

## ELECTROMYOGRAPHY

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### I. Introduction

Although electromyography (EMG) is almost as old as electroencephalography (EEG) and electrocardiography (ECG), its development in both research and diagnosis was delayed to World War II. The most

significant early contribution was that of Weddell *et al.* (1944), who were charged with the task of developing an improved technique for diagnosis and prognosis in traumatic nerve lesions. Out of their work and the simultaneous work of others (most notably Jasper and Forde, 1947; Bauwens, 1948) grew the extensive use of clinical EMG not only for nerve injuries, for but also the many neurological and myogenic diseases. Indeed, the improvement in the medical understanding, classification, and treatment of the myopathies was closely related to the growth of clinical EMG.

Clinical EMG has its own detailed literature and is not the subject of this chapter. Neither will we consider the extensive literature of EMG which directly underpins diagnostic work. Our concern here is with a basic understanding of the subject as well as a broad view of the general subject of muscle function revealed by the technique.

## II. Motor Units and Motor Unit Potentials

### A. Structure of Motor Units

The number of striated muscle fibers that are served by one axon has a wide range. Generally, muscles controlling fine movements (e.g., those of the middle ear, the eyeball, and the larynx) have the smallest number of muscle fibers per motor unit—about ten or fewer—large coarse-acting muscles (e.g., those in the limbs) have large units—as high as 2000 muscle fibers.

The motor units of the sheep extraocular muscles have 3–10 muscle fibers (Tergast, 1873) and those of man have 5–6 (Bors, 1926). More recently, Feinstein *et al.* (1955) reported nine muscle fibers per motor unit in the human lateral rectus and 25 in platysma. The rat diaphragm has 7–17 fibers per motor unit (Krnjević and Miledi, 1958). The size of motor units in the rabbit pharyngeal muscles is also quite small, ranging from as few as 2 to a maximum of only 6 (Dutta and Basmajian, 1960). In contrast, there are 108 in the first lumbrical of the hand, and 2000 fibers per motor unit in the medial head of gastrocnemius (Feinstein *et al.*, 1955).

Van Harreveld (1946) concluded that the fibers in a motor unit of the rabbit sartorius may be scattered and intermingled with fibers of other units. Thus, the individual muscle bundles one sees in cross section in routine histological preparations of normal striated muscles do not correspond to individual motor units as such. Our own studies and those

of Buchthal *et al.* (1957) indicate this is true in man as well, and Norris and Irwin (1961) state that in rat muscle the fibers of a motor unit are widely scattered.

### **B. Motor Unit Potentials**

When an impulse reaches the myoneural junction or motor end plate where the axonal branch terminates on the muscle fiber, a wave of contraction accompanying a wave of depolarization spreads over the fiber, resulting in a brief twitch followed by rapid and complete relaxation. During the twitch a minute electrical potential is generated and is dissipated into the surrounding tissues. Since the muscle fibers of a motor unit do not all contract at exactly the same time (some being delayed for several milliseconds), the composite electrical potential developed by the single twitch of all the fibers in the motor unit is prolonged to about 9 msec, with a range of 5–12 msec. The majority of motor unit potentials have a total amplitude of about 0.5 mV. The result is a sharp spike that is often diphasic or triphasic, though it may also have a more complex form partly dependent on the electrode type. Generally, the larger the motor unit potential being registered, the larger is the motor unit that produces it. However, complicating factors, such as the distance of the unit from the electrodes and the types of electrodes and equipment used, determine the final amplitude of individual motor unit potentials (Håkansson, 1956, 1957a,b; Buchthal, 1959).

In the human biceps brachii, the spike potentials of each motor unit are localized to an approximately circular region, with an average diameter of 5 mm to which the fibers of the unit are confined (Buchthal *et al.*, 1957). However, the potentials can be traced in their spread to over 20 mm distance, and the units overlap considerably.

By isolating and stimulating single alpha motor neuron fibers in the nerves to tibialis anterior in rabbits, Close *et al.* (1960) obtained pure recordings of single motor unit action potentials. These remained remarkably consistent over periods of more than an hour. Amplitudes varied from 4 to 8 mV and durations were much briefer than those found with standard techniques in a whole animal. The primary main spike is "almost constant" in duration, lasts only 2 msec, and is followed by a shorter reverse spike.

Under normal conditions, during a voluntary or reflex contraction, the smaller potentials appear first with a slight contraction. As the force is increased, larger and larger potentials are recruited (Henneman *et al.*, 1965). This is called the normal pattern of recruitment. It is absent

in cases of partial lower motor neuron paralysis, i.e., the small potentials never appear, apparently because only the larger motor units have survived. Recently, we have shown that man can be trained to suppress the action of small units and deliberately fire the much larger units individually (Basmajian *et al.*, 1965). This is discussed below in Section V.A.

### ***C. Single Muscle Fiber Potentials***

A motor unit potential represents the fusion of all accessible individual fiber potentials within a set limit of time (Fleck, 1962). Buchthal and Engbaek (1963) reported that the transmembrane potentials in single frog muscle fibers varies with temperature; at 25°C, the absolute refractory period is 2 msec, and the conduction velocity is 2.8 m/sec. Ekstedt (1964) found the single muscle fiber action potentials in normal man to have median values of 5.6 mV and 70 msec duration.

## **III. Technology**

### ***A. Background***

A great deal of controversy has centered around the techniques used in EMG. Many of the earlier studies were rendered useless by inadequate techniques. Because of unavoidable circumstances, many investigators used discarded ECG and EEG equipment. Unfortunately there was too strong a sense of caution in the approach to electrodes and many inappropriate techniques of electrode placement and insertion were employed. We now generally agree that there is a wide selection of different types of electrodes that have their special application; the good electromyographer employs the whole range.

### ***B. Electrodes***

The most useful recent methodology employs the fine-wire electrodes. Such inserted electrodes are being widely used in many centers because of their simplicity and lack of trouble for both investigators and human or animal subjects. For kinesiological studies, they are much to be pre-

ferred over other types of inserted electrodes. They may be inserted in pairs and in large numbers of pairs. For example, in one of our studies we have worked with fourteen pairs inserted in different areas around the human hip joint for the study of hip kinesiology. In other studies, we have placed a great many in the confined regions of the hand, of the tongue, and of the foot. Concentric needle electrodes (Adrian and Bronk, 1929) and unipolar Teflon-coated needles are used widely in clinical examinations.

Bipolar fine-wire electrodes isolate their pick-up either to the whole muscle being studied or, if it has a multipennate structure, to the confines of the compartment within a muscle. Barriers of connective tissue within a muscle or around it act as insulation, and so one records all the activity as far as such a barrier without interfering with pick-up from beyond the barrier (such as there always is with surface electrodes).

Surface electrodes are usually used where a broad or global pick-up of a number of muscles or a large area of muscle is desired. However, in the case of muscles without internal partitions, the bipolar fine-wire electrodes sample the activity of the whole muscle as broadly as the best surface electrodes. Indeed, investigation reveals that the surface electrodes will miss deeper potentials which the wire electrodes pick up very well; on the other hand, the wire electrodes do not miss any of the potentials that the surface electrodes immediately overlying them do miss.

Any type of insulated wire can be used. Our bipolar fine-wire electrodes (Basmajian and Stecko, 1962) are made from a nylon-insulated or polyurethane-insulated Karma alloy wire only 25  $\mu$  in diameter. Jonsen (1970) has shown that this small diameter of wire is not suitable for extremely energetic movements because the wire will occasionally break. Even coarser wire up to 75  $\mu$  in diameter is extremely fine and impalpable to human subjects.

### *C. Apparatus*

Electromyographs are simply amplifiers with a frequency range from about 10 to several thousand Herz. An upper limit of 1000 Hz is satisfactory. For kinesiological studies, the best instruments are multichannel. An obvious deficiency of ink-writing equipment is that the pens are too slow to record faster frequencies. This is dodged in some laboratories by the integration of potentials; but the concurrent monitoring of raw EMG potentials is essential to avoid integrating artifacts.

The recording device should either be photographic or employ electro-

magnetic frequency modulation (FM) tape recording. With multiple channels, one may photograph a row of cathode ray traces on photographic film in a variety of ways. Most convenient is the recording of multiple traces from miniature ultraviolet galvanometers on bromide recording papers. The paper requires no developing giving an immediate display. In recent years, multitrack FM tape recorders have provided a relatively cheap method of storing EMG signals (Basmajian, 1967). The signals can be converted and manipulated by analog-to-digital equipment and appropriate computing devices.

#### IV. EMG Kinesiology

No attempt can be made to touch upon the thousands of studies reported in the literature, especially on the individual actions of specific muscles in specific movements. These have been dealt with in detail elsewhere (Basmajian, 1967). Instead, several special areas will be discussed.

##### *A. Human Locomotion and Posture*

Although until recently its contribution has not been as great as it might have been, electromyography has added a new dimension in the latest studies on locomotion. The main reason for this slow start seems to have been that multifactorial studies are difficult and time consuming. Only recently has equipment improved to the point where electromyography gives especially useful results. Excellent multifactorial studies by Radcliffe (1962), Sutherland (1966), Murray *et al.* (1964), Liberson (1965), Battye and Joseph (1966), and many others have been reviewed elsewhere in detail (Basmajian, 1967). Some general findings will be given here.

During walking, the soleus begins to contract before it lifts the heel from the ground; it stops before the great toe leaves the ground. Apparently these are supportive rather than propulsive functions.

Quadriceps femoris contracts as extension of the knee is being completed, not during the earlier part of extension when the action is probably a passive swing. Quadriceps continues to act during the early part of the supporting phase (when the knee is flexed and the center of gravity falls behind it). Quadriceps activity occurs at the end of the

supporting phase to fix the knee in extension, probably counteracting the tendency toward flexion imparted by gastrocnemius.

The hamstrings contract at the end of flexion and during the early extension of the thigh, apparently to prevent flexion of the thigh before the heel is on the ground and to assist the movement of the body over the supporting limb. In some persons, the hamstrings also contract a second time in the cycle during the end of the supporting phase; this may prevent hip flexion.

Gluteus maximus shows activity at the end of the swing and at the beginning of the supporting phase. This is contrary to the general belief that its activity is not needed for ordinary walking. Perhaps gluteus maximus contracts to prevent or to control flexion at the hip joint.

Many other studies in the lower limb have been done in the last few years. For example, studies by Basmajian and Bentzon (1954), Joseph and Nightingale (1956), and Gray and Basmajian (1968) have emphasized the factors which might influence the arch support in the human foot. These studies indicate that muscles are not important in the primary maintenance of the arches of the foot in the plantargrade static foot. However, they are very important during locomotion when the extremes of force are applied to the foot. Apparently the first line of defence against flat feet is a ligamentous one, but the added stresses of walking require special mechanisms.

Tibialis anterior has two peaks of activity at heel-strike and toe-off of the stance phase (Battye and Joseph, 1966; Gray and Basmajian, 1968), is inactive during mid-swing and middle of the stance phase, is active at full-foot in flat-footed subjects, and is generally more active during toe-out and toe-in walking.

Tibialis posterior is inactive throughout the swing phase. In flat-footed persons it becomes activated at heel-strike and more active at full-foot during level walking. The toe-out position reduces its activity.

Flexor hallucis longus is most active in mid-stance; during toe-out walking, activity increases in both phases, generally being more active in normal persons than in flatfooted persons.

Peroneus longus is most active at mid-stance and heel-off and generally more active in flat-footed persons.

Abductor hallucis and flexor digitorum brevis are generally more active in flatfooted persons.

An important regular pattern of inversion and eversion during the walking cycle occurs. Contingent arch support by muscles rather than continuous support is the rule, muscles being recruited to compensate for lax ligaments and special stresses during the walking cycle (Gray and Basmajian, 1968).

### **B. Trunk Muscles**

Erector spinae shows two periods of activity during gait (Battye and Joseph, 1966). They occur "at intervals of half a stride when the hip is fully flexed and fully extended at the beginning and end of the supporting phase." Apparently the bilateral activity of the erectores spinae prevents falling forward of the body and also rotation and lateral flexion of the trunk. Sheffield (1962) found the abdominal muscles inactive during walking on a horizontal level.

Trunk musculature received most of the attention of electromyographers in the 1950s. Perhaps the most significant and largely ignored finding was that of Jones *et al.* (1953), who suggested that the intercostal muscles play a part in posture which is more important than their role in respiration. Their role in respiration seems to be the maintenance of a proper distance between the ribs while the rib cage is actively elevated by the neck muscles (scalenes) during inspiration. In quiet breathing, the diaphragm is the chief muscle of respiration in man.

### **C. Upper Limb**

In the upper limb, the classic work of Inman *et al.* (1944) on the shoulder girdle has been followed by a long series of scattered EMG studies. Bearn's (1961) finding, that the activity in the upper fibers of trapezius falls off after a minute or two to disappear completely while the person is upright, is especially significant. It is also rather surprising to find that serratus anterior has only slight activity in an upright posture.

At the shoulder joint, the downward dislocation of the shoulder is resisted by the superior capsule of the shoulder joint and supraspinatus (Basmajian and Bazant, 1959). This finding has also emphasized that muscles which cross a joint longitudinally are not necessarily active when there is distraction on the joint. Other work on the elbow joint has confirmed this finding. The general principle seems to be that capsules and capsular ligaments are sufficient to prevent distraction except where excessive forces are applied.

When muscle is a contributing factor, it often is part of a locking mechanism rather than a source of transarticular forces. On the other hand, during movement such as flexion and extension of a joint, certain muscles are extremely important as a transarticular component to prevent distraction of a joint. Thus, brachioradialis shows little if any activity



in maintaining flexed postures even against added loads, but it is very active in either flexion or extension of the elbow. This is its shunt muscle function, i.e., it acts chiefly during rapid movement along the long axis of the moving bone to provide centripetal force. The whole question of spurt and shunt muscles has been thoroughly discussed elsewhere. Of course such muscles are not confined to the upper limb and have widespread significance in the economy of the body. (See MacConaill and Basmajian, 1969, for a fuller discussion.)

## V. Neuromuscular Physiology

### A. Motor Unit Training

Given a clear response of his motor unit activity on a cathode ray oscilloscope and loudspeaker, and though completely unaware of any movement in the muscle, everyone can achieve notably wilful control over isolated motor-unit contractions in a muscle. We have known for a long time that almost anyone with EMG feedback can learn to relax a whole muscle instantly, on command. More striking, human subjects can recruit the activity of a single motor unit instantaneously and keep it active for a considerable period of time; also, they can deliberately change the frequency of firing of motor units (Basmajian, 1963).

Most persons can be trained to produce specific rhythms on motor units. It is easy for human subjects to gain control over a number of motor units and consciously switch the activity from one to the other. These and other findings on motor unit controls have deep significance in kinesiology. Indeed, they underlie the normal control of movement and muscles. This then would indicate that motor unit controls underlie the very topic of kinesiology itself.

#### 1. LOCAL FACTORS

Moving a neighboring joint while a motor unit is firing is a distracting influence, but most subjects can keep right on doing it in spite of the distraction (Simard and Basmajian, 1967; Basmajian and Simard, 1967). Wagman *et al.* (1965) believe that subjects require our form of motor unit training before they can fire isolated specific motor units with the limb or joints in varying positions. Their subjects reported that "activation depended on recall of the original position and contraction effort necessary for activation." This apparently is a form of proprioceptive

memory. Carlsöö and Edfeldt (1963) also concluded that, "Proprioception can be assisted greatly by exeroceptive auxiliary stimuli in achieving motor precision." However, conscious control can be easily maintained, despite the distraction produced by voluntary movements elsewhere in the body (head and neck, upper limbs, and contralateral limb) (Basmajian and Simard, 1967).

## 2. EFFECT OF COMPETITIVE NERVE STIMULATION

Contrary to expectation, the superimposition of a massive contraction in a muscle by electrical stimulation of its motor nerve does not significantly alter the regular conscious firing of a motor unit in that muscle. Even the coincidence of the motor unit potential with elements of the electrically induced massive contractions does not abolish the motor unit potential (Scully and Basmajian, 1969a).

## 3. EFFECTS OF PREVIOUS TRAINING AND SKILLS

The earliest studies, even though they included hundreds of subjects, failed to reveal any correlation between the ability of subjects to isolate and train individual motor units and such variables as sex, age, academic record, athletic ability, handedness, and general personality traits (Basmajian *et al.*, 1965). However, Scully and Basmajian (1969b), showed that the training time of most of the manually skilled subjects was above the median, although one might expect the opposite. If anticipatory tensions and/or position memory are learned, whether they are integrated at the cerebral level, at the spinal level, or both, these or some other cerebral or spinal mechanisms may be acting temporarily to block the initial learning of new skills. In a sense, perhaps some neuromuscular pathways acquire a habit of responding in certain ways, and it is not until that habit is broken that a new skill can be learned.

## 4. EFFECTS OF HANDEDNESS

When a long series of subjects was studied on two occasions using a different hand each time, Powers (1969) found that they always isolated a unit more quickly in the second hand.

### ***B. Relationship of EMG to Force***

Isometrically contracting muscle shows a direct relationship between the mechanical tension developed and the integrated EMG (Lippold,

1952; Bigland and Lippold, 1954; Lippold *et al.*, 1959; Bergström, 1959; Close *et al.*, 1960). However, in the muscles of amputees, there is no direct quantitative relationship between inherent power and the EMG (Inman *et al.*, 1944). With studies involving rapid movement, the mechanical tension lags (less than 0.1 sec) behind the main burst of potentials.

### **C. Tone and Relaxation**

EMG has shown conclusively that normal mammalian striated muscle at rest is completely relaxed (Lindsley, 1935; Clemmesen, 1951; Basmajian, 1957). While tone is not determined by continuous neuromuscular activity at rest, there is no denying its existence. Tone is determined to some extent by passive elasticity and tissue turgor, but its chief component is the reflex reaction of the nervous system to stimuli. Even spastic subjects (both men and rabbits) can be made to relax completely (Basmajian and Szatmari, 1955). Clinical examination is deceptive because the very examination itself is a stimulus for reactive contraction. Muscles are rapidly relaxed and remain relaxed until a reflex or volitional demand is made on them. Ironically, the EMG reveals considerable muscular activity in completely atonic denervated muscle (spontaneous fibrillations), but this cannot be detected by ordinary examinations. (A discussion of fibrillation is beyond the scope of this chapter.)

### REFERENCES

- Adrian, E. D., and Bronk, D. W. (1929). *J. Physiol. (London)* **67**, 119.  
Basmajian, J. V. (1957). *Can. Med. Ass. J.* **77**, 203.  
Basmajian, J. V. (1963). *Science* **141**, 440.  
Basmajian, J. V. (1967). "Muscles Alive: Their Functions Revealed by Electromyography," 2nd ed. Williams & Wilkins, Baltimore, Maryland.  
Basmajian, J. V., and Bazant, F. J. (1959). *J. Bone Joint Surg., Amer. Vol.* **41**, 1182.  
Basmajian, J. V., and Bentzon, J. W. (1954). *Surg., Gynecol. Obstet.* **98**, 662.  
Basmajian, J. V., and Simard, T. G. (1967). *Amer. J. Phys. Med.* **46**, 1427.  
Basmajian, J. V., and Stecko, G. (1962). *J. Appl. Physiol.* **17**, 849.  
Basmajian, J. V., and Szatmari, A. (1955). *Neurology* **5**, 856.  
Basmajian, J. V., Baeza, M., and Fabrigar, G. (1965). *J. New Drugs* **5**, 78.  
Battye, C.K., and Joseph, J. (1966). *Med. Biol. Eng.* **4**, 125.  
Bauwens, P. (1948). *Brit. J. Phys. Med.* **11**, 130.  
Bearn, J. G. (1961). *Anat. Rec.* **140**, 103.  
Bergström, R. M. (1959). *Acta Physiol. Scand.* **45**, 97.  
Bigland, B., and Lippold, O. C. J. (1954). *J. Physiol. (London)* **125**, 322.

- Bors, E. (1926). *Anat. Anz.* **60**, 444.
- Buchthal, F. (1959). *Amer. J. Phys. Med.* **38**, 125.
- Buchthal, F., and Engbaek, I. (1963). *Acta Physiol. Scand.* **59**, 199.
- Buchthal, F., Guld, C., and Rosenfalck, P. (1957). *Acta Physiol. Scand.* **39**, 86.
- Carlsöö, S., and Edfeldt, A. W. (1963). *Scand. J. Psychol.* **4**, 231.
- Clemmesen, S. (1951). *Proc. Roy. Soc. Med.* **44**, 637.
- Close, J. R., Nickle, E. D., and Todd, F. N. (1960). *J. Bone Joint Surg., Amer.* Vol. **42**, 1207.
- Dutta, C. R., and Basmajian, J. V. (1960). *Anat. Rec.* **137**, 127.
- Ekstedt, J. (1964). *Acta Physiol. Scand.* **61**, Suppl. 226, 96 pp.
- Feinstein, B., Lindegård, B., Nyman, E., and Wohlfart, G. (1955). *Acta Anat.* **23**, 127.
- Fleck, H. (1962). *Arch. Phys. Med. Rehabil.* **43**, 99.
- Gray, E. G., and Basmajian, J. V. (1968). *Anat. Rec.* **161**, 1.
- Håkansson, C. H. (1956). *Acta Physiol. Scand.* **37**, 14.
- Håkansson, C. H. (1957a). *Acta Physiol. Scand.* **39**, 291.
- Håkansson, C. H. (1957b). *Acta Physiol. Scand.* **41**, 199.
- Henneman, E., Somjen, G., and Carpenter, D. O. (1965). *J. Neurophysiol.* **28**, 599.
- Inman, V. T., Saunders, J. B. deC. M., and Abbott, L. C. (1944). *J. Bone Joint Surg.* **26**, 1.
- Jasper, H. H., and Forde, W. O. (1947). *Can. J. Res.* **25**, 100.
- Jones, D. S., Beargie, R. J., and Pauly, J. E. (1953). *Anat. Rec.* **117**, 17.
- Jonsson, B. (1970). Personal communication.
- Joseph, J., and Nightingale, A. (1956). *J. Physiol. (London)* **132**, 465.
- Krnjevic, K., and Miledi, R. (1958). *J. Physiol. (London)* **140**, 427.
- Liberson, W. T. (1965). *Arch. Phys. Med. Rehabil.* **46**, 37.
- Lindsley, D. B. (1935). *Amer. J. Physiol.* **114**, 90.
- Lippold, O. C. J. (1952). *J. Physiol. (London)* **117**, 492.
- Lippold, O. C. J., Redfearn, J. W. T., and Vučo, J. (1959). *J. Physiol. (London)* **137**, 473.
- MacConaill, M. A., and Basmajian, J. V. (1969). "Muscles and Movements: A Basis for Human Kinesiology." Williams & Wilkins, Baltimore, Maryland.
- Murray, P. M., Drought, A. B., and Kory, R. C. (1964). *J. Bone Joint Surg.* **46**, 335.
- Norris, F. H., Jr., and Irwin, R. L. (1961). *Amer. J. Physiol.* **200**, 944.
- Powers, W. R. (1969). Ph.D. Thesis, Queen's University, Kingston, Canada.
- Radcliffe, C. W. (1962). *Artif. Limbs* **6**, 16.
- Scully, H. E., and Basmajian, J. V. (1969a). *Arch. Phys. Med. Rehabil.* **50**, 32.
- Scully, H. E., and Basmajian, J. V. (1969b). *Psychophysiol.* **5**, 625.
- Sheffield, F. J. (1962). *Amer. J. Phys. Med.* **41**, 142.
- Simard, T. G., and Basmajian, J. V. (1967). *Arch. Phys. Med. Rehabil.* **48**, 12.
- Sutherland, D. H. (1966). *J. Bone Joint Surg.* **48**, 66.
- Tergast, P. (1873). *Arch. Mikrosk. Anat. Entwicklungsmech.* **9**, 36.
- van Harrevel, A. (1946). *Arch. Neer. Physiol.* **28**, 408.
- Wagman, I. H., Pierce, D. S., and Burger, R. E. (1965). *Nature (London)* **207** 957.
- Weddell, G., Feinstein, B., and Pattle, R. E. (1944). *Brain* **67**, 178.