Chapter 12

Electromyography: Recording Electrical Signals from Human Muscle

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Introduction

A record of the external electrical activity from a muscle is called an EMG, or electromyogram. EMG also refers to electromyography, the recording technique used to obtain an electromyogram (Basmajian, 1985; Loeb and Gans, 1986; Cram and Kasman, 1998). EMG recordings from human skeletal muscle offer a simple and reliable educational tool to stimulate student interest and learning in biology and physiology classrooms (Oakley and Schafer, 1978).

Full appreciation of EMG recordings, however, is challenging for students. It requires an integrated understanding of many structure-function relationships of nervous and muscle systems. In my experience, student understanding of these events is optimal when the EMG recording set-up is simplified and the capability of bio-feedback (especially audio feedback) is utilized. This allows students to focus attention on underlying biological mechanisms and electrical events.

I have used this exercise for more than twenty years in graduate and undergraduate neurobiology and neurophysiology lab classes. The exercise is also used in our department's core course in undergraduate physiology. It has proven to be a consistent favorite for many students and instructors.

To increase versatility and portability of EMG technology, and to decrease cost and complexity, I have designed and built most of the recording apparatus described here, including electrodes, straps, preamplifiers, power supplies, filters, and triggering devices. The apparatus may be used as a "stand-alone" portable setup, but it is also easily integrated with many types of physiological recording and display instruments. A special feature of the EMG setup here is that it may be used as a light-weight, battery-powered system.

In recent years, I assembled numerous EMG recording setups that have been used as educational outreach kits in high schools. Kits are freely loaned to teachers for 1-2 weeks, given that my department pays for shipping charges to the school and their school pays for return shipping. Dozens of teachers in Iowa have requested and used the kits. Student response has been keen. Most teachers use only the combination of preamplifier and audio monitor, but a few routinely interface the setup with an oscilloscope for visual analysis of EMG activity.

Materials

- Disc recording electrode assembly (two shielded recording leads, one unshielded ground lead)

- Wide elastic straps with Velcro closures (three straps per setup)
- Conductive electrode cream (e.g., Signa Creme; American Biotec, Ossining, NY 10562)
- Numerous small squares of clean, unused sandpaper (2 cm x 2 cm; medium grit)
- Large, wide rubber band (to fit comfortably around one knee)
- Meter stick or tape measure
- Ball-point pen
- Cables/Connectors
  BNC male-to-audio plug (connects amplifier to audio monitor)
  BNC male-to-BNC male, with built-in notch filter (connects amplifier to oscilloscope)
  BNC T-connector (splits amplifier output to audio monitor and oscilloscope)
- Percussion hammer (equipped with an inertia switch if used for triggering oscilloscope)
- Custom-made amplifier (100X and/or 1000X gain), with built-in power cable
- Regulated DC-power supply for powering amplifier
  [Examples are: (a) regulated ±15 VDC output power supply, 120VAC power (i.e., Analog Devices dual supply 902-2 and 950 chassis; or (b) ± 9 VDC battery pack, consisting of two 9V batteries.]
- Audio monitor for bio-feedback
  [*Alternative A*: Grass Instruments Model AM7 audio monitor -- a plug-in unit with built-in, high- and low-frequency filters; cost under $500; high-performance output for many types of electrophysiology recordings. NOTE: Simultaneous outputs from several units in one lab room may create a din. *Alternative B*: Radio Shack audio preamplifier: a small, battery-powered unit (9VDC); cost under $15. Because it has weak amplification, a 1000X amplifier gain setting is required. In addition, it is necessary to make a simple technical modification of this preamplifier to reduce its unacceptably high levels of background "hiss." For description of this modification, ask the author for the supplemental handout entitled: *"Schematics and Technical Details."*]
- Storage oscilloscope (OPTIONAL)
  [The highest quality and most economical digital storage oscilloscope currently available is the Tektronix Model TDS 210 (cost ≈ $1000). A computer-based oscilloscope emulation may also work if the system has (1) a digital sampling rate of at least one sample every 50 microseconds, and (2) a reliable means for triggering oscilloscope sweeps. Since EMG signals are in the microvolt range, preamplification may also be needed.]

[NOTE: With institutional approval and support, I am granted permission to sell any custom-made components of the EMG recording apparatus and materials listed above. This is done purely on a non-profit, cost-recovery basis via inter-institutional transaction. Upon request, I also freely provide a supplement entitled "Schematics and Technical Details," which gives complete lists of components and schematics for all custom-made apparatus.]

Notes for the Instructor

Difficulty in this exercise may arise from poor electrode contact with the skin or improper electrode placement. Usually, this is indicated by high levels of noise and/or poor signal quality in recordings. Excellent recordings are the rule when students carefully read and follow instructions.

Aside from electrode placement, other factors that significantly influence the quality of EMG recordings are skin thickness and conductivity, which vary among subjects. Amplitudes of motor unit spike potentials in subjects with thick skin or a thick layer of subcutaneous fat are usually small due to signal attenuation through the skin. If students work in groups, I suggest that a simple skin pinch test be done on the skin overlying the gastrocnemius muscle of each member of the group to select a subject with a relatively thin skin layer.

Before beginning this laboratory exercise, instructors should ensure that anatomical and physiological concepts underlying motor control of human skeletal muscle are fully explained (see Buchthal, 1980; Basmajian, 1985; Cram and Kasman, 1998). If this is not done, students will fail to recognize many subtle but important features related to neural control of human movement. The following are key concepts that should be stressed:

1) The basic functional unit for excitation and contraction in vertebrate skeletal muscle is the *motor unit*.

2) Anatomically, a motor unit is composed of both neural and muscular components (Figure 12.1). The neural component is a *motor neuron,* its cell body being in the spinal cord and its axon extending peripherally from the spinal cord to a particular muscle. The muscular component of the motor unit consists of all skeletal muscle fibers innervated by the motor axon (often several dozens or several hundred). The terminals of the *motor axon* are connected to this set of fibers by a chemical synapse. This synapse is usually referred to as the *neuromuscular junction* or *motor end-plate*.

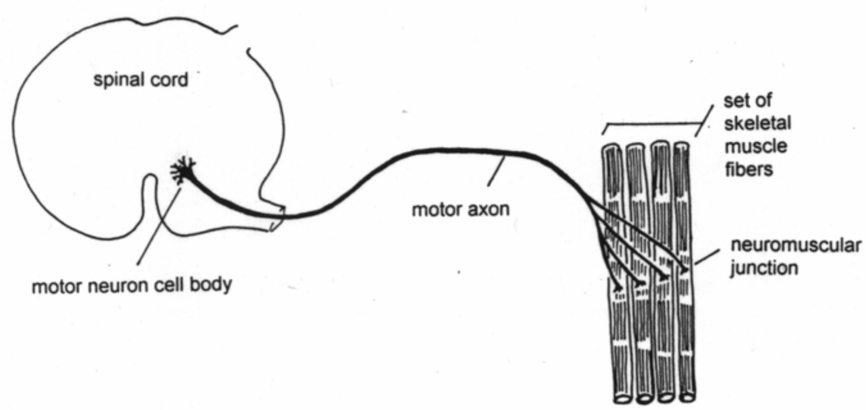

Figure 12.1. Simplified diagram showing components of a motor unit. [NOTE: In most limb muscles, one motor axon typically branches to innervate hundreds or even thousands of muscle fibers, rather than just a few, as illustrated.]

3) Physiologically, the motor unit works as a unit. That is, when an action potential occurs in a motor neuron, all muscle fibers in the unit are simultaneously excited and produce an action potential, resulting in a brief, twitch-like contraction of the fibers.

4) Typically, electrical activity in a motor unit consists of a rhythmic series of action potentials.

5) When an action potential occurs simultaneously in all muscle fibers in one motor unit, the resulting external electrical effect is small, spike-like potential (= *motor unit spike*) which can be detected with electrodes placed on the surface of the muscle.

6) A surface electrical recording of the spiking activity derived from one or more motor units is called an *electromyogram*, or *EMG*.

7) The EMG is a record of electrical, *not mechanical*, events.

8) During repeated firing of a motor unit, the amplitude and waveform of a motor unit spike tend to be constant. Spikes from different motor units may be distinguished from one another based on differences in amplitude and waveform.

9) Each skeletal muscle is composed of many motor units. A large and powerful limb muscle, such as the gastrocnemius, may be composed of hundreds of motor units.

10) Motor units vary in size. In a small motor unit (one that generates a weak contraction force), diameters of the motor neuron cell body and axon are relatively small, and the axon connects to relatively few muscle fibers. In contrast, in a larger motor unit (that generates a stronger contraction), diameters of the motor neuron cell body and axon are larger, and the axon connects to a relatively large number of muscle fibers (Tables 12.1 and 12.2).

11) Motor unit activity can be controlled voluntarily by the brain. Action potentials are first initiated in specific subsets of interneurons within the pre-motor and motor cortex regions of the cerebrum (Figure 12.2). Some of these interneurons (also referred as “upper motor neurons”) have long axons that project downward from the motor cortex and make excitatory connections to motor neurons (also referred to as “lower motor neurons”) at various levels of the spinal cord.

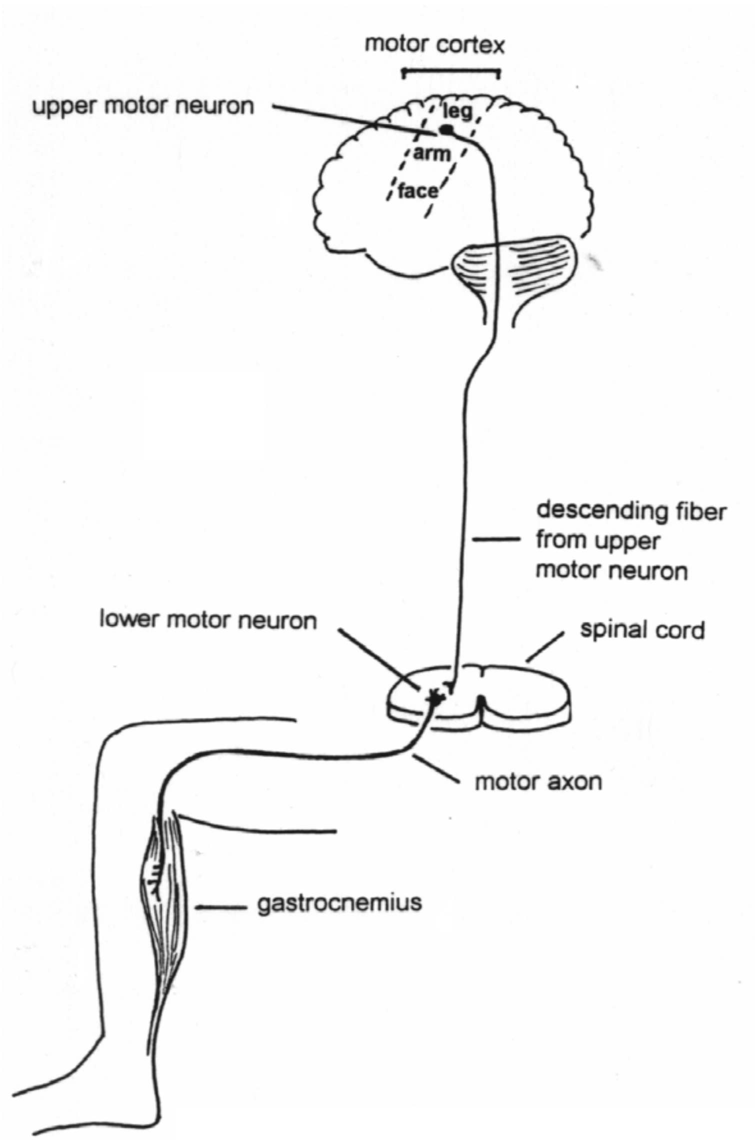

Figure 12.2. Simplified drawing showing the descending, excitatory interneuronal pathway connecting the brain's motor cortex to motor neurons in the spinal cord.

12) During voluntary movement, the level of descending excitation onto lower motor neurons varies in direct relation to the intended strength of a contraction. Higher levels of descending excitation translate into higher frequencies of motor unit impulse activity.

13) With very weak voluntary excitation of a leg muscle, only one or a few small motor units are active and their spike frequency is low (typically only a few spikes per second; Gilson and Mills, 1941). Consequently, there is little or no overt muscle contraction.

14) If a stronger effort of voluntary movement is made, then more motor units are recruited, or "willed," into excitation by activity in descending, excitatory interneuronal pathways originating in the brain's motor cortex (Figure 12.2).

15) Thus, as conscious effort increases, spike frequency in small motor units increases. At the same time, larger motor units are progressively “recruited” into spiking (Figure 12.3; Tables 12.1 and 12.2). This orderly and predictable recruitment of motor units, according to size, is called *Henneman’s size principle* (Henneman and Olson, 1965; Cram and Kasman, 1998).

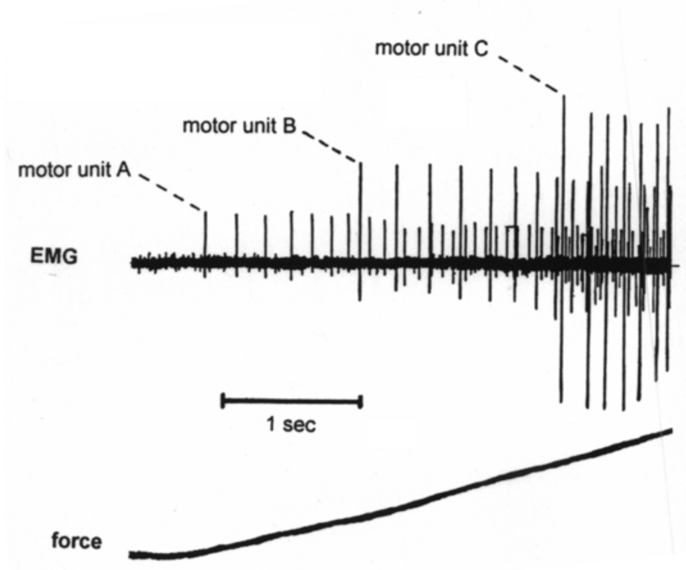

Figure 12.3. Recruitment of motor units in a human EMG recording during weak voluntary movement. Note that each motor unit has a different spike amplitude. and that the spike amplitude of each recruited unit is progressively greater. Also note the progressive increase in spike frequency and force as units are recruited.

16) Thus, two co-existing and complementary mechanisms are used to achieve graded increases in the strength of voluntary muscle contraction. The first involves an *increase in the spike frequency* of motor units that are already active. The second involves *recruitment of additional (larger) motor units* that were previously inactive.

17) If effort is gradually diminished, then “de-recruitment” of motor units occurs. De-recruitment follows a pattern of reverse ordering. That is, larger units cease firing first; smaller units cease firing last.

18) Motor units in limb muscles are also excited *involuntarily through reflex activation.*

19) Brief muscle stretch, caused by a tendon tap, excites stretch-sensory nerve fibers in the belly of the stretched muscle (Figure 12.4). Impulses in these sensory fibers are conducted to the spinal cord where excitatory, mono-synaptic connections are made between the sensory fibers and motor neurons that innervate the muscle that was stretched.

20) A tendon tap evokes a large EMG wave derived from the additive electrical effect of motor unit spike potentials, evoked nearly synchronously, in numerous motor units.

21) The time interval from a tendon tap to onset of motor unit excitation is a relatively constant value, referred to as *reflex time*, or *reflex latency*.

22) During the reflex response to a tendon tap, onset of the EMG wave (an electrical event) precedes onset of muscle contraction (a mechanical event) by about 5 msec, which is the time required for excitation-contraction coupling in skeletal muscle.

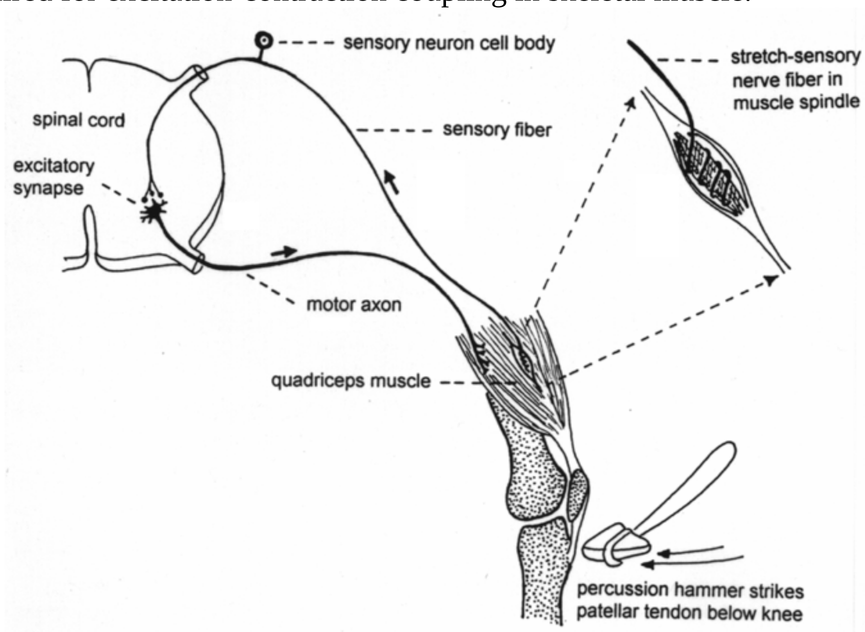

Figure 12.4. Illustration of the sensory and motor pathways involved in the tendon-tap (stretch) reflex for the human quadriceps muscle.

After witnessing recordings from about 200 student subjects, I have noted several interesting trends related to motor unit control and EMG activity. First, subjects with a history of athletic training are often more facile in isolating and controlling single motor unit spiking than students with no such training. Second, I have seen some strikingly abnormal patterns of motor unit firing and/or stretch reflex responses in a few subjects who, otherwise, seemed normal. After questioning, I discovered that each of these subjects had once been treated for serious brain and/or spinal trauma and associated motor debilitation. Interestingly, even though the subjects had recovered and motor abilities seemed to be normal, abnormal EMG patterns persisted and these were probably related to their original injury. Their recovery is a testimony to the nervous system's capacity for regeneration, plasticity, and/or compensation of motor control pathways. Such cases are of great interest and educational value to classes, but instructors should be tactful and sensitive to students whose EMG responses, for any reason, appear attenuated or abnormal.

Student Outline

Introduction

Every deliberate movement a person makes involves contractions of various skeletal muscles in the body. Each skeletal muscle is composed of many thousands of muscle fibers and each of these fibers is a multi-nucleated cell. An example of a skeletal muscle is the biceps, which contracts as you reach to touch your nose, and the gastrocnemius, which contracts when you slightly press your foot down on the accelerator of a car, or stand on your tiptoes.

Skeletal muscles do not normally contract on their own; rather, they are excited through a sequence of electrical events involving the central and peripheral nervous systems. For example, to perform a simple voluntary movement, such as deliberately *depressing a car's accelerator* with your foot, a complex sequence of electrical events must occur -- first in your brain, then spinal cord, and finally leg. The following is the normal sequence of events.

a) Electrical impulses (= action potentials) are initiated in specific subsets of interneurons within the pre-motor and motor cortex regions of your cerebrum (Figure 12.2).

b) Some of these interneurons in the motor cortex, referred to as “upper motor neurons,” have axons that project down the spinal cord and make excitatory connections with regular motor neurons (= “lower motor neurons”) at various levels of the spinal cord. For the calf muscle (= gastrocnemius), the pool of motor neurons that controls this muscle is located at sacral levels of the spinal cord -- levels S1 and S2. [NOTE: If you decide to scratch your nose, instead of press the accelerator, then a different, but parallel, set of upper motor neurons in your brain activates motor neurons at cervical levels that control arm muscles.]

c) Next, motor neurons innervating the gastrocnemius produce a series of impulses that are conducted, via their motor axons, through the sciatic nerve and toward the gastrocnemius.

d) Within the gastrocnemius, each motor axon impulse is conducted simultaneously into many branches and sub-branches of the axon. Each sub-branch terminates on a different muscle fiber where it forms a chemically transmitting synapse, called a “motor end-plate.” Collectively, each motor axon, plus all the muscle fibers with which it makes synaptic connection, is called a *motor unit* (Figure 12.1). Typically, a motor unit in the gastrocnemius is comprised of about 2,000 muscle fibers, while the entire muscle itself is composed of more than a hundred motor units.

e) Acetylcholine, released by axon terminals at the motor end-plate, causes depolarization and an action potential in all muscle fibers innervated by the axon. Thus, all muscle fibers in a motor unit produce an action potential at nearly the same instant in time.

f) Soon after an action potential occurs in the muscle fibers, all muscle fibers in the motor unit produce a tiny twitch-like shortening, or contraction.

When stronger contraction of the gastrocnemius is desired, steps a-f above are simply magnified. That is, more interneurons in the cerebral motor cortex are activated which, in turn, leads to more excitation of motor units in the gastrocnemius. Graded increases in strength of skeletal muscle contraction are thus achieved by two mechanisms: (1) increase in the spike frequency of motor units that are already active, and (2) "recruitment" of additional, larger motor units that were previously inactive. Normally, these two mechanisms act in concert with one another.

Motor unit activation thus follows a specific pattern. Let's say, for example, there are four different motor units (A, B, C, and D) which contribute to the progressive increase of contraction strength of a muscle. The expected activity and recruitment patterns for these units is shown below in Tables 12.1 and 12.2.

Table 12.1. Characteristics that vary with motor unit size in four hypothetical motor units.

Unit	Diameter of motor neuron cell body	Diameter of motor axon	Number of muscle fibers innervated by unit	Contraction force produced by motor unit
A	small	small	small	small
B	medium-small	medium-small	medium-small	medium-small
C	medium-large	medium-large	medium-large	medium-large
D	large	large	large	large

Table 12.2. Recruitment pattern for four hypothetical motor units.

Number of motor units recruited	Spike frequency in motor units	Total strength of contraction
A only	low in A (smallest unit)	very weak
A and B	medium in A low in B	weak
A, B, and C	high in A medium in B low in C	moderate
A, B, C, and D	very high in A high in B medium in C low in D (largest unit)	strong

How long does it take from the time we decide to produce a movement until the movement actually begins? In humans, the entire sequence of steps a-f (above) occurs in a few tenths of a second. Since each action potential in a motor axon is a very brief electrical event lasting only about 1 millisecond, then, in theory, up to several hundred action potentials could occur in a motor axon in a single second. Usually, however, a typical range of impulse frequency in motor units is from a few impulses per second to about 50 impulses per second.

Principle of Electromyography

With metallic electrodes placed on the skin over a muscle, a complex series of electrical potentials is detected as the muscle contracts. This type of electrical recording is called an electromyogram, or EMG. Principles involved in obtaining EMG recordings are essentially the same as those used to detect the heart muscle's electrical activity from the skin surface, a recording called an electrocardiogram, or ECG.

During strong contraction of a skeletal muscle, electrical potentials recorded with surface EMG electrodes may have a relatively large signal strength, perhaps a few hundred microvolts. [NOTE: one microvolt = one millionth of a volt.] Such potentials derive from the combined electrical effects of numerous motor units that are rapidly firing action potentials in the muscle. By comparison, the signal strength generated when an action potential occurs in just one motor unit is much smaller -- typically only a few microvolts. Nevertheless, it is often possible to use EMG electrodes to resolve activity from single motor units. This requires appropriate technology for amplifying and monitoring EMG signals. Such monitoring may be done visually on an oscilloscope, or audibly with an audio monitor (bio-feedback), or both.

By using bio-feedback, along with EMG recording, it is often possible (with practice) to consciously and precisely control the number and frequency of spikes generated by single motor units. This ability, referred to as *single motor unit training* (SMUT), illustrates the exquisite neural control we have over muscle contraction. It is this type of motor control that allows us to make all kinds of muscle movements, ranging from the delicate finger manipulations used to thread a needle to the powerful arm and leg movements required for a slam dunk.

Objectives

The objectives of this investigation are to (a) learn principles of EMG recording and interpretation, (b) use bio-feedback to study patterns of motor unit activation during voluntary movements of skeletal muscle in a limb, and (c) analyze the pattern and timing of involuntary EMG responses evoked by excitation of stretch-reflex pathways.

Procedures

Safety measures and recording set-up

Recording instruments should be securely arranged on a broad counter top or heavy table equipped with three-pronged (grounded) AC outlets. Plug in the audio monitor if it is an AC-powered unit. Plug in the oscilloscope (an optional instrument). Make sure all power cords are positioned well away from human entanglement, wet surfaces, or sinks.

Skin preparation and electrode placement

The subject should wear gym shorts, or loose-fitting pants with one pant leg rolled up above the knee. Place a rubber band at about knee level (Figure 12.5). With the recording electrode assembly disconnected from the amplifier, have the subject hold onto the three banana plugs (red, black, and green) on one end of the electrode assembly. Insert the other ends of the cable (with the disk electrodes) under the rubber band, and let them hang freely near the inner surface of the lower leg. The longer and thicker wire will be used as the ground electrode. The two shorter and thinner wires are the recording leads.

Referring to Figure 12.5, locate the two recording sites on the belly of the gastrocnemius (calf) muscle and locate the grounding site on the ankle. Have the instructor confirm that these positions are correct. Then, use a ball-point pen to mark each of these three sites with a one inch-diameter circle. The centers of the two circles on the calf should be no more than 5-6 cm apart. The circle on the outside surface of the ankle should be about 6-7 cm above and lateral to the Achilles tendon.

Next, use a small piece of clean, un-used sandpaper to abrade the skin lightly within each of the three circles. The idea is to remove some of the dead skin layer *without irritating or breaking the skin*. Then, place a small dab of electrode cream in the center of each circle. Have the subject use his/her fingertip and fingernail to work the cream gently and carefully into the skin, making sure to keep the cream confined within each circle. This helps to increase electrical conductivity of the skin where each electrode will be located. *It is especially important not to spread electrode cream in the narrow area between the two circles on the calf.*

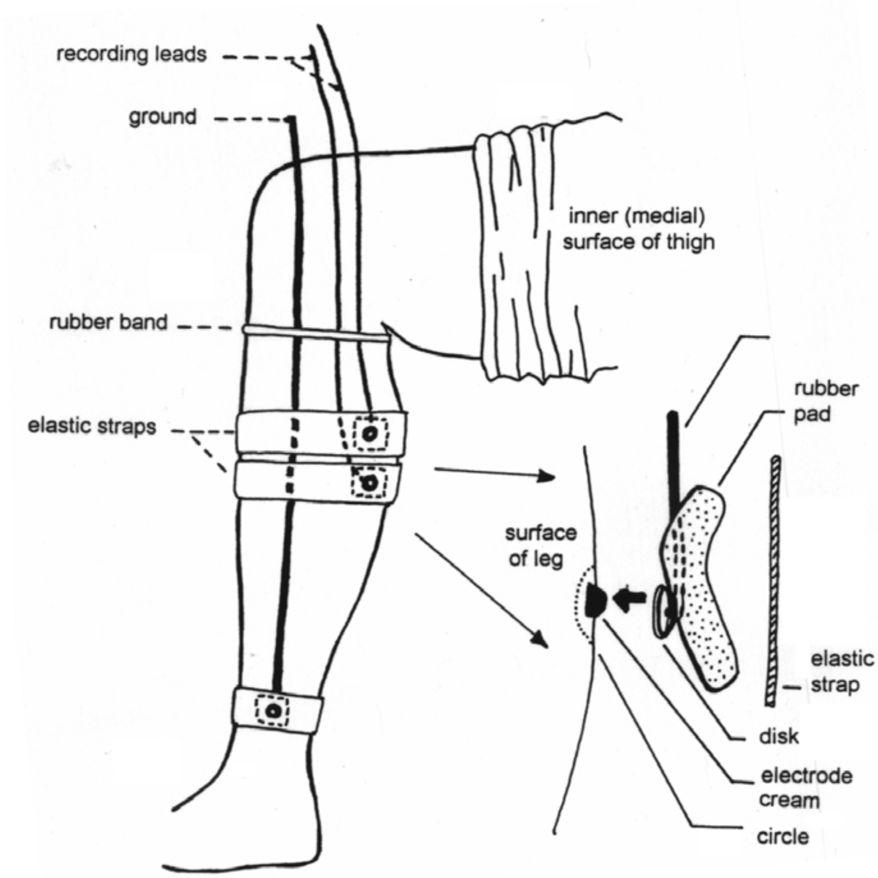

Figure 12.5. Placement of recording and ground electrodes for EMG recording from the human gastrocnemius.

Now, place a pea-sized glob of electrode cream in the center of the circle on the ankle. Place the ground disk electrode in direct contact with the glob of electrode cream on the ankle. [NOTE: The ground electrode is at the end of the longer and thicker cable labeled with green.] Also, make sure the ground cable extends upward, toward the knee (Figure 12.5). Have the subject hold the electrode in place by pressing down on the green mesh that provides backing for the electrode. The mesh helps provide direct pressure that keeps the electrode in close contact with the skin. Next, have a lab partner snugly secure a short Velcro strap around the ankle so that the strap is directly over the green mesh.

Place a pea-sized glob of electrode cream in the center of one circle on the calf. Position one of the two recording electrode disks directly on the glob. Firmly hold the electrode in place by pressing on the red mesh backing behind the electrode. Snugly secure a long Velcro strap around the calf so that the strap is directly over the red mesh. Repeat the procedure for the other recording electrode. When properly positioned, the two straps on the calf should be side by side, one directly above the other, as shown in Figure 12.5. Recheck that positioning of all three electrodes is correct and secure.

Recording voluntary EMG activity

1) For initial observations, the subject should be seated in a comfortable and relaxed position on a wide counter top (not a chair). The subjects lower legs should hang freely.

2) Locate the red, white, and blue banana plugs on the end the cable attached to the amplifier. Insert these three plugs into the corresponding red, white, and blue sockets on the amplifier power supply. Note that the red wire delivers a positive voltage to the amplifier (either +9 or +15 VDC), the blue wire delivers a negative voltage to the amplifier (-9 or -15 VDC), and the white wire provides a connection to ground.

3) Make sure the three-way switch labeled AC/OFF/DC on the front panel of the amplifier is OFF (central position). Locate the red, black, and green banana plugs on the end of the electrode cable assembly that is already attached to the subject. Insert these plugs into the corresponding red, black, and green INPUT sockets on the front panel of the amplifier. Note that the red and black inputs on the amplifier detect the *voltage difference* between the two recording electrodes on the calf. The green input is the ground connection to the ankle.

4) Make sure the ON\OFF power switch on the audio monitor is in the OFF position. Connect an appropriate cable from the amplifier OUTPUT (a BNC-type socket on the right front panel of the amplifier) to the CHANNEL 1 INPUT socket on the audio monitor. Make sure the BNC collar at the amplifier OUTPUT is turned fully clockwise and the audio jack is fully pushed into the socket on the audio monitor.

5) Turn the ON\OFF switch on the amplifier power supply to the ON position. [NOTE: If the power supply unit is battery-powered, there is no ON/OFF switch and power is continuously provided to the amplifier as long as the amplifier power cable is connected to the power supply.]

6) Move the amplifier ON\OFF switch to the ON position and the amplifier GAIN switch to X100. A gain setting of X100 means that the incoming electrical signals from the electrodes on the muscle are amplified by a factor of 100 before reaching the audio monitor. [NOTE: If the audio monitor is battery-powered, then the amplifier GAIN setting should be 1000X.]

7) Turn the audio monitor VOLUME to the lowest setting (0), and move the monitor ON\OFF switch to the ON position. Slowly increase the VOLUME until you hear a low-level “static” or hissing sound on the monitor. If the subject’s leg is fully relaxed, most of the static you hear is “electrical noise” rather than electrical activity from motor units in the gastrocnemius.

8) Now, have the subject make slow and deliberate movements in various directions at the ankle joint. Try movements such as rotation of the foot to one side or the other, or *plantar flexion* (that is, pushing the foot down, as if pressing on a car's accelerator), or plantar extension. Which of these movements involves contraction of the gastrocnemius? During which movement is the audio signal most intense? What does an increase in the audio signal indicate about electrical activity in motor units in the gastrocnemius?

9) Now have the subject stand upright with both feet on the floor and alternately rise up on his/her tiptoes, and then stand on his/her heels. If the audio output is too loud, decrease the VOLUME setting. Repeat these movements and hold each position for a few seconds. During which movement (standing on tip-toes or standing on heels) is the most intense electrical activity heard? Explain how variations in the intensity of the activity relate to the concept of motor unit recruitment? Compare the intensity of audio activity heard when the subject is *rising up* onto tip-toes versus the intensity level when the tip-toe position is *constantly maintained*. Explain differences and relate these to considerations of muscle force and body inertia during movements.

10) Next, try to identify and control activity of a single motor unit. To do this, the subject should again be seated on the counter top with legs fully relaxed. Either let the legs hang down freely or comfortably rest the heel on a low stool or other stable support. Have the subject close his or her eyes, relax, and *make a very slight effort to weakly and constantly contract the gastrocnemius*. Note that contraction of the gastrocnemius tends to move the ball of the foot downward (away from the knee) and bring the heel upward (toward the knee). When doing this, have the volume turned up so that low-level static can be heard. Listen especially for a rhythmic series of crisp popping or ticking sounds of constant intensity. Each tick results from an action potential in a single motor unit. The use of an audio monitor to provide a subject with cues about the level of voluntary muscle excitation is an example of electrophysiological “bio-feedback.”

With practice the subject should be able to use bio-feedback to consciously and precisely increase (or decrease) the frequency of these ticks in accordance with his/her efforts to slightly change the strength of gastrocnemius contraction. After a bit of practice, some subjects (especially those with good muscle control) may be able to produce very precise amounts of single motor unit spiking voluntarily, such as doublets or triplets of firing, or a “counting” sequence of just one, then two, then three spikes, each followed by a pause of electrical silence.

Remember that each tick you hear is the consequence of one action potential occurring in the muscle fibers of a single motor unit in the gastrocnemius. As efforts are made to produce a slightly stronger contraction you should hear more frequent and rhythmic activity in one or several additional motor units that are now recruited into firing. Often the loudness of ticks for recruited units will be greater because the motor units are larger.

In general, the smallest motor units (i.e., fewest muscle fibers per unit) are the first to fire action potentials during weak voluntary movements. As effort increases, progressively larger units are recruited. The orderly recruitment of motor units, in accordance with motor unit size, is called Henneman's Size Principle (Figure 12.3; Tables 12.1 and 12.2).

Involuntary EMG responses to gravitational effects and muscle stretch

In addition to the brain's voluntary control over motor unit activity, there are several important mechanisms by which this activity is involuntarily controlled -- namely, through reflex pathways that involve special sensory neurons in the body. You can easily demonstrate this involuntary, reflex control of motor units in limb muscles in several ways. First, note the spontaneous EMG activity from the gastrocnemius while the subject stands erect. Then, have the subject slowly lean forward, holding a position that just keeps him/her from falling over; then do the same while leaning backwards. You should hear a considerably greater amount of motor unit activity in the gastrocnemius as the subject leans forward. Since the subject cannot willingly prevent this activity from occurring, it is involuntary.

At least two different sensory pathways are involved in triggering this reflex activation of motor units. One source is the equilibrium receptors found in the inner ear. These receptors are stimulated as the body axis changes position relative to gravity. The equilibrium receptors, in turn, stimulate descending interneuronal pathways in the spinal cord that excite motor units to specific leg muscles. The resulting muscle contraction restores the person to an upright position.

A second potential source for reflexive activation of motor units is the *stretch receptors* in the gastrocnemius (Figure 12.4). In each torso and limb muscle, there are numerous specialized endings of sensory nerve fibers, called muscle stretch receptors. These specialized endings are particularly sensitive to a *stretch* stimulus -- remember that muscle stretch involves an *increase* in muscle length caused by some external force on the muscle, such as gravity or load. As the subject leans forward, muscles in the back of the leg, including the gastrocnemius, are stretched (lengthened), thus exciting stretch sensory fibers in these muscles. Such stretching may lead to reflex excitation and contraction of muscles in the back of the leg, thus keeping the subject from falling. [NOTE: It is still not known exactly how influential the stretch reflex is in controlling these gravity-induced adjustments in posture.]

Can the subject consciously prevent the reflex excitation of these muscles from occurring when the subject leans forward? Think of all the muscles in your body that are constantly reflexively contracting while you maintain a standing or sitting posture. Imagine how important these reflexes are to a mountain climber, or anyone else whose life depends on maintaining balance and reacting to sudden changes in footing.

Reflex responses to a tendon tap

Reflex responses of limb muscles are strongly stimulated by abrupt stretching of the muscle. This causes stretch receptor endings in the muscle to depolarize and initiate a series of action potentials that are conducted along the sensory fiber to the spinal cord. In the spinal cord, these sensory fibers directly excite (by way of a mono-synaptic excitatory connection) motor neurons that innervate the same muscle that was stretched. The resulting muscle contraction is thus called a *stretch reflex*. Synonyms for the stretch reflex are the "tendon jerk" or "myotatic" reflex.

Stretch reflexes, induced by an abrupt tap of the tendon, are commonly used by physicians for neurological testing and diagnosis. For example, a rubber mallet may be used to tap on the patellar tendon just below or above the kneecap. The tap causes a brief stretching of the quadriceps (thigh) muscle which, in turn, excites stretch-sensitive nerve fibers in the thigh muscle. The resulting action potentials in these sensory nerve fibers are conducted toward the spinal cord. This activity leads to mono-synaptic excitation of the motor neurons innervating the thigh muscle. Excitation of these motor units causes quadriceps contraction and involuntary straightening of the leg. Failure to respond to the tendon tap may indicate a malfunction in the sensory, motor, or muscle components of the reflex. Such failure could be due to disease or trauma.

Now, test the patellar tendon ("knee jerk") reflex in a subject who is not connected to EMG electrodes. Have that person sit on the edge of a counter with legs hanging down, or on a chair with legs crossed. Tap firmly on the patellar tendon with a percussion hammer and note the response. In some subjects the reflex response will be clear-cut and vigorous. In others only weak responses (or no responses) to strong tapping on the Achilles tendon may be seen. In these subjects, the Achilles tendon may be slack or flaccid so that tapping the tendon causes little or no excitation of muscle stretch receptors. In this case, have the subject fully relax the lower leg as someone else uses a hand to apply a constant upward push on ball of the subject’s foot. This passive movement of the ankle joint should decrease slack in the Achilles tendon and increase stretch sensory and muscle responses to the tendon tap. How effective is tapping at other locations around the knee or on leg muscle itself?

Next, record a subject’s gastrocnemius EMG response to a tendon tap. Which tendon in the subject’s leg is attached distally to the gastrocnemius? With the subject's shoe removed and leg hanging freely, tap the Achilles tendon and listen on the audio monitor for an audible electrical response in the muscle. Is the electrical response accompanied by a visible muscle contraction and leg movement? Describe the movement. Tap on other parts of the leg and foot. Does tapping at these other locations evoke reflex responses in the gastrocnemius? Why or why not?

Is the strength of the reflex response always the same when the tendon is tapped? How does the strength of the electrical response (or contractile response) relate to the strength of the tap on the Achilles tendon? Explain your results in terms of stretch reflex design and function.

Calculation of nerve conduction velocity

A reflexive electrical response in the gastrocnemius does not occur at exactly the same instant that the Achilles tendon is tapped. Rather, there is a brief delay (or *latency*) from the tap until the onset of the muscle electrical response. This latency is easily measured using an instrument such as an oscilloscope. The reflex latency for the human gastrocnemius is about 25-35 milliseconds. Only about 1-2 milliseconds of this latency is attributed to synaptic transmission events at the two chemically transmitting synapses in the reflex pathway (i.e., the sensory-to-motor synapse in the spinal cord and the neuromuscular synapse). Most of the latency is due to the time required for nerve action potentials to conduct along stretch sensory pathways (toward the spinal cord) and back along motor axonal pathways toward the muscle. Normally, short latency times (about 25 msec) are seen in short people and long latencies (about 35 sec) are seen in tall people. Explain why.

If we know the total distance of the reflex pathway and assume that the average reflex time is 30 milliseconds (or 0.030 second), we can calculate an *average conduction velocity* for the stretch sensory fibers and motor axons in the leg nerve. The equation is:

(Equation 1)

$$\text{conduction velocity} = \frac{\text{total length of reflex pathway}}{\text{reflex time}} \qquad \frac{\text{(in meters)}}{\text{(in seconds)}}$$

To determine the total length of the pathway, first measure the distance (in meters) from one point, just between the two recording electrodes, to a second point in the middle of the back, about belt high. This distance should then be doubled to obtain the numerator. Why does the distance need to be doubled?

Next, divide the total length of the pathway (expressed in meters) by the reflex time (expressed in seconds). This should give you a velocity expressed in meters per second, the standard units used to express nerve conduction velocity. What is the velocity in miles per hour?

Displaying EMG activity on a digital oscilloscope (OPTIONAL)

Refer to the list of additional materials in Appendix A. Make cable connections and follow procedures described in Appendix A.

Measuring reflex time and conduction velocity (OPTIONAL)

Refer to the list of additional materials in Appendix A. Make cable connections and follow procedures described in Appendix B.

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Appendix A. DISPLAYING EMG ACTIVITY ON A DIGITAL OSCILLOSCOPE

Additional materials;

- Tektronix TDS 210 digital storage oscilloscope
- BNC-to-BNC cable with built-in filter
- BNC T-connector
- Percussion hammer with trigger device (e.g., hammer fitted with an inertia switch or piezoelectric disc that generates trigger signal for oscilloscope sweep)
- Hard copy device (e.g., printer or oscilloscope camera) [OPTIONAL]

1. To obtain simultaneous audio and oscilloscope monitoring of EMG signals, make cable connections as shown in **Figure 6** below. Then, use **Figure 7** to identify the oscilloscope controls which will be referred to in subsequent steps.

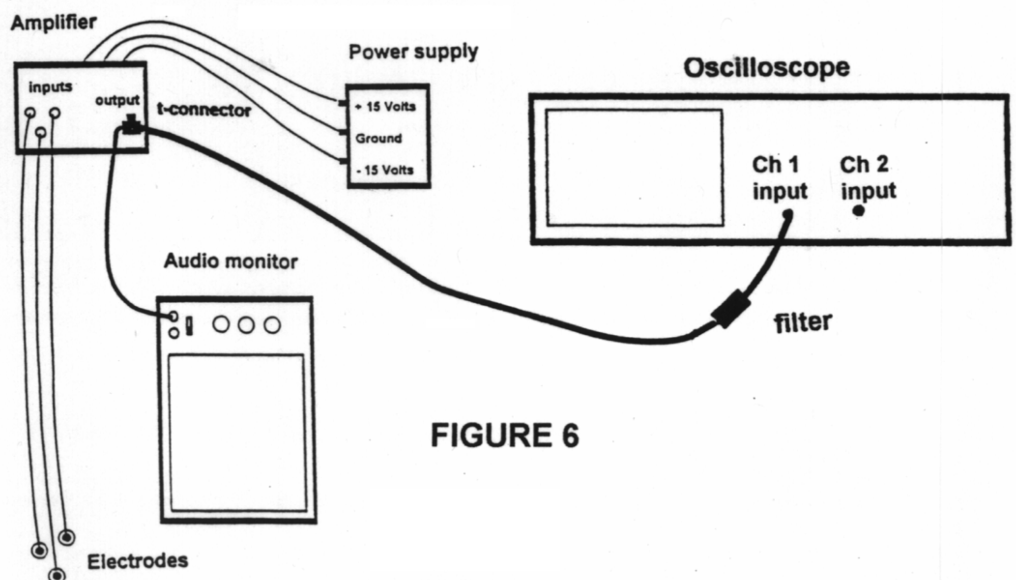


FIGURE 6

FIGURE 7

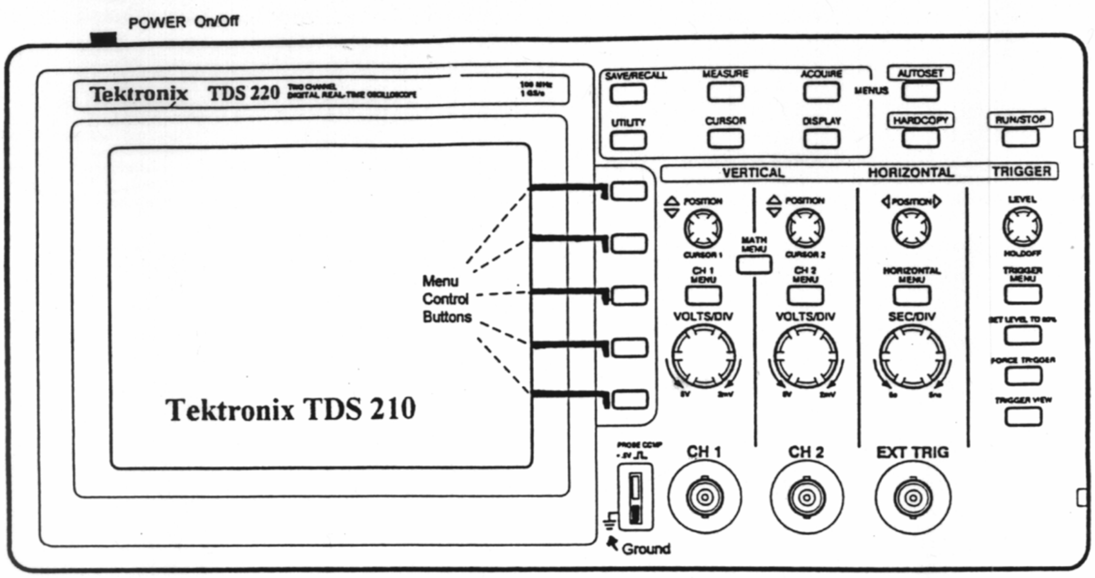
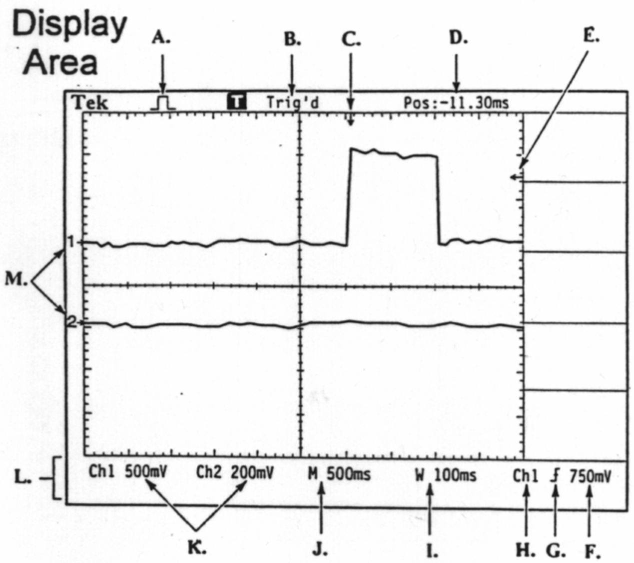


FIGURE 8



A. Icon display shows acquisition mode.

- Sample mode
- Peak detect mode·
- Average mode

B. Trigger status shows if there is an adequate trigger source or if the acquisition is stopped.

C. Marker shows horizontal trigger position. This also indicates the horizontal position since the Horizontal Position control actually moves the trigger position horizontally.

D. Trigger position display shows the difference (in time) between the center graticule and the trigger position. Center screen equals zero.

E. Marker shows trigger level.

F. Readout shows numeric value of the trigger level.

G. Icon shows selected trigger slope for edge triggering.

H. Readout shows trigger source used for triggering.

I. Readout shows window zone timebase setting.

J. Readout shows main timebase setting.

K. Readout shows channels 1 and 2 vertical scale factors.

L. Display area shows on-line messages momentarily.

M. On-screen markers show the ground reference points of the displayed waveforms. No marker indicates the channel is not displayed.

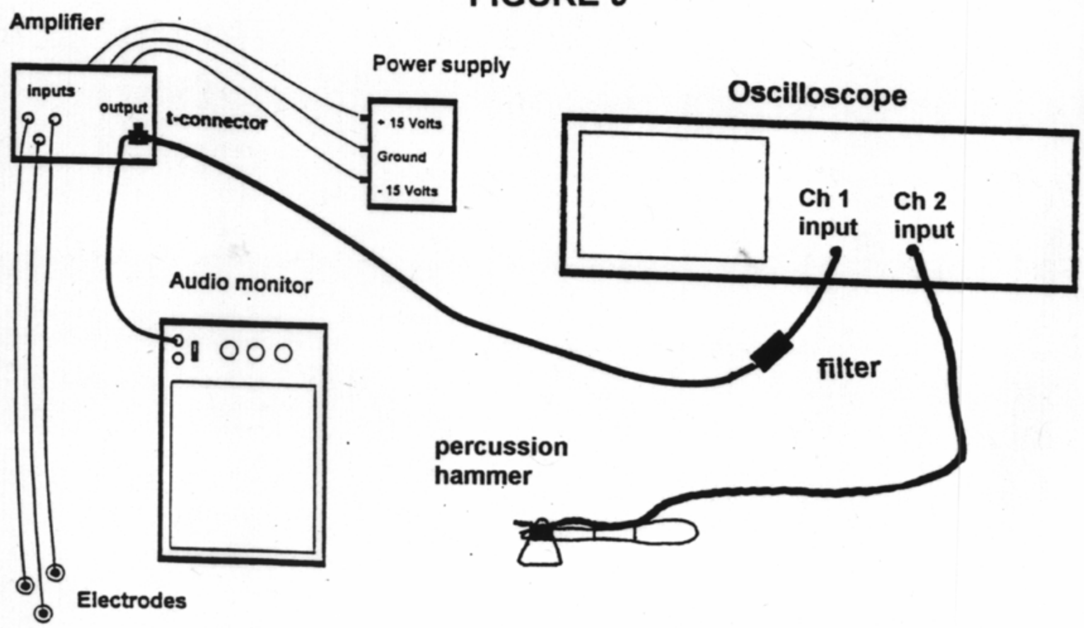
2. Push the **POWER ON/OFF** button to turn on the oscilloscope. Press **SAVE/RECALL**. Then make sure the number "1" is highlighted in the Menu at the right of the screen. Next, press the "Recall" button (lowest button of the five Menu Control Buttons).
3. Press the **TRIGGER/MENU** button.
4. Set the vertical sensitivity (**VOLTS/DIV**) for Channel 1 to 10 mV/div. Note that the digital readout for this setting is displayed near the bottom-left of the screen, as shown in the Display Area of **Figure 8** and denoted by the arrow labeled "K."
5. Set the sweep speed (**SEC/DIV**) knob to 250 msec/div. The digital readout for this setting is displayed near the bottom-middle of the screen, as shown in the Display Area and denoted by "I" (**Figure 8**)
6. Press the **TRIGGER/MENU** button again.
7. Find the **MODE** button from among the five Menu Control Buttons just to the right of the menu display at the right of the oscilloscope screen. Press the **MODE** button until the "Auto" message appears in the menu column at the right on the screen. You should now see the oscilloscope trace sweeping automatically across the screen.
8. Next, press the **CH2/MENU** button repeatedly until the trace for channel 2 disappears.
9. Confirm that you are looking only at the trace for Channel 1 by turning the **POSITION** control just above the **CH1/MENU** button. Adjust the position of the trace so that it is in the middle of the screen.
10. Now have the subject make slight attempts to contract the gastrocnemius. When this is done, bursts of electrical activity should be visible on the oscilloscope as spike-like vertical deflections of the moving trace. These should coincide precisely with the audio signal you hear. Note that each time the sweep moves across the screen the "old" display is erased and replaced updated by an updated, current display.
11. Press the **RUN/STOP** button. This is used to capture events which occurred during the last sweep. The "on-off" status of the trigger is indicated by the message "Ready" or "Scan" at the top of the screen (refer to arrow "B" in Display Area of **Figure 8**.
12. Have the subject try to initiate rhythmic firing of one or several motor units by very slightly and gradually contracting the muscle. Then, quickly press the **RUN/STOP** button to capture this sweep. Note differences in amplitude of various motor unit spikes as each unit is recruited. Try to demonstrate the Size Principle during motor unit recruitment.

13. Have the subject generate a series of rhythmic spiking from a single motor unit. While spikes are firing, press the **ON/OFF** button to capture the sweep. Then, press the **CURSOR** button to activate cursors which are used to measure timing differences of electrical events. Note that the Cursor menu is now visible on the right of the screen and that the two **POSITION** control knobs (also labeled CURSOR 1 and CURSOR 2) can now be used to change the position of the two vertical cursor lines on the oscilloscope screen. Note that the time difference between the two cursor positions is displayed in the window labeled "Delta" at the right of the screen.
14. Use the cursors to measure the peak-to-peak time difference (in msec between two successive of the same motor unit -- this time is also referred to as the *interspike interval*. The reciprocal of interspike interval is spike frequency, a value that is calculated by dividing interspike interval (in msec) into 1000 (the number of msec in 1 sec). The frequency value (expressed in spikes/sec or Hz) is also displayed just below the "Delta" value. Obtain several other samples of single unit firing and measure interspike intervals and frequencies. Note how interspike intervals change in a series of spikes as a new unit is recruited. Give the range of high and low frequencies for each identifiable motor unit.
15. Change the **SEC/DIV** setting to 10 msec/div. Press **RUN/STOP** to obtain automatic sweeping. While a motor unit is repeatedly firing at low frequency, press the **RUN/STOP** button to capture a single sweep. Capture one motor unit spike while recording at this fast sweep speed. Use cursors to measure the spike duration from the spike. Repeat these measurements several times for different spikes and calculate a mean..

Appendix B. MEASURING REFLEX TIME NERVE AND CONDUCTION VELOCITY

1. Make connections between the oscilloscope, percussion hammer/trigger assembly, as shown in **Figure 9**.

FIGURE 9



2. Set the oscilloscope sweep speed (**SEC/DIV**) to 10 msec/div. Press **CH2/MENU** button until a second trace for Channel 2 is seen on the oscilloscope screen. Adjust Ch2 **POSITION**, if needed.
3. Adjust the **VOLTS/DIV** knob for *both* Ch1 and Ch2 to 20 mV/div.
4. Press the **TRIGGER/MENU** button and then the "Source" button (middle button on the Menu Control) to select "CH2" as the Trigger Source, as displayed in the middle menu window. By doing this, the oscilloscope sweep will now be triggered when a sufficiently large electrical event occurs on the Channel 2 input.
5. Use the **TRIGGER/LEVEL** to adjust the trigger level knob (indicated by the arrow at the right edge of the screen) about 10 mV (= 1/2 div) below the Ch2 baseline. [Note: the readout for the trigger level is shown in window "F" of the Display Area.
6. Next, find the **HORIZONTAL/POSITION** and note that adjustment of this control changes the trigger position, as indicated by the arrow at the top of the screen (see "D" in **Figure 8**). Adjust the trigger position arrow so that it is about 30 msec (3 divisions) from the left edge of the screen.
7. Press **TRIGGER/MENU**. Then use Menu Control Buttons to set Mode to "Normal" and Slope to "Falling."
8. Press **RUN/STOP** until the "Ready" message appears.
9. Now tap the hammer on the table top. The oscilloscope sweep should be triggered with each tap. There should also be a large electrical signal (trigger signal) displayed on Ch2. Onset of this signal should coincide closely in time with the trigger position arrow. [NOTE: The trigger signal is actually electrical noise generated when the inertia switch opens as a result of tapping.]
10. Then, with the subject seated comfortably on the edge of the counter/tabletop, tap on the Achilles tendon with the percussion hammer. Look for a wave of electromyographic activity that occurs on Ch1 after the trigger event. Repeatedly tap the tendon. You

should see that the wave of activity varies somewhat in size -- it should be larger when the tendon tap is stronger) but the time interval between the trigger signal on Channel 2 and the electrical wave on Channel 1 should be relatively constant. This interval is the reflex latency.

This reflex latency represents the reflex time for the tendon tap reflex (or stretch reflex). During this time the following events must occur:

a) stretch-sensitive sensory nerve fibers in the gastrocnemius are stimulated by the stretch and produce nerve action potentials;

b) the action potentials in these sensory nerve fibers are conducted to the spinal cord where they make direct synaptic connection with motor neurons innervating the gastrocnemius muscle;

c) synaptic transmission occurs between these sensory and motor neurons in the spinal cord;

d) motor neurons produce action potentials that are conducted along the motor axon to axon terminals located within the muscle;

e) synaptic transmission occurs at the neuromuscular synapse;

f) a muscle action potential is produced in each skeletal muscle fiber innervated by the axon. [Note: each muscle action potential occurs just before each motor axon action potential].

11. Press the **CURSOR** button and use the cursor **POSITION** controls to measure the reflex time. Make repeated measures of the reflex time. Obtain a mean and calculate conduction velocity as described on p. 7 of "ELECTROMYOGRAPHY" manual.

12. Calculate average nerve conduction velocity previously done using Equation 1.