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Introduction

Electromyography is the study of muscle function through the inquiry of the electrical signal the muscles emanate.

Inherent movement is the prime sign of animal life. For this and many other reasons, man has shown a perpetual curiosity about the organs of locomotion in his own body and in those of other creatures. Indeed, some of the earliest scientific experiments known to us concerned muscle and its functions.

With the reawakening of science during the Renaissance, interest in muscles was inevitable. Leonardo da Vinci, for example, devoted much of his thought to the analysis of muscles and their functions. So, too, did the acknowledged "father" of modern anatomy, Andreas Vesalius, whose influence through his monumental work, the *Fabrica*, extends down to this day. In one sense, however, the heritage of Vesalius was unfortunate because it stressed the appearance and the geography of dead muscles rather than their dynamics (Fig. 1.1).

During subsequent years, a series of scientists gave life back to the muscles. The first logical deduction of muscle-generated electricity was documented by Italian Francesco Redi in 1666. He suspected that the shock of the electric ray fish was muscular in origin and wrote, "It appeared to me as if the painful action of the electric ray was located in these two sickle-shaped bodies, or muscles, more than any other part" (Biederman, 1898). The relationship between electricity and muscle contraction was first observed by Luigi Galvani in 1791. In his epoch-making experiments, he depolarized the muscles of a frog's legs by touching them with metal rods (see Fig. 1.2). His concept of "animal electricity" was enthusiastically received throughout Europe. Galvani's original book, *De Viribus Electricitatis*, has been translated into English by Green (1953). This discovery is generally acknowledged as representing the birth of neurophysiology, thereby making Galvani the father of this field which continues to expand rapidly.

Many rushed to confirm Galvani's results and praise his discovery. Among them was Alessandro Volta, who initially embraced the discovery and in retrospect wrote "it contains one of the most beautiful and surprising discoveries and the germ of many others" (Volta, 1816). But, within two years, in 1793, Volta questioned Galvani's findings by proving that dissimilar metals in contact with an electrolyte (such as those present in body tissues) would generate an electric current. In the following year Galvani reaffirmed his concept when he found that a muscle contraction

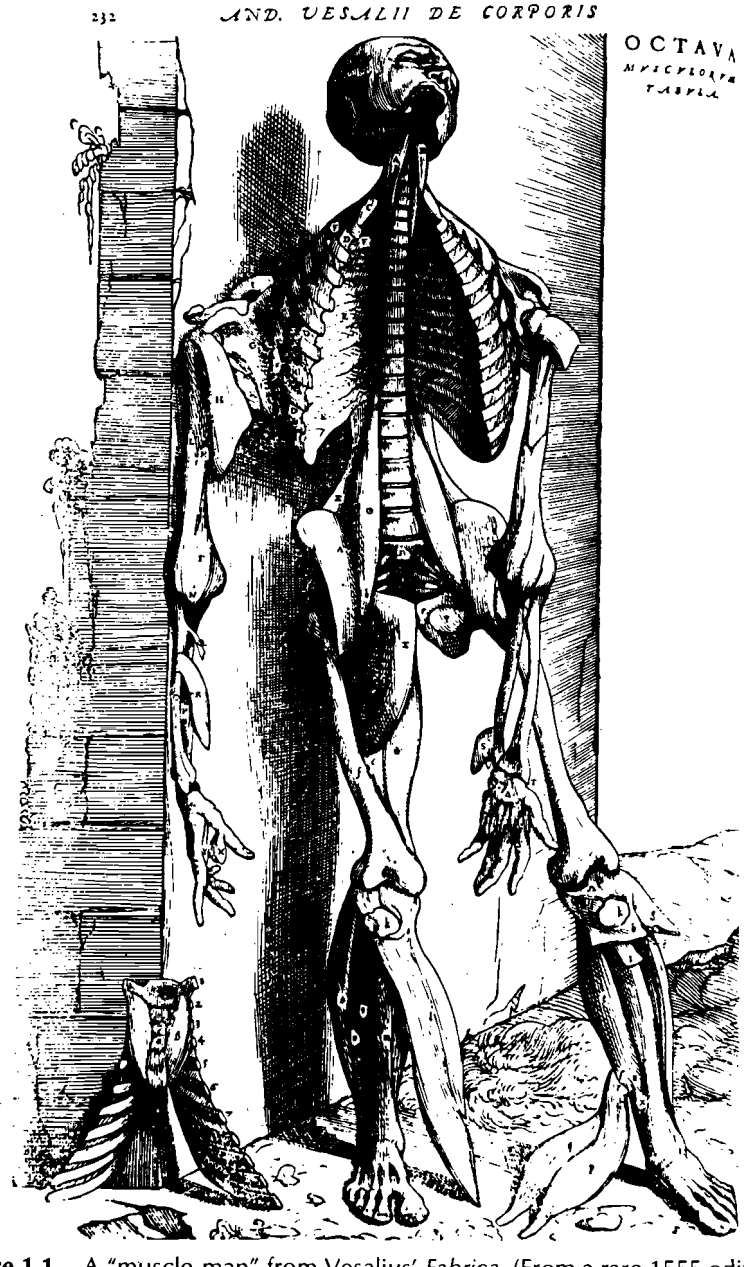

Figure 1.1. A "muscle-man" from Vesalius' *Fabrica*. (From a rare 1555 edition in the Library of Queen's University.)

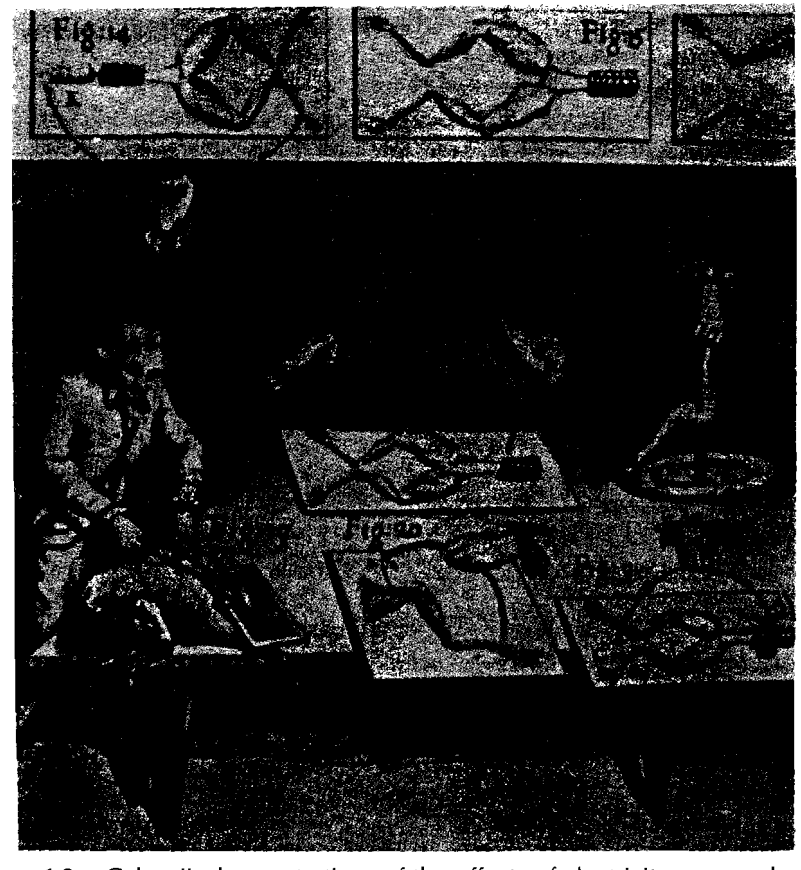

Figure 1.2. Galvani's demonstrations of the effects of electricity on muscles of frogs and sheep. (From Fulton's reproduction of a plate in Galvani's *De Viribus Electricitatis in Motu Musculari Commentarius*, 1792.)

could be elicited by placing the free end of a nerve across a muscle without the intervention of metals.

However, Volta's blow was so powerful that the concept of animal electricity was not discussed meaningfully for four decades. The engineering development of Volta, in providing a device for generating electrical currents and stimulating muscles conveniently, was not matched by a comparable engineering development in providing equipment and techniques to detect the electrical current in the muscles. In 1820, Schweigger built the first practical galvanometer based on Oersted's discoveries on magnetism. Five years later Nobili improved the sensitivity by compensating for the torque of the earth's magnetic field. Using this improved galvanometer, Carlo Matteucci in 1838 finally proved that electrical currents did originate in muscles. In 1844 he

wrote, "The interior of a muscle place in connection with any part whatsoever of the same muscle. . .produces a current which goes in the animal from the muscular part to that which is not so."

The work of Matteucci attracted the interest of the Frenchman Du-Bois-Reymond, who in 1849 was the first to report the detection of voluntarily elicited electrical signals from human muscles. DuBois-Reymond's achievement was an example of ingenuity and stalwartness. He devised a surface electrode which consisted of a wire attached to a blotting paper immersed in a jar of saline solution. Figure 1.3 is a reproduction of Figure 147 in his book. This diagram demonstrates the recording apparatus. He found that when the fingers were immersed in the saline solution, and the arms and hand were contracted (as shown in the figure) the deflection on the galvanometer was minute (approxi-

Figure 1.3. Depiction of the first recorded detection of the EMG signal from human muscles during voluntary contraction. (From Figure 147 of the book *"Uber Thierische Elektricitat"* by Du Bois-Reymond published in 1849.)

mately 2 to 3°). He realized that the impedance of the skin reduced the current which he could detect to drive the galvanometer. He circumvented this problem by inducing a blister in each forearm. Then he removed the skin and placed the open wounds in contact with the saline solution of the electrode. Upon contraction he measured a sizable deflection (65°) on his galvanometer. He repeated the contraction three times for each arm and always obtained similar results. To remove doubt, he repeated the whole experiment several weeks later, after the original wounds had healed. He obtained the same results.

However, measurements from human musculature remained unwieldy until the metal surface electrode was employed by the German Piper (1907). The detection techniques were further simplified with the advent of the cathode ray tube, which was invented by Braun (1897) and was first used to amplify action potentials in conjunction with a string galvanometer by Forbes and Thacher (1920). Two years later, Gasser and Erlanger (1922) used a cathode ray oscilloscope in place of the galvanometer, which up to this time was the sole apparatus able to "show" the signals from the muscles. This application, along with their wise interpretation of the action potentials which they were able to "see," earned Gasser and Erlanger a Nobel Prize in 1944.

During the 19th century, the capability of detecting the electromyographic or myoelectric signal from a human remained a sophisticated and delicate venture. As such, it was mastered only by a few, and useful achievements were slow in coming. On the other hand, the task of electrically stimulating a muscle by applying current through the skin was relatively simple and gained wide attention. In fact, many unqualified charlatans rushed to exploit its novelty by claiming that a "properly" applied dose of electricity could perform miraculous cures on a wide variety of ailments ranging from tic douloureux to chronic functional disorders (Holbrook, 1959).

However, among this morass of deceptions flowered the work of few individuals who remained true to the scientific inquiry. Towering above them was the Frenchman Duchenne, who in the middle of the past century, skillfully applied electrical stimulation to investigate systematically the dynamics and functions of intact skeletal muscles (Figure 1.4). His immortal work, *Physiologie des Mouvements*, is now available in an English edition (translated by E.B. Kaplan). No one before or after has contributed so much to our understanding of muscular function, although Beevor's (1903) work cannot be ignored.

It was only natural that the business of detecting electric signals from, and applying electric currents to, muscles should attract the attention of an electrical engineer. Such was the case for the Englishman Baines, who published his works in 1918. He argued that appropriate technical considerations should be administered before obtaining or interpreting

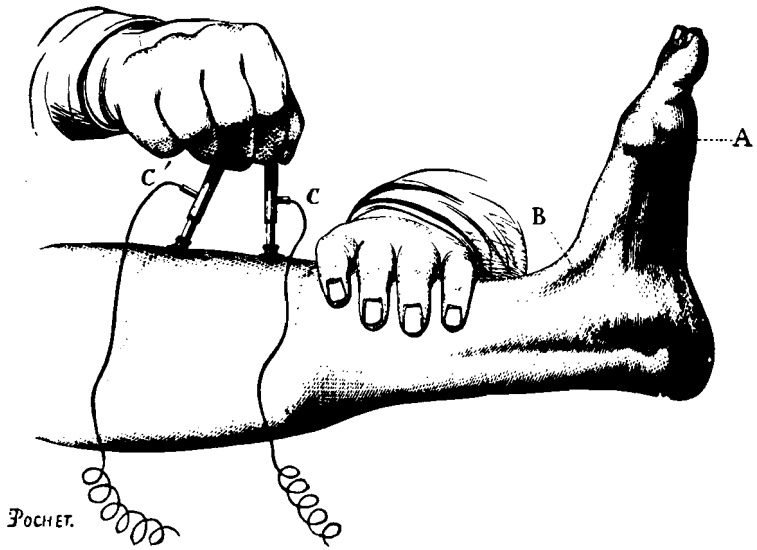

Figure 1.4. Duchenne's illustration of electrical stimulation of muscles.

data related to electrophysiological phenomena. This call still echoes among the numerous abuses that have been promulgated throughout the past seven decades. Baines was the first to formalize the analogy between the propagation of pulses in a nerve trunk and an electric cable. This approach subsequently became known as the cable theory. He initiated the concept of modeling parts of the nervous system with electrical circuits in attempting to explain their behavior (see Fig. 1.5). It may be said that he was the first biomedical engineer.

With the introduction of vacuum tube amplifiers, the task of detecting the electromyographic signal was greatly simplified. Soon the new "art" of electromyography was put to practical usages in the clinical environment. The first successful attempt at detecting a signal from a dysfunctional muscle was made by Proebster (1928) who obtained "tracings" from a muscle with peripheral nerve paralysis.

However, the impact on the clinical community occurred after the introduction of the needle electrode by Adrian and Bronk (1929). This approach, for the first time, enabled us to observe the electrical activity associated with individual muscle fibers (or small groups of muscle fibers). Although Adrian and Bronk's motivation was the investigation of the motor control schemes which acted on the muscle, the immediate impact was on the clinical community. The use of the needle electrode was methodologically exploited by Buchthal and his colleagues during the 1950s and 1960s.

As the quality and availability of electronics apparatus improved;

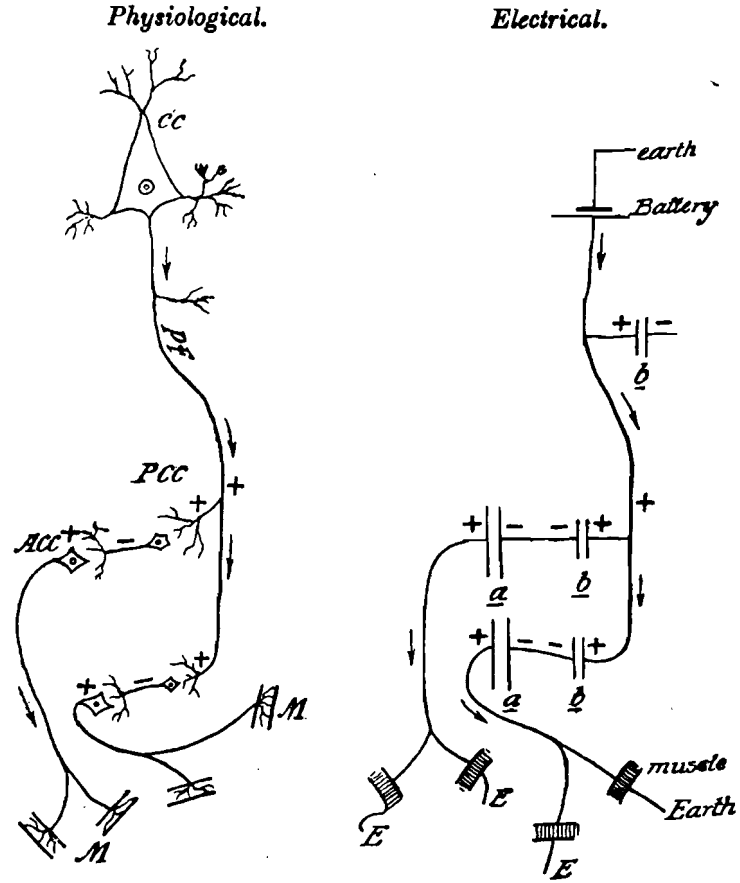

Fig. 106. (*After Halliburton.*)

PCC = small cells at the base of the posterior cornu.
ACC = large motor-cells of the anterior cornu.
M = muscular fibres.
PF = axon.
CC = cell of the cerebral grey matter.

Fig. 107.

aa = low-tension condensers.
bbb = high-tension condensers.

Figure 1.5. First known electrical model of the nervous system. Published by Arthur E. Baines in 1918. He was possibly the first biomedical engineer. (Reproduced from Figures 106 and 107 of his book.)

anatomists, kinesiologists, and orthopedic surgeons began to make increasing use of electromyography. The first study that gained wide acceptance was that of Inman et al (1944), who reported their work on the movement of the shoulder region. However, kinesiological studies proliferated only after the appearance of the electrically stable silver-

silver chloride surface electrode and the nonobtrusive inserted wire-electrode which appeared on the scene circa 1960.

In 1960, a group of Russian engineers led by Kobrinsky revealed the design of a hand prosthesis controlled by myoelectric signals detected from the forearm muscles. This demonstration excited the engineering and rehabilitation community. Engineers in Canada, England, Sweden, Austria, and the USA rushed to explore and exploit this new area. Their interest was fueled by funds made available to provide replacement limbs for numerous children who were born with undeveloped limbs due to the ingestion of the drug thalidomide by their mothers during pregnancy. Although the work of the Russians generated the excitement, it should be mentioned that the earliest recorded effort to employ electromyographic signals for controlling prostheses should be accorded to Reinhold Reiter, who applied for a patent describing the concept in 1945 in Germany.

Thus, we have seen that during the past two centuries a wide variety of individuals of diverse training have been fascinated by and have contributed to the understanding of the electrical phenomenon which is associated with a muscle contraction. The contents of this book were chosen to describe the more recent developments in electromyography which are the heirs of all the efforts that have preceded.

TERMINOLOGY

Sure signs of a progressive and developing field are the evolution and modification of definitions and standards. Two groups have offered such guidelines: the IFSECN at its Second International Congress (Guld et al, 1970), and the Second Congress of the International Society of Electrophysiological Kinesiology (ISEK) in 1972. The latter group has revised its definitions and has published a manual (Winter et al, 1980).

Some of the following terminology and set of definitions are an abridged version of those found in the ISEK manual "Units, Terms and Standards in the Reporting of EMG Research" (1980). They have been extracted with permission.

Alpha-motoneuron—The neural structure whose cell body is located in the anterior horn of the spinal cord and which, through its relatively large diameter axon and terminal branches, innervates a group of muscle fibers.

Motor unit (MU)—The term used to describe the single smallest controllable muscular unit. The motor unit consists of a single alpha-motoneuron, its neuromuscular junction, and the muscle fibers it innervates (as few as 3, as many as 2000).

Muscle fiber action potential or motor action potential (MAP)—The name given to the detected waveform resulting from the depolarization wave as it propagates in both directions along each muscle fiber from its motor end plate.

Motor unit action potential (MUAP)—The name given to the detected waveform consisting of the spatiotemporal summation of individual muscle fiber action potentials originating from muscle fibers in the vicinity of a given electrode or electrode pair.

Motor unit action potential train (MUAPT)—The name given to a repetitive sequence of MUAPs from a given motor unit.

Interpulse interval (IPI)—The time between adjacent discharges of a motor unit. It is a semirandom quantity.

Instantaneous firing rate—The parameter which represents the inverse value of the interpulse interval.

Average firing rate—The average firing rate of a motor unit over a given period of time. It is measured in units of pulses per second.

Synchronization—The term which describes the tendency for a motor unit to discharge at or near the time that another motor unit discharges. It therefore describes the interdependence or entrainment of two or more motor units.

Electromyographic (EMG) signal—The name given to the total signal detected by an electrode. It is the algebraic summation of all MUAPTs from all active motor units within the pick-up area of the electrode.

Myoelectric signal—An alternative nomenclature for the electromyographic signal.

Amplitude—That quantity which expresses the level of the signal activity.

Time duration—The amount of time over which a waveform presents detectable energy.

Phase—In electromyography, the net excursion of the amplitude of a signal in either the positive or negative direction.

Shape—The characteristics of a signal which remain unaltered with linear scaling in either the amplitude or time domains. An example of such characteristics are the phases of an action potential.

Waveform—The term which describes all aspects of the excursion of the potential, voltage, or current associated with a signal as a function of time. It incorporates all the notions of shape, amplitude, and time duration.

Decomposition—The process whereby individual MUAPs are extracted from the electromyographic signal.

Electrode—A device or unit through which an electrical current enters or leaves an electrolyte, gas, or vacuums.

Detection surface—The portion of the electrode which is in direct contact with the medium which is being sensed.

Unipolar electrode—One which consists of one detection surface.

Bipolar electrode—One which consists of two detection surfaces.

Concentric electrode—A unipolar electrode in which the detection surface is located in the center of a metallic shield (typically, the cannula of a needle), which in turn is connected to ground.

Detection—The process of sensing the signal by the electrode.

Recording—The process which creates a record of the detected signal on any media (CRT, paper, magnetic tape, etc.)

Isometric contraction—One during which the length of the contracting muscle remains constant. Generally, the muscle length is assessed by monitoring the angle of the joint being affected.

Anisometric contraction—One during which the length of the contracting muscle may vary.

Ballistic contraction—One that is executed with the greatest speed physiologically possible.

Maximal voluntary contraction (MVC)—The greatest amount of effort that an individual may exert. Usually, the effort is concentrated on one muscle or on

one joint. It is generally measured by monitoring the force or torque output.
Agonist muscle—One which initiates a contraction.
Antagonist muscle—One which actively provides a negative contribution to a particular function during a contraction.
Synergist muscle—One which actively provides an additive contribution to a particular function during a contraction.

We would like to draw attention to the appellation of two terms: *firing rate* and *interpulse interval*. These terms are used to describe parameters which in the past have been referred to as firing frequency and interspike interval. Such terminology has its origin in the early days of electrophysiology when the available electronics apparatus was considerably more limited than today's versions and could not provide either detailed or correct representation of the behavior of the MUAPT. Thus, earlier investigators could only observe the presence of spikes (deflections) in a noisy signal. Modern technology enables us to observe the individual action potentials as distinguishable pulses. Thus, it is more proper to describe the time interval as the interpulse interval. The use of the term firing frequency is improper because the concept of frequency implies periodicity. It is now clear that the motor unit does not discharge in a periodic fashion, but rather in a semirandom fashion. It is, therefore, more correct to use the terminology of stochastic processes, i.e., firing rate. The concept of rate provides information concerning the number of firings per unit time without any restriction on the temporal regularity of the discharges.

THE MOTOR UNIT

The reader must have a clear knowledge of the structural and functional units in striated muscles to appreciate fully much of the literature in electromyography. The structural unit of contraction is, as everyone knows, the muscle cell or muscle fiber (Fig. 1.6). Best described as a very fine thread, this muscle fiber has a length ranging from a few millimeters to 30 cm and a diameter of 10 to 100 μm. On contracting it will shorten to about 57% of its resting length (Haines, 1932, 1934).

By looking at the intact normal muscle during contraction, one would believe, quite erroneously, that all the muscle fibers were in some sort of continuous smooth shortening. In fact, this is not true; instead, there is a virtual buzzing of asynchronous activity in which the fibers are undergoing very rapid contractions and relaxations.

In normal mammalian skeletal muscle, the fibers probably never contract as individuals. Instead, small groups of them contract in concert. On investigation, one finds that all the members of each of these groups of muscle fibers are supplied by the terminal branches of one nerve fiber or axon whose cell body is in the anterior horn of the spinal grey matter. Now, this nerve cell body, plus the long axon running down the motor

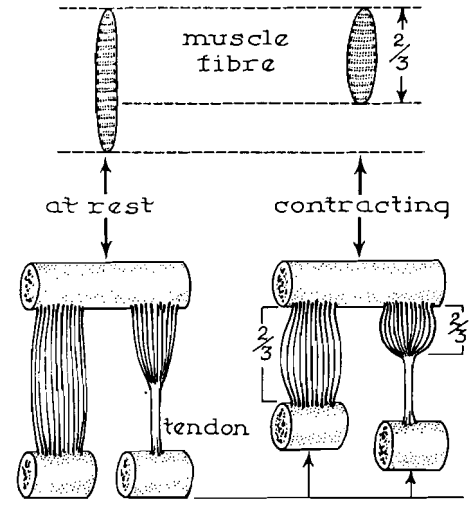

Figure 1.6. The structural unit of contraction is the muscle fiber. The greatest amount a whole muscle can actively shorten is dependent on the maximal contraction of its contractile units. (From Basmajian, © 1970, Williams & Wilkins, Baltimore.)

nerve, plus its terminal branches and all the muscle fibers supplied by these branches, together constitute a *motor unit* (Fig. 1.7). The motor unit is, then, the functional unit of striated muscle, since an impulse descending the motoneuron causes all the muscle fibers in one motor unit to contract almost simultaneously. The disparity in the time activation of different muscle fibers of the same motor unit has two causes. One is the variable delay introduced by the length and diameter of the individual axon branches innervating individual muscle fibers. This delay is fixed for each muscle fiber. The other delay is introduced by the random discharge of acetylcholine packets released at each neuromuscular junction. Because this is a random process, the excitation of each muscle fiber of a motor unit is a random function of time. This random excitation of each muscle fiber appears as a *jitter* when the electrical discharges of the individual muscle fibers are monitored. This phenomenon was first observed by Ekstedt (1964), who coined the name. In normal individuals the standard deviation of the jitter is about 20 μs. The chief use of this discovery has been in clinical diagnosis.

The termination of the axon of the muscle fiber defines an area known as the endplate region. These endplates (neuromuscular junctions) are usually, but not always, located near the middle of the muscle fibers (Fig. 1.8). This has been shown by Coërs and Woolf (1959) in human skeletal muscle, by Gurkow and Bast (1958) in the trapezius and sternomastoid of the hamster, by Jarcho et al (1952) in the gracilis of the rat, and by

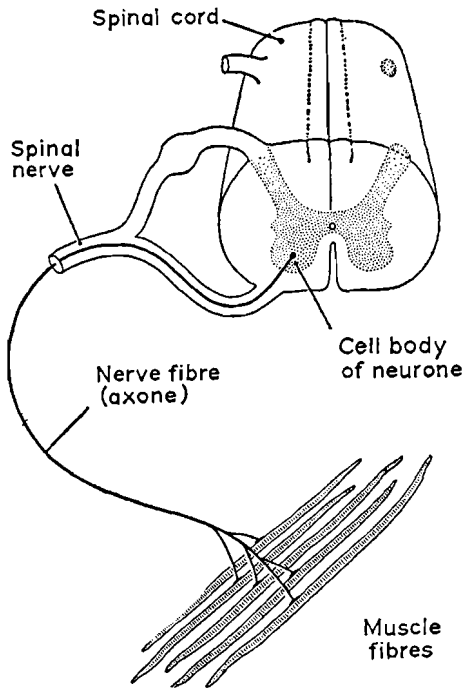

Figure 1.7. Scheme of a motor unit. (Modified from Basmajian, 1955a.)

Dutta and Basmajian (1960) in the pharyngeal constrictors of the rabbit. However, our own observations indicate that in the case of the human tibialis anterior, the endplate region is proximal to the middle of the muscle. In some muscles of some individuals, two aggregations of motor endplates or motor points may exist in a single muscle. Such is often the case in the long head of the human biceps brachii.

The number of muscle fibers that are served by one axon, i.e., the number in a motor unit varies widely, but certain rules have been established in recent years. Generally, it has been agreed that muscles controlling fine movements and adjustments (such as those attached to the ossicles of the ear and to the eyeball and the larynx) have the smallest number of muscle fibers per motor unit. On the other hand, large coarse-acting muscles, i.e., those in the limbs, have larger motor units. The muscles that move the eye have small motor units with less than 10 fibers/unit, as do the human tensor tympani muscle of the middle ear, the laryngeal muscles and the pharyngeal muscles. These are all rather small delicate muscles which apparently control fine or delicate movements.

Krnjević and Miledi (1958) report 7 to 17 fibers/motor unit in the rat

Figure 1.8. Bundle of parallel muscle fibers with endplates (*dark dots*) stained by cholinesterase technique (From Coërs and Woolf, © 1959, Blackwell Scientific Publications, Oxford, and Charles C Thomas, Springfield, IL.)

diaphragm, which suggests that this muscle too has a fine or delicate control. 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). The size of the motor units in our study was determined by tracing the individual nerve fibers along their final distribution to the muscle fibers (Figs. 1.9 and 1.10). Other observers have calculated the total number of muscle fibers in a muscle and the total number of nerve fibers in its motor nerve. Then, by dividing the former by the latter figure, they have calculated the size of the motor units. The latter method is rather questionable because it involves sympathetic fibers as well as motor fibers (Fig. 1.11). Nonetheless, it is a method that does produce reasonable approximations.

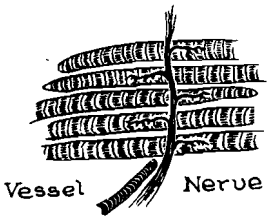

Figure 1.9. Drawing of a nerve bundle ending on muscle fiber-teased specimen (low power, phase contrast microscope). (From Dutta and Basmajian, © 1960, *Anatomical Records.*)

Tergast (1873) estimated that the motor units of the sheep extraocular muscles have 3 to 10 muscle fibers; Bors (1926) estimated 5 to 6 for human extraocular muscles. More particularly, Feinstein et al (1955) reported 9 muscle fibers/motor unit in the human lateral rectus, 25 in platysma, 108 in the first lumbrical of the hand, and 2000 in the medial head of gatrocnemius. Christensen (1959) reported 770 muscle fibers/motor unit in the biceps brachii of infants. Van Harreveld (1947) reported 100 to 125 muscle fibers/motor unit in the sartorius of the rabbit; Berlendis and De Caro (1955), 27 in the stapedius and 30 in the tensor tympani of the rabbit; Wersall (1958), 10 in the human tensor tympani; and Ruedi (1959), 2 to 3 muscle fibers/motor unit in the human laryngeal muscles.

The above innervation ratios represent average values. In fact within a muscle, there exists a hierarchical arrangement of motor unit sizes.

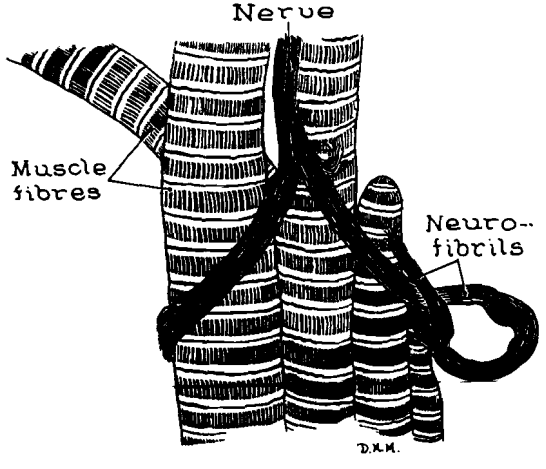

Figure 1.10. Drawing of a photograph of nerve fibers ending on muscle fibers. (Magnification, about ×500.) (From Dutta and Basmajian, © 1960, *Anatomical Records.*)

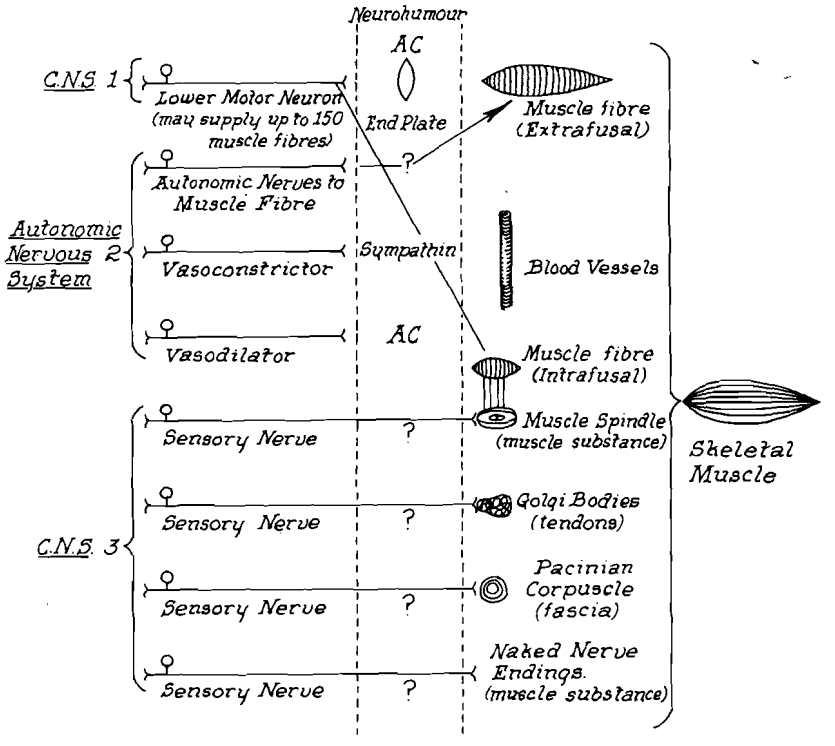

Figure 1.11. Scheme of multiple innervation of skeletal muscle. (After Solandt, from Dutta and Basmajian, © 1960.)

The motor units with a smaller number of muscle fibers are innervated by the smaller alpha motoneuron and are excited earlier during a contraction requiring a progressively increasing force. Larger motor units are innervated by larger alpha motoneurons and become activated at progressively higher force levels.

Van Harreveld (1946, 1947), working with the rabbit's sartorius, concluded that the fibers in a motor unit 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 rarely, if ever, correspond to individual motor units as such. Norris and Irwin (1961) went further with their conclusion (supported by excellent evidence) that in rat muscle the fibers of a motor unit are widely scattered.

Buchthal et al (1957), using an elegant 12-lead multielectrode technique, finally demonstrated quite conclusively that (in the human biceps brachii) the fibers of each motor unit were localized in an approximately circular region with an average diameter of 5 mm, but in some cases reaching a spread of 20 mm. As a rule of thumb, the motor unit territory

may be considered to be approximately one-third of the cross-sectional area of the muscle. Buchthal and his colleagues also showed that fibers of up to 30 different motor units may be located within the territory occupied by any one motor unit.

MUSCLE FIBER TYPE

It is beyond the scope of this book to entertain a detailed discussion on the various classifications of muscle fibers, but some basic knowledge is necessary to appreciate better the structure of muscles.

During the past several decades there has been a growing tendency to establish definable, meaningful categories describing the physiological and biochemical properties of muscle fibers. During the decade of the 1970s, numerous investigations were performed attempting to establish criteria for the distinction of the muscle fiber categories. Although such distinctions are undeniably useful, they may be self-defeating in some cases. For example, overemphasis on the differences among some populations of fiber types tends to make us forget that the physiological and biochemical properties of muscle fibers are a continuum. Depending on which segment of the distribution of the continuum we look at, we see distinctions from other segments. If the segments are sufficiently far apart, the characteristics of the fiber population described therein will be definably different. Most of the work on fiber type categorization has been performed on cats, with some relevant work on guinea pigs and rabbits. In these animals the typing distinction appears to be more clearly apparent than in human muscle fibers.

Muscles of higher-order mammals (including the human) consist of muscle fibers which vary widely in their physiological, morphological, and biochemical properties. Within any one animal, different muscles contain varying amounts of the different fiber types. For related details on 36 human muscles, the reader is referred to the work of Polgar et al (1973) and Johnson et al (1973). However, the muscle fibers belonging to one motor unit show a remarkable homogeneity in their properties.

For several decades muscle fibers have been categorized according to their appearance. Some fibers have a pinkish or reddish visual appearance due to the relatively large amount of blood that is supplied to them by their large vascularization; other fibers appear much paler in coloring, reflecting a less prolific vascularization. These two categories have been referred to as *red* and *white* fibers. Numerous investigations have shown that when the motoneuron of a motor unit consisting of red fibers is stimulated, the resulting force twitch is slower rising and longer lasting than the force twitch which results when a motor unit consisting of white fiber is stimulated. Thus, we have a situation in which red fibers are slow twitch and white fibers are fast twitch.

During the 1960s and 1970s these basic subdivisions of muscle fiber types were subjected to more detailed analysis, and additional subdivisions have been defined and proposed. Engel (1962, 1974) proposed that the fibers be identified as type I and type II. Histochemical tests for key enzymes which correspond closely to the physiological properties of muscle fibers have been performed. The myosin ATPase affinity is an indicator of the fibers' contractile speed (Bárány, 1967). Based on this fact, Brooke and Kaiser (1970) suggested that the muscle fibers be categorized according to the different sensitivities of the myosin ATPase. The type I fibers are acid stable and alkaline labile, whereas the converse is true for the type II fibers. The intensity of staining for specific enzymes of the glycogenolytic and glycolytic metabolic pathways provides an indication of the fibers' capacity to perform work (usually in short bursts) in the absence of oxygen. This is known as the anaerobic capacity. Conversely, oxidative enzymes provide information concerning the capability of the contractile mechanism to use oxygen as its fuel. This is known as aerobic capacity. A high aerobic capacity indicates that a muscle fiber is resistant to fatigue as long as oxygen can be supplied to it via its vascularization. It also follows that a muscle fiber with a high aerobic capacity would have a reddish appearance.

The terminology of Peter et al (1972) is commonly accepted to describe these biochemical-histological properties. Thus, FG stands for fast (high myosin ATPase) glycolytic (high anaerobic and low aerobic capacity); FI stands for fast with high anaerobic and "intermediate" aerobic capacity; FOG stands for fast oxidative (high aerobic capacity) and glycolytic (high anaerobic capacity); SO stands for slow (low myosin ATPase) with oxidative capacity.

An alternative approach for subdividing the categories of muscle fibers has been proposed by Burke et al (1971). They suggested the following classification based on the mechanical response of all the muscle fibers of a motor unit when their motoneuron was stimulated by a single electrical pulse (contractile response) and to a sustained train of stimuli (contractile fatigue response). They expanded the classification of the slow and fast twitch by introducing the evaluation of contractile fatigue, which may be measured by observing the time at which the amplitude of the twitch response declines and/or the rate at which it declines. They denoted FF for fast (contracting), quickly fatigable units; F(Int) for fast, intermediate fatigable units; FR for fast, fatigue-resistant units; and S for slow (contracting) fatigue-resistant units.

It should be noted that these histochemical distinctions may be made much more easily in cat soleus and gastrocnemius muscles than in human muscles. Saltin and Gollnick (1981) argue for the distinction among human muscle fiber types to be made solely on the basis of the myofibrillar ATPase stability to low pH. They point out that the oxidative capacity of fast twitch human muscle fibers is not discrete. Furthermore,

the contractile fatigue measures which have been described apply to artificial stimulus train, which provides a similar excitation to all the motor units. Natural, voluntary stimulus trains are not similar for the various motor units involved in generating a muscle contraction. For example, the firing rate of latter recruited motor units is lower than that of earlier recruited motor units. Thus, the proposed classification provides a description of the mosaic of the motor unit fatigability but may not provide a description of the motor unit fatigability during a voluntary contraction.

CHAPTER 2

Apparatus, Detection, and Recording Techniques

In this chapter we will discuss details concerning electrode types and configurations, as well as associated instrumentation that has a bearing on the quality of the EMG signal that is detected and subsequently displayed, recorded, or processed. The process of sensing the signal by the electrode is referred to as *detection.* The word *recording* is reserved for describing the process that creates a record on any media (CRT, paper, magnetic tape, etc.).

Before beginning a substantive discussion on electrodes, it is necessary to ensure some minimal knowledge concerning the concepts of "impedances" and "filter functions."

CONCEPT OF IMPEDANCE AND FILTER FUNCTIONS

All forms of matter present an impedance to the transmission of an electric current. The impedance function is a vector quantity, hence it is expressed in terms of complex numbers, the real part of which denotes the resistance and the imaginary part of which denotes the susceptance. This latter part exists due to the presence of capacitance and/or inductance, two basic electrical properties of matter. In media such as muscle tissues, fatty tissue, and skin, the inductance is essentially unmeasurable. However, the capacitance is present in a significant amount and cannot be overlooked.

One of the simplest expressions of an impedance function, which is useful for conceptualizing the electrical characteristics of electrodes and tissue, is the impedance of a resistance in series with a capacitor presented in Figure 2.1. In this configuration the impedance function is expressed as a vector

$$Z(\omega) = R + \frac{1}{j\omega C}, \quad \text{where } j \text{ is } \sqrt{-1}, \text{ an imaginary quantity}$$

R = the resistance (ohms), C = the capacitance (farads), $\omega = 2\pi f$ and f = the frequency (Hz).

A vector may also be expressed in terms of its magnitude and phase (direction). The magnitude is the square root of the sum of the squared real part and the squared imaginary part.

$$|Z(\omega)| = \frac{(1 + \omega^2 C^2 R^2)^{1/2}}{\omega C}$$