laryngeal mechanisms for pitch control by any convenient means. However, there are some problems where electromyography seems to me to be the method of choice. These examples do not constitute a compendium of all interesting speech research using EMG technique. The work done has been too scattered to be sensibly presented in this fashion. I shall assume that the reader is using other sources for a detailed description of the articulatory muscles.

Suitable problems for EMG research will be divided into three classes—not that they are really mutually exclusive, but it will make discussion easier: first, "which muscle" problems; second, "which mechanism" problems; and third, a more vaguely defined class of problems having to do with the general organization of the speech mechanism.

"Which Muscle" Problems

In some cases, we have enough interest in a practical anatomical problem that the exact identity of the muscle controlling a particular articulatory act is important. This identity is not necessarily obvious from anatomy alone; individual differences in organization are common, as we mentioned above, and good anatomical studies, particularly of the tongue, are scarce. More important, as Hiki (1969) has pointed out with particular reference to the tongue, any one of several muscles sometimes may be presumed to have the same effect from geometric considerations.

A few examples will suffice. The function of the various muscles surrounding the velopharyngeal port has long been a subject of controversy. In particular dispute is whether the tensor does (Calnan's [1953] point of view) or does not (Rich's [1920] point of view) contribute, with the levator, to palatal elevation. In an elegant series of experiments, Fritzell (1969) showed that the tensor showed no consistent activity pattern in speech. He came to the practically useful conclusion that its anatomical action is not likely to affect speech. Whether his data justified the conclusion is open to question; the important point is that there is a practical consequence of the use of EMG technique.

A second area where specific muscle function is of interest is the pitch-control mechanism of the larynx. It is well known that the cricothyroid muscle acts to raise pitch, but it is not known whether the vocalis functions in parallel with it. Indeed, Luchsinger and Arnold (1965) have suggested that the cricothyroid is responsible for gross adjustments in pitch, while the vocalis makes fine adjustments. Recent work by Sawashima, Gay, and Harris (1969) confirms earlier work by Faaborg-Anderson (1957) showing that the gross activity of the vocalis increases with rises in pitch. Furthermore, the more recent work shows that the function relating cricothyroid and pitch increase is no steeper than that relating vocalis activity to pitch. However, there do seem to be individual differences which presently cannot be related to any other variables, due to the scantiness of the data.

Probably more interesting from a general theoretical point of view is the now classic study of Ladefoged and his associates (1962) on the action of the external and internal intercostals in syllabification. Stetson (1951) had erected a theory which suggested, in essence, that the syllable had a physiological basis, in that each syllable was initiated by an action pulse from the internal intercostals, and arrested by a pulse from the external intercostals.

Recording from the intercostals as well as from the other respiratory muscles, Ladefoged was able to show, first, that there is no simple pulse in either of these muscles that is associated consistently with syllabification. Beyond, and more important than, this negative conclusion, was the demonstration of the correlation between the action of all the respiratory muscles and the overall course of pressure events in the lungs. In the course of a single utterance, the pressures leading to the collapse of the lungs are high at the beginning, and the inspiratory muscles, including the external intercostals, are used to brake the outflow of air. On the other hand, at the end of an utterance, air must be pressed actively out of the lungs; and the expiratory muscles, including the internal intercostals, are active then. Thus, in this instance, an examination of a muscle identity problem has aided in the clarification of the whole speech respiratory function.

"Which Mechanism" Problems

In some cases, electromyographic study enables one to establish, or at least to limit, the function of muscular action in executing a particular articulatory maneuver. In the first two cases cited, there is a question as to whether a pair of opposing movements are both muscularly controlled, or whether one of the pair is merely passive.

The first example is from Fritzell's monograph on the action of the velopharyngeal muscles in speech (Fritzell, 1969). Again, it is quite clear that the chief agent of velopharyngeal closure in speech is the levator muscle. However, the muscle which appears to oppose it on anatomical grounds, the palatoglossus, is a small muscle, and often damaged during tonsil removal. It has been suggested, therefore, that the velopharyngeal port may be opened for the nasal sounds simply by the action of gravity plus the cessation of levator activity. Simultaneous EMG recordings of levator and palatoglossus muscle, however, show clearly that the latter is active in the transition from oral to nasal sounds. This leaves the question of why a tonsillectomy which damages the faucial pillars does not have more drastic effects on speech. Fritzell suggests that the palatopharyngeus may take over the function of the palatoglossus in these cases, but obviously, further work is needed.

A second, similar, problem arises in studying the action of the laryngeal muscles in pitch control. The cricothyroid and vocalis muscles both are active in pitch raising; one question at issue is whether there is an active muscular pitch-lowering mechanism. Lieberman (1967) has suggested that the pitch fall at the end of simple declarative sentences may be an effect of the fall in subglottal air pressure. However, certain features of sentence stress (Chomsky and Halle, 1969) and certain types of accent features seem to suggest that there is some specific mechanism for rapid pitch lowering which opposes the pitch-raising mechanism of the cricothyroid group. Ohala, Hirano, and Vennard (1968) have suggested that the sternohyoid may serve this purpose, apparently in part because Hirano, Koike, and von Leden (1967) have shown that the sternohyoid is active both at high and at low pitch extremes. Some preliminary work by Garding[3] and Ohala and Hirose (1969) suggests that, in speech, sternohyoid activity is connected both with jaw opening and with pitch lowering. No one

[3]Garding, E., personal communication (1969).

seems to have demonstrated finally the mechanism for active pitch lowering. It may be that pitch lowering takes place when the muscles which actively raise pitch are inactive.

Organization of the Speech Mechanism

This topic is a rather general one, relative to the two preceding topics. Indeed, the experiments cited are really only very preliminary looks at very large questions. However, the questions themselves suggest ways electromyographic data may be used in discussions of the organization of speech behavior.

The first example is drawn from what Dorothy Huntington has called "experimental speech pathology." Experienced pathologists are aware that people with different pathologies sound unlike each other, but it is frequently difficult to characterize these differences except by rather vague subjective terms. Thus, deaf speakers are sometimes described as having "deaf voice quality" and so forth. The reason for this is, in part, that while it is easy to identify correct productions perceptually, it is much harder to say in articulatory terms what is wrong with a production which sounds grossly abnormal. Electromyography may help us to specify the dimensions of abnormality. For example, Huntington and I (with Sholes, 1968) studied the production of a few congenitally deaf speakers. As Calvert (1961) and others had previously noted, their articulation was abnormally slow. What was striking, however, was that their productions of visible consonants were grossly similar to normal, while their productions of nonvisible consonants were far more eccentric. Moreover, the productions of all consonants were as stereotyped and invariant as normal. That is, the deaf speakers appeared to have a normal articulatory habit, even when it was the wrong habit. By contrast, Shankweiler and I (1968) examined the articulation of some dysarthric speakers. The EMG signals we saw were both weak and highly variable—that is, their articulation was not stereotyped. While neither of these studies is anything but extremely preliminary, they show the ways electromyographic data might be used to characterize and contrast speech pathologies.

A final example indicated some ways that electromyographic studies can be used to clarify the role of sensory feedback in articulation, a question which has preoccupied several authors in this *Report*. Several years ago, Ringel and Steer (1963) published a study in which they examined articulation before and after mandibular block of the tongue. They found articulation was poorer after the block, and attributed the deterioration to the lack of sensory feedback from the tongue articulators. A student of mine, Gloria Borden, did an EMG study to determine the precise nature of the deterioration. We expected to find articulatory variability, or incoordination of the various muscles, particularly those involved in tongue-tip manipulation. We found that the coordination of most of the muscles we examined was perfectly normal following the block, but the mylohyoid appeared to be paralyzed. Apparently it was possible that anesthetic could leak from the mandibular foramen onto the mylohyoid nerve, which runs behind the space. The observation has been made only once, and must be repeated; but at the moment, we are not at all convinced that the Ringel-Steer phenomenon is sensory.

Let me conclude the discussion of this random assortment of experiments by repeating what was said at the beginning of the paper—electromyographic research is not simply a substitute for direct-viewing techniques. Instead, it carries us one step farther back in the chain of speech events that leads from the higher nervous system of the speaker to that of the listener. We hope that, in the years ahead, it will be another useful tool in the difficult task of breaking the speech code.

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