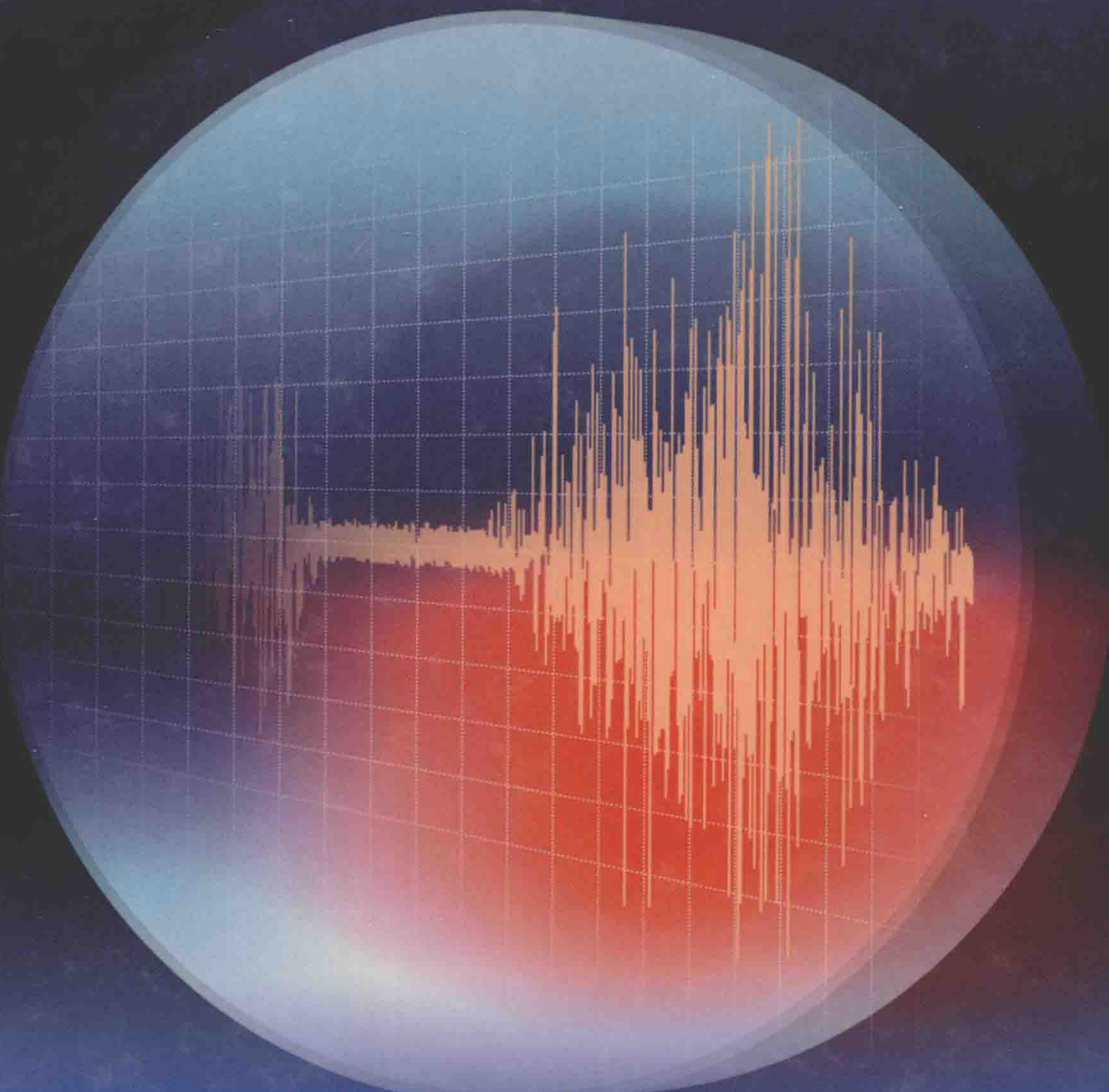
Essentials of Electromyography



Gary Kamen ▪ David A. Gabriel

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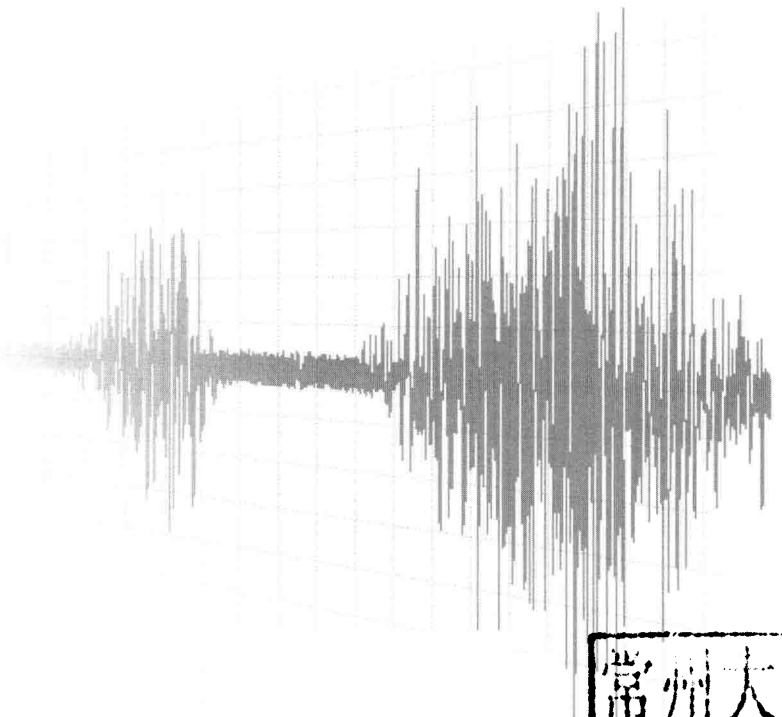

Gary Kamen, PhD
University of Massachusetts, Amherst

David A. Gabriel, PhD
Brock University, St. Catharines, Ontario

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Human Kinetics
Web site: www.HumanKinetics.com

United States: Human Kinetics
P.O. Box 5076
Champaign, IL 61825-5076
800-747-4457
e-mail: humank@hkusa.com

Canada: Human Kinetics
475 Devonshire Road Unit 100
Windsor, ON N8Y 2L5
800-465-7301 (in Canada only)
e-mail: info@hkcanada.com

Europe: Human Kinetics
107 Bradford Road
Stanningley
Leeds LS28 6AT, United Kingdom
+44 (0) 113 255 5665
e-mail: hk@hkeurope.com

Australia: Human Kinetics
57A Price Avenue
Lower Mitcham, South Australia 5062
08 8372 0999
e-mail: info@hkaustralia.com

New Zealand: Human Kinetics
Division of Sports Distributors NZ Ltd.
P.O. Box 300 226 Albany
North Shore City
Auckland
0064 9 448 1207
e-mail: info@humankinetics.co.nz

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To Bobbie and Suzanne

Preface

Imagine that you are living in an apartment with rather thin walls and your neighbor is throwing a party. From your apartment it seems like there are groups of conversations next door, and you're wondering who's at the party, how many people there are, whether they are men or women, and so on. The conversations closer to the wall are easier to hear, and the voices sound a bit different from those deeper in the room. A radio is playing so it is somewhat difficult to hear the conversations, and as more people enter the party, everything gets louder.

The challenge of recording and interpreting electromyographic activity (EMG) is analogous to the task you face in this thin-walled apartment. If you record from the skin surface (the wall), the superficial muscle fibers nearest the skin (voices closer to the wall) contribute greater activity than those farther from the surface electrodes. Groups of motor units (analogous to groups of human conversations) make unique contributions to the EMG signal. As more motor units participate in the muscle contraction (more people enter the room), the EMG signal increases in amplitude. Numerous sources of noise (like background music) can make the interpretation of the EMG signal difficult.

Ever since Luigi Galvani discovered "animal electricity" in frog muscle, researchers and practitioners have found numerous clinical and research uses for the EMG signal. Applications for the use of EMG include biofeedback, gait analysis, and clinical diagnosis for neuromuscular disorders. Moreover, numerous kinesiological researchers have reported their results of EMG studies involving many issues such as spinal reflexes, the action of specific muscles in various movements, muscle fatigue, the use of EMG for rehabilitation, and ergonomic design.

Only a handful of research articles using EMG techniques were published in the early 1950s. Today, over 2,500 research publications appear each year (figure 1). The growth of the EMG literature and the availability of appropriate instrumentation and techniques might suggest that our understanding of the procedures used to record the EMG signal and the relevant analysis methods must be complete. Yet the

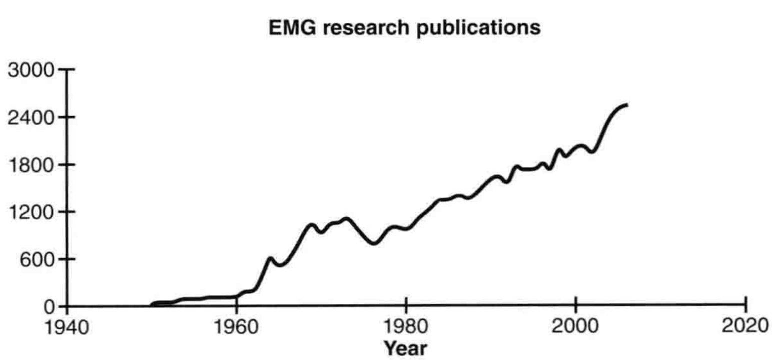


FIGURE 1 The growth in the number of EMG-related publications since the mid-1940s is a clear indication of the significant growth in the interest in and use of EMG in the past six decades.

interpretation of the signal remains controversial; and there are few sources available to help the novice electromyographer understand the physiological and biophysical basis of EMG, characteristics of the instrumentation, signal analysis techniques, and appropriate EMG applications.

This book is written for the novice who is just beginning to discover EMG and is considering its use for clinical or research purposes. Our intent is *not* to review cutting-edge research in the field. Rather, we hope to provide a starting point from which individuals who plan to use EMG can understand the underlying physiological basis of the signal and basic principles of the technology, and be able to apply appropriate analysis techniques to avoid pitfalls in interpretation.

What You Will Find in This Text

We start with a review of the physiological basis of the EMG signal (chapter 1). Since the EMG signal is ultimately a signal based on physiology, it is important to understand the origin and generation of the muscle fiber action potential, the numerous factors that determine muscle fiber conduction velocity, various physiological mechanisms responsible for the gradation of muscular force, and the many physiological factors that affect the electromyogram.

The bioelectricity chapter (chapter 2) then proceeds with a review of fundamental biophysical principles. Here we lead the reader from the very elementary ideas of electric charge to the recording of muscle action potentials. The basics of electric charge are linked to the electric potential recorded at the electrode and an explanation of the use of two electrodes to detect a potential difference at the muscle. Electric fields are an important part of the explanation that connects these concepts. We review volume-conducted potentials in the same manner. This is an important topic because action potential shape determines amplitude and frequency content of the signal. The geometry of action potential "appearance," based on its position relative to the electrode, is described qualitatively using explanatory figures. Our discussion of bioelectricity then closes with an introductory treatment of alternating current (AC) since EMG is treated as an AC signal and is subject to many of the same measurement conventions.

The chapter on EMG instrumentation (chapter 3) is unique in the inclusion of topics frequently omitted in introductory treatments. For example, most surveys of electrode types omit the mechanistic events underlying signal transduction from the muscle action potential to a voltage recorded at the amplifier. Electrode configuration is also a common topic; however, the effect of interelectrode distance on the amplitude and frequency content of the EMG is discussed only in more advanced texts. We have developed figures and qualitative explanations to convey the same information as might be presented in a more mathematical treatment. The formulas that are used to present these concepts are simplified and explained in detail. For example, Kirchhoff's loop law is mentioned in more advanced treatments in discussions of amplifier input impedance. In the present text, we first describe input impedance and why it is important. The electrical circuit and associated formulas are then described in detail, assuming only the background presented in the previous chapter. New concepts in electrode placement relative to the motor point, innervation zone, and tendon are presented with recommendations that depend on the goal(s) of the study. We also introduce bode plots, demonstrate how they are generated, and use them to describe both analog and digital filtering.

The EMG signal-processing presentation (chapter 4) is a unique blend unavailable anywhere else. It is based on traditional signal-processing theory, experience, and recommendations for practical applications. The material combines concepts from more advanced texts in signal-processing theory, communications theory, and papers published on EMG methodological issues. There is a heavy reliance on figures to illustrate physical concepts. Elaborate qualitative explanations are then reinforced with the basic formula associated with the concept or methodology. For example, the origins of linear envelope detection in communications theory are reviewed so that the reader understands its predominant use as a signal-processing method. Of course, the traditional amplitude and frequency measures are described. However, since the frequency measures are often more difficult to understand, calculate, and apply properly without violating the basic assumptions of their use, a significant portion of the chapter is dedicated to reviewing the principles of frequency analysis.

The appropriate location to extract the EMG signal in a discrete trial has not been presented in previous texts but is discussed here. Similarly, the inclusion of specific recommendations and procedures for handling noise contamination of the EMG signal is unique to this text. This chapter integrates both theory and practice to describe the extraction of useful measures from the EMG signal. Area, slope, and variability of the EMG signal are discussed. The interaction between linear envelope detection and low-pass cutoff frequency is described with respect to the detection of EMG onset. Power spectral analysis and the calculation of frequency measures from the EMG signal based on Fourier analysis are discussed. The chapter concludes with a basic explanation of digital filtering.

The last two chapters of the text (chapters 5 and 6) provide examples of the use of EMG techniques with numerous references to the existing literature. The relationship between EMG activity and muscular force has considerable relevance for the development of prosthetic devices and other applications. Much of the research on this issue is discussed, as well as the important work related to the characteristics of the EMG signal that accompany muscular fatigue. We also discuss the use of EMG techniques for recording evoked potentials such as the M-wave, H-reflex, and motor-evoked potentials using transcranial magnetic stimulation (TMS). Chapter 6 also includes an overview of the use of EMG techniques for gait analysis with examples from the extant research literature.

Although simplified explanations of concepts in communication theory, signal processing, electronics, and other issues are presented in the chapters, we include extensive appendixes for those readers interested in more advanced topics and derivations. For example, basic electrode geometry is described in the text, but we include two associated appendixes that provide a computational understanding of the topic through detailed examples. Modeling and simulation of the EMG signal has moved to prominence in the physiological literature, and we include an appendix providing information relevant to understanding that material. Fundamental concepts of EMG frequency measures are provided in the text, but an appendix is then provided with a worked example to help readers internalize this important methodology. A list of acronyms precedes the first chapter for those unfamiliar with the typical acronyms used in the field of electromyography. The text also includes a glossary of new terms introduced throughout the book, as well as brief lists of suggested readings for each chapter, including classic readings in the field. Terms defined in the glossary appear in bold type in the text.

The reference list is far from complete, but it does provide a starting point for the individual intent on gaining additional knowledge. EMG is a rapidly changing technology. Advances in instrumentation, such as array electrodes, and in analysis techniques, such as nonlinear analysis and pattern classification, mean that the future for this field is bright, particularly for those with a thorough understanding of the underlying concepts.

Additional Unique Contributions of This Text

Relatively few previous texts have been made available, and these have provided valuable information about electrode placement, the relationship between applied anatomy and EMG, and EMG applied to clinical areas such as biofeedback and neuromuscular diagnosis. In this text, we provide updated information from the latest available sources. Much of the information in this text is available only in scattered books and papers among the numerous disciplines that use EMG as a tool. For example, although basic electrophysiology is covered in several EMG texts and neurophysiology texts, it is difficult to find summarized materials that relate muscle architecture to EMG. The bioelectricity chapter is particularly novel in how it relates concepts of electric charge to EMG action potentials. The chapter on EMG analysis includes concepts that would otherwise be available only in journal review articles, such as techniques for defining EMG onset and issues relevant to electromechanical delay.

The text is written for individuals with a wide variety of backgrounds, including engineers, physical therapists, kinesiologists, physicians, biofeedback practitioners, and ergonomists. The level of the book is aimed at a fourth-year undergraduate or entry-level graduate student who has a modest background in science. The book relies heavily on the use of figures and qualitative explanations to convey important concepts to bridge any gap that may exist in the background preparation of the reader. However, mathematical derivations have been included in the appendixes to allow able readers to work through equations associated with detecting, filtering, and processing the EMG signal. These mathematical skills require only a first-year calculus course. The algebraic steps have been included because this is often the first skill to go “rusty.” Grasping these basic equations contributes to the depth of understanding of the physical side of EMG. For example, certain changes in the EMG signal are predictable based on the physical properties of the electrode detection system and are of no physiological consequence. Once the physical effects have been identified, a clear understanding of anatomy and physiology is then necessary for valid interpretation of the EMG signal.

As a resource for instructors using this text in their courses, an image bank is provided at www.HumanKinetics.com/essentialsofelectromyography. The image bank contains most of the figures and tables from the text, sorted by chapter. These images can be used to develop a custom presentation based on specific course requirements. A blank PowerPoint template and instructions are also included.

We hope you will find this book a useful primer and frequent reference as you begin your exploration of the field of electromyography.

Gary Kamen
David A. Gabriel

Acknowledgments

No text of this scope could be complete without acknowledging the many contributions from professional and research colleagues as well as from technical personnel. We would like to thank our mentor, Walter Kroll, for providing our initial introduction to electromyography and the inspiration to seek new knowledge in this important field. In addition, our graduate students and faculty colleagues, too numerous to mention without mistakenly excluding some, raised a never-ending string of intriguing and challenging questions and encouraged us to engage in the important research needed to obtain the answers.

Several staff at Human Kinetics were helpful in ensuring completion of the book in an accurate and timely manner. These individuals included Loarn Robertson, Elaine Mustain, Kate Maurer, Martha Gullo, and Dalene Reeder. Many obstacles to the timely completion of the book were overcome with the help of Greig Inglis.

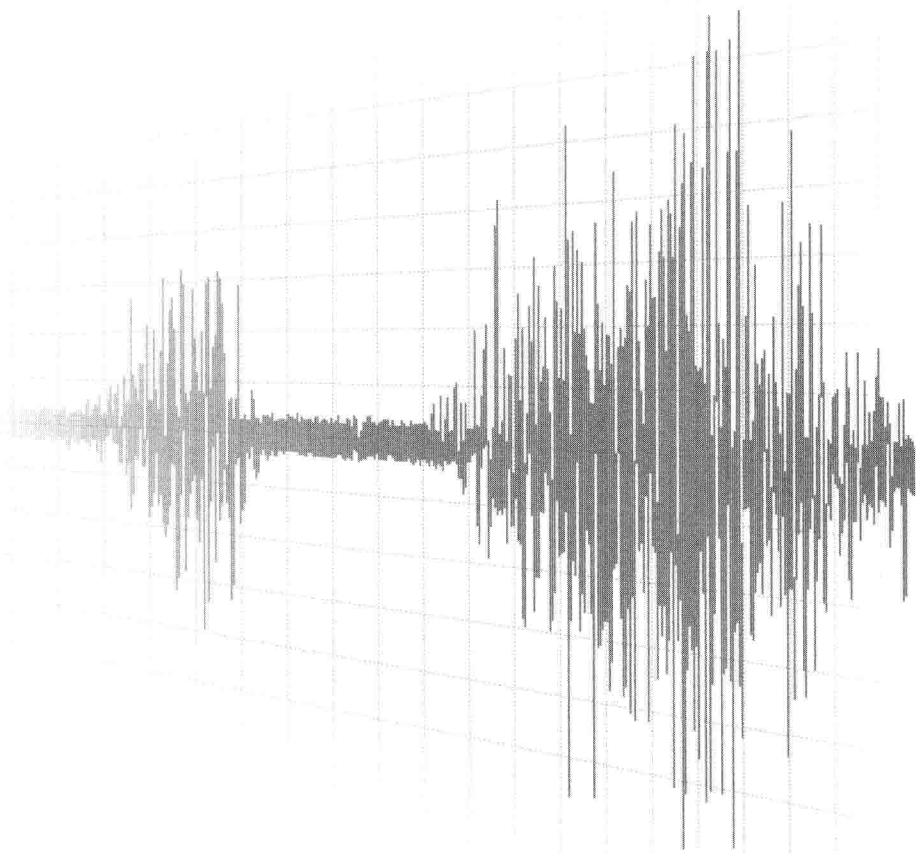
Acronyms and Symbols

A	area
A/D	analog-to-digital
AC	alternating current
ARV	average rectified value
C	coulomb
CMAP	compound muscle action potential
CMRR	common mode rejection ratio
CV	conduction velocity
DC	direct current
DFT	Discrete Fourier transform
E	electric field
ECG	electrocardiogram
EMD	electromechanical delay
EMG	electromyography
f	frequency
F	force
FFT	Fast Fourier transform
FT	Fourier transform
G	gain
i	current
ICC	intraclass correlation
IED	interelectrode distance
IEMG	integrated electromyography
IFFT	inverse Fast Fourier transform
IPA	interference pattern analysis
J	current density
m	meter
M-wave	massed action potential
MDF	median power frequency
MEP	motor evoked potential
MEPP	miniature end-plate potential
MFAP	muscle fiber action potential
MFCV	muscle fiber conduction velocity
MNF	mean power frequency
MSA	mean spike amplitude
MSF	mean spike frequency
MU	motor unit
MUAP	motor unit action potential
MVC	maximal voluntary contraction
N	newton
PDF	probability density function
PSD	power spectral density
P-P	peak-to-peak
Q	charge
Q_{30}	The area on the EMG–time curve computed between the onset of EMG activity and a point 30 ms following EMG onset
QE	quantization error
r	radial distance
R	resistance
RMS	root mean square
SD	standard deviation
sEMG	surface electromyography
SI	International System of Units
SNR	signal-to-noise ratio
TMS	transcranial magnetic stimulation
TP	total power
U	potential energy
V	volt
VR	variance ratio
W	work
X_C	reactive capacitance
Z	impedance
$\mathcal{E}$	electromotive force
λ	length constant
ρ	resistivity to the flow of charge
σ	conductivity
Ω	ohm

Contents

chapter 1

Anatomy and Physiology of Muscle Bioelectric Signals



Electromyography (EMG) is a valuable technique for studying human movement, evaluating mechanisms involving neuromuscular physiology, and diagnosing neuromuscular disorders. However, there are many potential pitfalls in the use of EMG as a tool. The question that a researcher is asking may not be amenable to solution using EMG techniques. The researcher could err in the selection of recording electrodes, the recording site, or the data acquisition specifications. Furthermore, the interpretation of the EMG signal requires a thorough knowledge of the origin of the signal.

Although researchers frequently evaluate electromyographic waveforms as an electrical signal whose characteristics can be assessed using traditional signal-processing techniques, the EMG signal has physiological origins in individual fibers or groups of muscle fibers. The anatomical features of individual fibers, the architectural features of whole muscle, and the physiological origins of action potentials are key to understanding how to record, analyze, and interpret the EMG signal. In this chapter, we study the origins of the EMG signal, including relevant muscle physiological concepts.

Anatomical Features of Muscle

The salient anatomical features that affect the EMG signal include variations in muscle fiber length and fiber type composition, muscle partitioning, and variations in the distribution of sensory receptors. These anatomical and architectural muscle features differ among muscles and even within and among individual subjects. Thus, they need to be considered to ensure proper EMG recording and interpretation.

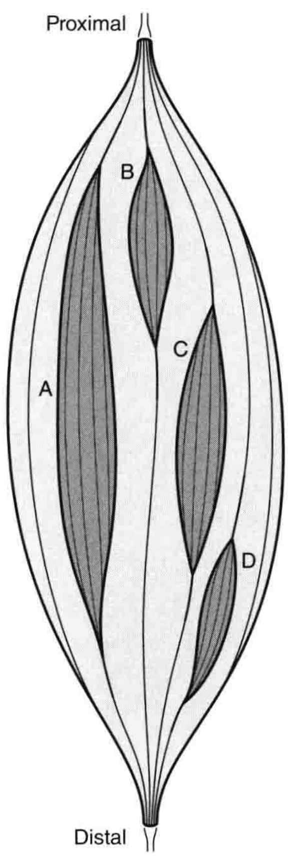


FIGURE 1.1 Muscle fibers vary in length. Some muscle fibers range from proximal tendon to distal tendon *(A)*. Other fibers lie chiefly in proximal *(B)* or distal *(D)* portions of the muscle. Still other muscle fibers may range from proximal to distal tendon but vary considerably in length *(C)*.

- **Muscle fiber length.** Although it is frequently assumed that muscle fibers run continuously from distal to proximal tendon, this is not always the case. Some muscle fibers are short and may lie at proximal, distal, or middle portions of the muscle (Gans and de Vree 1987; Heron and Richmond 1993; van Eijden and Raadsheer 1992). The human hamstrings, for example, is composed of fibers that range from 4 to 20 cm in length, and some muscle fibers may be tapered at one or both ends (Heron and Richmond 1993). Surface electrodes placed longitudinally on either a distal or proximal part of the muscle, then, will record only from those muscle fibers underlying the electrode. Action potentials may differ at different portions of a tapered muscle fiber (figure 1.1).

- **Muscle fiber architectural characteristics.** The characteristics of fibers may vary between deeper and more superficial portions of the muscle (Dwyer et al. 1999; Lexell et al. 1983; Pernus and Erzen 1991; Roeleveld et al. 1997). Deeper muscle fibers seem to comprise a greater proportion of slow-twitch fibers, while muscle fibers lying more superficially comprise a greater proportion of larger, fast-twitch fibers (Polgar et al. 1973). Electrophysiological evidence in human muscle using a technique termed **macro-EMG** supports this idea (Knight and Kamen 2005). The variance in fiber type composition in different areas of the muscle could be due to the greater access to the blood supply afforded to slow-twitch fibers lying deeper in the muscle, though this speculation has yet to be corroborated. Since the global EMG signal recorded from surface EMG electrodes presents a biased estimate of activity closer to the electrodes (which we will discuss later), this anatomical feature is important.

■ **Muscle partitioning.** Another factor concerning gross muscle structure that affects the interpretation of the EMG signal relates to *muscle partitioning* (figure 1.2). Many human and animal muscles are partitioned, and each partition may have a specific role in the function of a particular muscle (Blanksma and van Eijden 1990; English et al. 1993; Segal 1992; Segal et al. 1991, 2002; van Eijden and Raadsheer 1992). For example, the flexor carpi radialis consists of three major architectural divisions based on both muscle architecture and the innervation pattern (Segal et al. 1991). A lateral partition functions during radial deviation, while both lateral and medial partitions function during pure wrist flexion. If one obtains multiple recordings from the human extensor carpi radialis longus, proximal and distal portions of the muscle are shown to be selectively active, depending upon whether the movement is pure extension or extension and radial deviation (English et al. 1993). Even small facial muscles like the orbicularis oris can have specific divisions (Abbs et al. 1984). Thus, the electromyographer needs to be aware of whether the recording is representative of the entire muscle or is characteristic of a specific muscle partition.

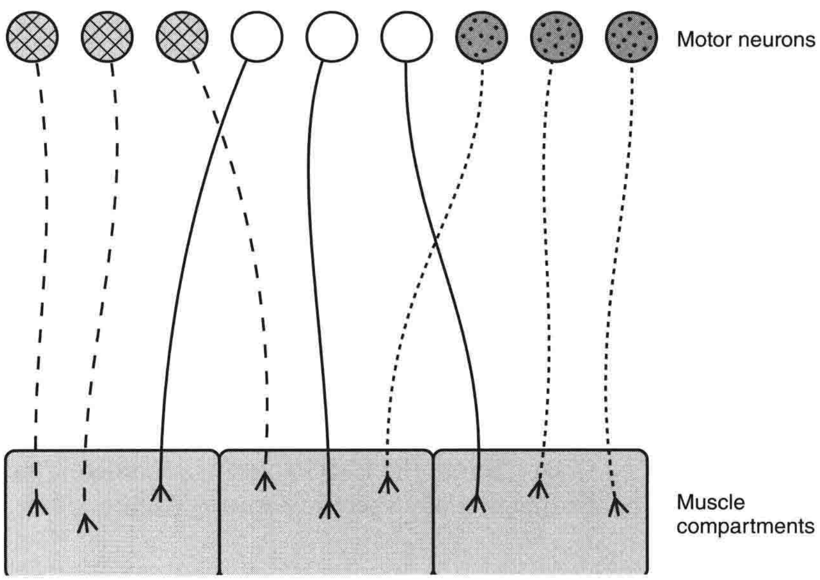


FIGURE 1.2 Muscle partitioning. Groups of motor neurons may innervate specific compartments. Note that one population of motor neurons may innervate more than one compartment.

■ **Neuromuscular compartment partitioning.** Neuromuscular compartments may also be partitioned, such that specific receptors like muscle spindles and tendon organs may be sensitive to the activity of a specific, localized group of motor units. This neuromuscular partitioning has been well demonstrated in the cat but is also present in some human muscles (Kamibayashi and Richmond 1998; Windhorst et al. 1989). One way to identify partitioning may be to observe EMG responses to stimuli presented to different parts of a muscle. The human tibialis anterior may not be compartmentalized, for example, since vibration and tendon tapping, which serve as strong inputs to Ia receptors, failed to identify localized reflex responses (McKeon et al. 1984).

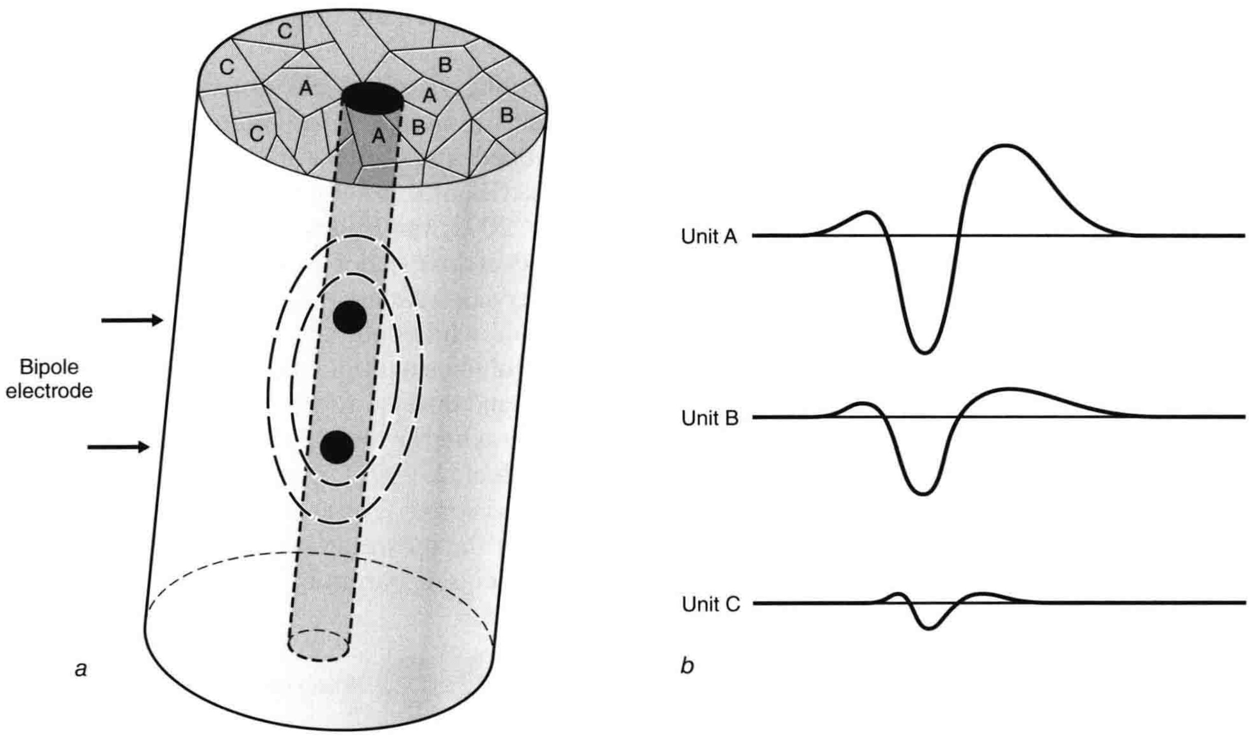


FIGURE 1.3 The electromyogram is affected by the architectural features of the muscle. In this schematic figure, an electrode placed in the center of the muscle would record the largest action potential from motor unit A, the next largest from unit B, and the smallest from unit C.

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- **Sensory receptor distribution.** In feline muscle and perhaps in human muscle, the distribution of sensory receptors within the muscle may not be homogeneous. Thus, the muscle region with the greatest density of receptors may provide regional information about localized changes in muscle length, force, and limb displacement (Richmond and Stuart 1985). Clearly, a knowledge of the specific anatomy of the muscle(s) of interest is necessary before the EMG signal is recorded. The function revealed by EMG may be the function of a specific partition (figure 1.3).

KEY POINTS

- The length of individual muscle fibers within the whole muscle varies, and the characteristics of the muscle fiber action potential change at different fiber sites, rendering the EMG signal dependent on the specific location at which the electrodes are placed.
- Larger, type II muscle fibers tend to lie more superficially, while deeper muscle fibers tend to be smaller, type I fibers. Since the surface EMG signal is biased toward the fibers closest to the electrode, this means that the action potentials from the superficial type II fibers are disproportionally represented in the EMG signal. In other words, a greater proportion of the EMG signal is derived from superficial fibers than from deeper fibers.
- Due to compartment partitioning, the interpretation of the EMG signal may depend on the part of the muscle from which recordings are made. Hence, knowledge of neuromuscular architecture is critical.

Physiology of the Muscle Fiber

Muscle is a tissue constantly bathed in an ionic medium. Like all living cells, muscle is surrounded by a membrane—the **sarcolemma,** which is about 75 angstroms (Å) thick. At regular intervals, the **transverse tubular system** interrupts the membrane. In some places, the transverse tubules (T-tubules) run longitudinally, connecting with other T-tubules and the **sarcoplasmic reticulum** (SR) network (Hayashi et al. 1987). T-tubules serve as important structures for carrying the action potential deep transversely into the myofibrils to fully activate all portions of the muscle fiber.

Resting Membrane Potentials

Under resting conditions, a voltage gradient exists across the muscle fiber membrane such that the inside of the fiber lies about –90 mV with respect to the outside. The voltage gradient arises from the different concentrations of sodium (Na^+), potassium (K^+), and chloride (Cl^-) and other anions across the membrane. Under resting conditions, the concentration of Na^+ is relatively high outside the membrane and relatively low inside the fiber. On the other hand, the concentration of K^+ is relatively low outside the membrane and relatively high on the inside of the muscle fiber. The size of the resting membrane potential is slightly more positive in slow-twitch fibers. The greater positivity arises from the enhanced Na^+ permeability and higher intracellular Na^+ activity in slow-twitch fibers than in fast-twitch fibers (Hammelsbeck and Rathmayer 1989; Wallinga-De Jonge et al. 1985). Also, the resting membrane potential can be changed by exercise training (Moss et al. 1983).

Generation of the Muscle Fiber Action Potential

Muscle fibers are excitable tissues. When the muscle fiber is depolarized by about 10 mV or more, the **membrane potential** reacts in a stereotypical and predictable fashion, producing a response we call the **muscle fiber action potential (MFAP),** or just action potential. The action potential generated at the neuromuscular junction proceeds along the muscle fiber in both directions from the neuromuscular junction. In the first phase of the action potential, Na^+ permeability increases and Na^+ rushes into the cell, ultimately reversing the polarity of the cell so that the cell is momentarily about 10 mV positive. As the Na^+ permeability increases, so does the membrane permeability to K^+, and it is the outflow of K^+ that ultimately results in the return of the membrane potential to its resting state (figure 1.4).

The sodium permeability exerts considerable control over the time course of the action potential. A **refractory period** follows the nerve or muscle impulse, during which time there is a decrease in the excitability of the membrane. For a brief period of time, the membrane is *absolutely* refractory and all the Na^+ channels are closed, and so the membrane cannot respond with an action potential regardless of the size of the excitatory stimulus. There follows a *relative* refractory period during which some Na^+ channels are open, and an action potential can be generated so long as the excitatory stimulus is sufficiently large to overcome the increase in the threshold needed for excitation.

The main spike portion of the muscle fiber action potential (MFAP) is followed by a **terminal wave,** produced by the termination of the action potential at the muscle–tendon junction (McGill et al. 2001). Muscle fiber action potentials also have a unique feature called the slow **afterwave,** also termed the slow **afterpotential** (Lang and