

Investigation of physiological properties of nerves and muscles using electromyography

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Roe SM, Johnson CD, Tansey EA. Investigation of physiological properties of nerves and muscles using electromyography. *Adv Physiol Educ* 38: 348–354, 2014; doi:10.1152/advan.00018.2014.— The measurement and representation of the electrical activity of muscles [electromyography (EMG)] have a long history from the Victorian Era until today. Currently, EMG has uses both as a research tool, in noninvasively recording muscle activation, and clinically in the diagnosis and assessment of nerve and muscle disease and injury as well as in assessing the recovery of neuromuscular function after nerve damage. In the present report, we describe the use of a basic EMG setup in our teaching laboratories to demonstrate some of these current applications. Our practical also illustrates some fundamental physiological and structural properties of nerves and muscles. Learning activities include 1) displaying the recruitment of muscle fibers with increasing force development; 2) the measurement of conduction velocity of motor nerves; 3) the assessment of reflex delay and demonstration of Jendrassik's maneuver; and 4) a Hoffman reflex experiment that illustrates the composition of mixed nerves and the differential excitability thresholds of fibers within the same nerve, thus aiding an understanding of the reflex nature of muscle control. We can set up the classes at various levels of inquiry depending on the needs/professional requirements of the class. The results can then provide an ideal platform for a discovery learning session/tutorial on how the central nervous system controls muscles, giving insights on how supraspinal control interacts with reflexes to give smooth, precise muscular activation.

neuromuscular control; nerve properties; reflexes

IN THIS PRACTICAL, students use a basic electromyography (EMG) setup, with surface stimulating and recording electrodes to illustrate some basic properties of muscles and nerves. They record electrical activity from a muscle [the abductor digiti minimi (ADM)] that is contracting voluntarily and contrast this with that from the same muscle when it is passively moved, showing the electrical nature of muscle activation (*experiment i*). *Experiment ii* then involves the measurement of conduction velocity of motor nerves by recording the time taken between nerve stimulation and contraction of the muscle (ADM) whose activity was recorded in *experiment i*. This is simple to do because the ulnar nerve supplying the ADM passes close to the skin surface at several points from the elbow to wrist and so is easy to stimulate (11). Reflex delay of the ankle jerk stretch reflex may then be measured in *experiment iii*, using the same recording setup attached to the gastrocnemius muscle. Finally, in *experiment iv* for the more advanced classes, the medial popliteal nerve to the gastrocnemius muscle may be stimulated, eliciting two re-

sponses: a short-latency motor nerve response (M response), elicited by direct stimulation of motor nerves, and longer-latency Hoffman reflex muscle activation [Hoffman (H) response], resulting from the stimulation of sensory nerve fibers from stretch receptors within the muscle (11). This last activity is particularly useful as a starting point for a discovery learning session on the functional anatomy of mixed nerves, on the differential excitability of nerve fibers, and on the concepts of synaptic transmission, anterograde conduction, and refractory period.

Background

EMG, the recording of electrical potential from muscles, is a simple experiment to perform in the teaching laboratory, requiring simple surface electrodes and amplification and display equipment, most of which is readily commercially available. Although clinically, for greater precision, implanted electrodes are used (1, 3, 11, 12), for the purposes of the classroom, simple bipolar plate electrodes are sufficient for the recording of simple muscle summated action potentials (2, 6, 13), as has been performed in our institution for teaching purposes (8, 9). EMG has many uses in both research and clinical areas, and this classroom activity replicates many of these. As an added benefit, many of the fundamental principles of motor control are illustrated by simple procedures centered on an EMG setup. The experiments described here expand on the work of Lennartz (13), in whose practical classes students studied the nature of EMG, described the associations between electrical and mechanical activity in muscles, measured reaction times, and investigated the concepts of flexion and extension. In addition to some similar activities, our experiments also involve the use of computer recording and reproduction of data, calculation of nerve conduction velocities, and demonstrations of the Jendrassik phenomena and the properties of mixed nerves.

The class may start with a delineation of the history and progression of ideas surrounding EMG, a particularly useful exercise for students of the basic sciences. These students may also benefit from a description of the myriad research uses for the EMG setup. Of more use to medical students may be the value of EMG to the clinician in diagnosing diseases of the nerve and muscle. For both science and clinical students, an EMG practical may be set up to illustrate some of the fundamental anatomic and physiological properties of mixed nerves.

EMG can be used in this class to highlight to students the progression of ideas on a physiological phenomenon and the incremental nature of the advancement of concepts. With EMG and motor control, there has been speculation since ancient times with texts from, for example, Arateus of Cappadocia contemplating the nature of the motive force. From the 16th century, investigators working in northern Italy (Redi and Mateucci) proposed that this motive force

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was similar in nature to the electrical force that had been characterized by Alessandro Volta and Luigi Galvani working nearby (14). This was confirmed with the advent of modern measurement equipment by researchers such as Erlanger and Gasser, who measured and displayed electrical activation of muscles and were able to characterize the components of mixed nerves using the techniques developed (4). A seminal work in EMG was published in 1910 by Hoffmann; an elicited muscle response named for him will be investigated and displayed in this practical activity (5).

Currently, EMG is used in both research and clinical settings. Where the timing and relative magnitude of muscle activity needs to be measured noninvasively in humans, EMG is often used. Examples of this use are in biomechanics and gait analysis (7, 10, 16) and in sleep studies (15, 18), where the magnitude of muscle activation and latencies are important. In the activity described below, this property of EMG is illustrated by contrasting EMG traces from muscles that are actively contracting with the same muscles when passively moved. Also in the clinical setting, EMG can be used to assess the progress of diseases that compromise nerve conduction (such as the demyelinating neuropathies), as it can be used as a tool to measure nerve conduction velocity (11). The basis of deficits in muscle function can also be differentiated with EMG. Where the deficit is due to a lesion in the upper motor neuron, signs in an EMG trace evidencing this are large-amplitude deflections or "giant potentials" (17). These are due to collaterals to the muscles originally supplied by the damaged upper motor neurons travelling from the remaining intact motor neurons. This means that each upper motor neuron will potentially control more motor units (so-called "giant" units). Other signs of upper motor neuron lesion are fasciculations and fibrillations, easily discernible on an EMG trace (3, 12, 17). With lower motor neuron lesions, the EMG amplitude is normally reduced, as a reduced number of motor units are activated by the damaged nerve (although there may also be giant potentials present with lower motor neuron lesions) (3, 12, 17). While this precise differential diagnosis can only be performed with intramuscular EMG, it is useful for students to appreciate the myriad applications of the technique, and we can still determine conduction velocities with our simple plate electrode apparatus.

EMG analysis of the stretch reflex can yield valuable lessons on the fundamental properties of motor control. The stretch reflex is an example of a classic reflex arc. The muscle spindle generates afferent sensory information on muscle length, which travels in a sensory fibre (the 1a fiber) to the spinal cord, where it synapses directly with the A α motor fiber supplying the muscle. In this situation, the muscle contracts against its own stretch. Two experiments in this activity (*experiments iii* and *iv*) investigate this. We investigate reflex delay in *experiment iii* by activating the ankle jerk reflex using a hammer that initiates recording when it strikes the Achilles tendon. The nerves involved in the reflex may also be directly electrically stimulated at the medial popliteal nerve. Stimulating the medial popliteal nerve electrically in *experiment iv* gives rise, at low stimulation voltages, to activation of motor units via 1a sensory fibers from muscle spindles. This muscle activation (the H response) has a similar latency to the stretch reflex and is easier to elicit because 1a fibers have a larger diameter in mixed nerves and are therefore more readily stimuable. At higher

stimulation voltages, direct activation of A α nerve fibers results in more of the motor units being activated directly (the M response, latency < 10 ms). As stimulation voltage is increased, an interesting situation occurs, where stimulation of one mixed nerve in one place gives rise to two separate muscle contractions visible on the EMG trace. The first is a short-latency response due to direct stimulation of A α fibers, with any remaining motor units not stimulated thus giving the longer-latency reflex response mediated by stimulation of 1a sensory fibers. At higher stimulation voltages, all of the motor units are stimulated directly with no H responses evident, due to the motor nerve fibers being refractory after their initial activation (11).

Learning Objectives

After completing this activity, the student will be able to the following:

1. Record and display electrical activity in a human muscle
 2. Show that force developed in a muscle is roughly proportional to EMG amplitude and suggest research and clinical uses for this phenomenon (*experiment i*)
 3. Calculate conduction velocity in the ulnar nerve and apply this knowledge to describe how EMG may be used to assess the progress of some common neuropathies (*experiment ii*)
 4. Measure reflex delay in the stretch reflex and calculate the approximate conduction velocity of the nerves involved (*experiment iii*)
 5. Elicit two responses from the gastrocnemius muscle by stimulating the medial popliteal nerve at different stimulation voltages (*experiment iv*)
 6. Understand why one stimulus pulse to the nerve supplying it can cause two separate contractions in the gastrocnemius muscle
 7. Explain how nerve refractory period results in the long-latency H response dying away at higher stimulation voltages
 8. Describe the concept of differential stimulation thresholds within mixed nerves
 9. Apply this knowledge of differential stimulation thresholds to aid an understanding of how muscle force and timing is controlled by activation of motor units
- Learning objectives 6–9* may be further explored in a discovery learning/tutorial class arising out of the results from the practical activities in *experiment iv*.

Activity Level

This activity is suitable for any students interested in human motor control and basic neurophysiological principles. It can be adapted to suit science students who may be more process oriented and need to see basic principles illustrated. The Hoffman reflex exercise is ideal for this as it shows basic neurophysiological principles of nerves and illustrates the anatomy of a mixed nerve, which is composed of sensory and motor fibers with different activation thresholds. Indeed, subsequent inquiry-based learning sessions on many basic neurophysiological principles (recruitment, different excitation thresholds, compound action potentials, refractory period, composition of mixed nerves, and reflex control of muscle force) may use the results from the Hoffman reflex as their basis. For medical students, the clinical applications of EMG can be emphasised, with calculations of conduction velocity described in the con-

text of their diagnostic value. We currently run this class for second-year medical and first-year biomedical science/human biology students.

Prerequisite Student Knowledge or Skills

Before doing this activity, students should have a basic understanding of the following:

1. Physiological properties of nerves and muscles (action potentials, activation threshold, and muscle stretch reflex)
2. Neuroanatomy (structure of the reflex arc and composition of mixed nerves)

Before doing this activity, students should know how to do the following:

1. Use computer and software for data recording
2. Locate the ulnar and medial popliteal nerves where they travel close to the skin surface
3. Locate the ADM and gastrocnemius muscles

Time Required

This practical activity can be conducted many ways. We suggest a 30-min introductory talk followed by a 60- to 90-min period of time during which data may be gathered. Suggested times are included below in the *Instructions*. Depending on time available, this can be followed by a separate discovery learning session, which may aid in the applications of the results to basic neurophysiological and anatomic phenomena. This is particularly appropriate for the demonstration of the Hoffman reflex.

METHODS

Equipment and Supplies

The following equipment and supplies are needed per group of four to six students:

1. A small bipolar plate surface electrode (consisting of a pair of 8-mm plates separated by 7 mm, linked to a reference plate) and a large-plate earth electrode.
2. An amplifier and means of displaying the amplified signal from the electrode. This is most conveniently one of the commercially available computer-based analog-to-digital converter and display systems (e.g. LabTutor, AD Instruments, Dunedin). Currently we use equipment and software that has been manufactured on site and adapted for display on personal computers. Our own hardware is an alternating current-coupled isolated amplifier that uses a custom-built integrated circuit (constituents available through RS Components, Corby, UK), which measures and amplifies the voltage drop between its inputs. In house-designed software enables the control of sampling time (0.002–0.5 s) and amplification ($\times 100$ –50,000). Alternatively, an EMG amplifier may be cheaply constructed from commercially available electronic integrated circuits and displayed on a soundcard-equipped laptop, following instructions presented by Bhaskar et al. (2).
3. A stimulating electrode in the form of a prong, with a stimulus generator. This is also commercially available from many sources. Again, our equipment and software have been manufactured and written on site and adapted for display on commercially available personal computers. Our stimulating electrodes have a negative (black) and positive (red) prong terminating in 6-mm-diameter cotton pads soaked in saline and separated by 30 mm. They are linked to an isolated stimulator with a software controlled 0- to 100-V range and 0.1-ms pulse width (8, 9).
4. To conduct reflex delay experiments, a tendon hammer may be constructed that contains a contact that closes on impact, starting recording. Ours is composed of a 200-mm outer metal tube with an

internal wire, which completes a circuit when struck. Alternatively, the simple adaptation of a commercially available patellar tendon hammer for this purpose has been previously described by Lennartz (13).

Human or Animal Subjects

The proposed activities are for human subjects. Because they use surface electrodes and are therefore noninvasive, they do not require ethical approval at our institution. Adopters of this activity are responsible for obtaining permission for human research from their home institution. For a summary of the Guiding Principles for Research Involving Animals and Human Beings, please see www.the-aps.org/mm/Publications/Ethical-Policies/Animal-and-Human-Research.

Instructions

There are a number of suggested experiments that can be carried out. Those described below are performed with first- and second-year biomedical science and medical students. A diagrammatic representation of the equipment setup for each of the experiments is shown in Fig. 1.

Experiment i: demonstration of the link between mechanical activity and electrical recording from muscle (~20-min activity time). A small bipolar plate electrode is secured using a rubber strap to the skin above the ADM on the hypothenar eminence and connected to the recording apparatus. An earth electrode is also attached to the skin close by on the surface of the hand. Electrical contact is enhanced using electrode gel (with care taken not to allow the two plates of the bipolar electrode to come into electrical contact). The subject is then asked to maximally activate the muscle by abducting the fingers against a resistance (ideally the other hand holding the fingers closed). The trace recorded when actively abducting the fingers is contrasted with that obtained while the fingers are moved passively by the other hand.

Experiment ii: calculation of conduction velocity of the ulnar nerve (20-min activity time). In this experiment, the ulnar nerve is stimulated at two points using the stimulating electrode prongs. Measurement electrodes are situated similarly to *experiment i*. The stimulating electrodes should be positioned with the negative pole of the prong closest to the muscle being stimulated. The initial site of stimulation is where the ulnar nerve passes the medial epicondyle of the humerus at the elbow. This large nerve can be palpated in the groove formed between the medial epicondyle of the humerus and the ulnar head (11). Stimulation voltage should be increased until there is a visible contraction of the ADM. Our typical stimulus is an electrical pulse of 0.1 ms wide and between 40 and 100 V. The latency between stimulation at the elbow and ADM activation can then be measured. The stimulating prongs are then positioned to stimulate the ulnar nerve at the wrist, medial to the flexor carpi ulnaris just before the nerve enters Guyon's canal. The nerve is deeper here and so is likely to require a greater stimulation voltage. Latency between stimulation at the wrist and ADM activation is recorded. Using the distance between the two sites of stimulation and the time difference for muscular activation between stimulating at the elbow and stimulating at the wrist, conduction velocity in a main motor nerve can be calculated by dividing time taken by distance travelled (3, 11, 12).

Experiment iii: measurement of latency of activation of the ankle jerk reflex and demonstration of the Jendrassik effect (20-min activity time). To record the ankle jerk reflex latency, the bipolar recording electrode is positioned at the gastrocnemius heads. For this experiment, recording is started when a specially adapted tendon hammer strikes the Achilles tendon, closing a switch inside the hammer itself. Latency of the reflex is recorded as the time between the hammer strike initiating the recording and the EMG trace of gastrocnemius activity. This is reflex delay. A rudimentary calculation of the conduction velocity of the nerves involved in the reflex may also be made by doubling the distance between the small of the back and middle of the gastrocnemius muscle and using a similar calculation to that in

ELECTROMYOGRAPHY

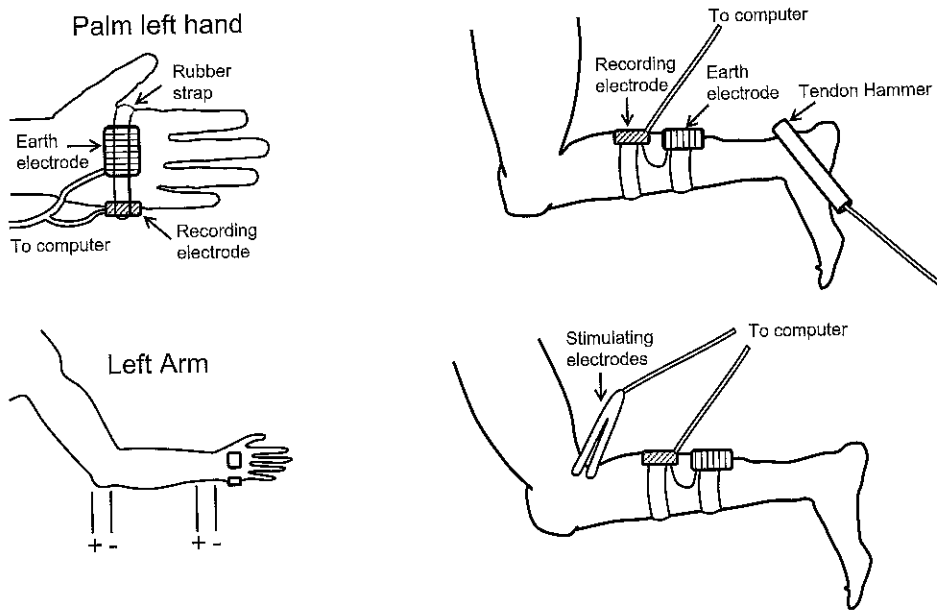


Fig. 1. Diagrammatic representation of the setup for *experiments i and ii* (left) and for *experiments iii and iv* (right). The position of recording electrodes for *experiment ii* is similar to that for *experiment i*, and the position of recording electrodes for *experiment iv* is similar to that for *experiment iii* (see text for details).

experiment ii to ascertain conduction velocity. The effect of the Jendrassik maneuver (in which the subject clenches the teeth and/or flexes the fingers from both hands, interlocks the fingers from one hand with those from the other, and pulls hard just as the reflex is elicited) on the latency, amplitude, and shape of the reflex may also be investigated.

Experiment iv: demonstration of the Hoffman reflex and investigation of the anatomic and physiological properties of mixed nerves (30-min activity time, allowing time for discussion). These results can potentially form the basis of future tutorial classes on motor control. For a demonstration of the H response, the recording electrodes remain in the same position as for *experiment iii*. In this case, however, the gastrocnemius muscle is electrically stimulated at the tibial nerve where it runs in the popliteal fossa. This nerve is large enough to be palpated here in lean individuals approximately midway between the tendons of the biceps femoris and semitendinosus. Stimulation voltage is increased gradually until two separate electrical responses are observed in the gastrocnemius muscle. One of these is a short-latency response that occurs <10 ms after activation of the muscle, with the other one, termed the H response, occurring with much longer latency (~ 30 ms) (11). It may be useful to note the stimulation voltage at which the student gets each response and then at which voltage at which both responses appear simultaneously.

Troubleshooting

The main difficulty surrounding these sets of activities is ascertaining where to place the stimulating and recording electrodes. Students require close instruction in this. We advise them to maximally activate the muscle from which they are recording and place the electrode where the muscle is most evidently bulging. Recording EMG from the maximally activated muscle with the electrode thus placed should confirm the correct location of the recording electrode. Placement of stimulating electrodes also presents challenges. We tell students to palpate the nerve they hope to stimulate at the elbow and in the popliteal fossa, (although this is not possible with stimulation of the ulnar nerve at the wrist as it travels quite deep here). Once they can feel the nerve, it's easier to decide where best to position the stimulating prongs.

Difficulties in recording can be due to a number of reasons beside the incorrect positioning alluded to above. If the two plates on the bipolar plate electrodes are in electrical contact, they will "short circuit" and not record a signal. Inadequately earthing the subject results in a large 50-Hz signal obscuring the trace, so good contact

between the earth and subject must be established before the experiment (see Fig. 2).

Safety Considerations

Individuals using cardiac pacemakers should not participate as subjects in the experiments. Students acting as volunteers should also be assured that there is a sensation associated with electrical stimulation of nerves but that, at the voltages and stimulus widths used, pain fibers are not activated.

RESULTS AND DISCUSSION

Expected Results

Demonstration of the link between mechanical activity and electrical recording from muscle. A trace from our laboratory of electrical activity recorded from voluntarily activated mus-

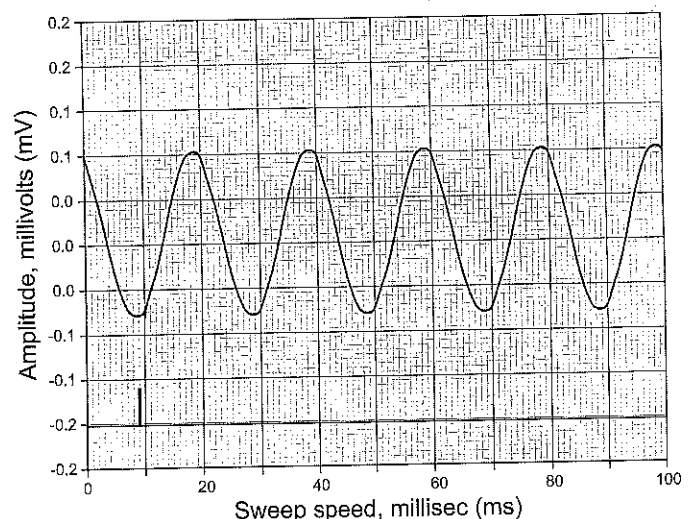


Fig. 2. Large 50-Hz signal recorded using electromyography (EMG) electrodes from an inadequately earthed subject. Any EMG thus recorded will be obscured by the noise, necessitating adequate earthing of subject before making any recordings.

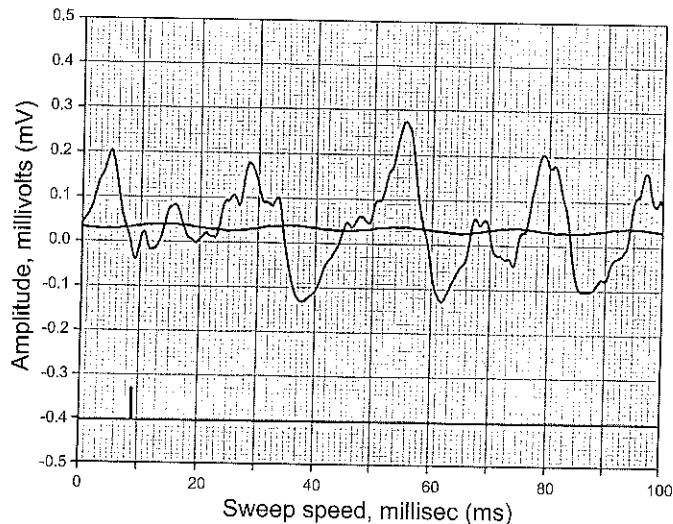


Fig. 3. Electrical activity recorded from a voluntarily activated abductor digiti minimi muscle (large amplitude oscillations) overlaid over one from the same muscle being passively moved (smooth trace).

cle overlaying one from the same muscle being passively moved is shown in Fig. 3. The asynchronous activity of many motor units of the ADM muscle is apparent as an erratic waveform with large amplitude deflections. This contrasts with the relatively smooth waveform from the muscle when it is passively moved by the other hand.

Calculation of conduction velocity of the ulnar nerve. Figure 4 shows a trace from the ADM muscle activated by stimulus electrodes positioned at the elbow overlaying one from the same muscle activated by stimulating electrodes positioned at the wrist. In this example, if we calculate conduction velocity as distance/time, using the distance between the two points of stimulation (300 mm in this case) and the time difference for muscular activation between stimulation at the elbow and stimulation at the wrist (5 ms in this case), a conduction velocity of 60 m/s can be calculated.

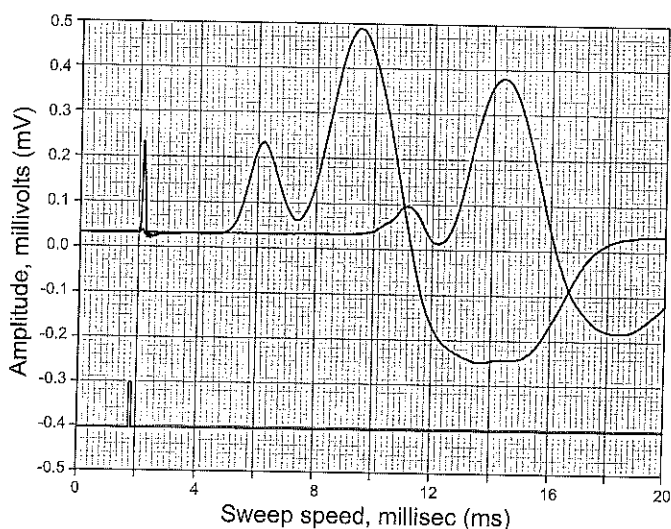


Fig. 4. Electrical activity recorded from abductor digiti minimi muscle activated by stimulating the ulnar nerve at the wrist (short-latency response) and at the elbow (long-latency response) using a bipolar prong electrode.

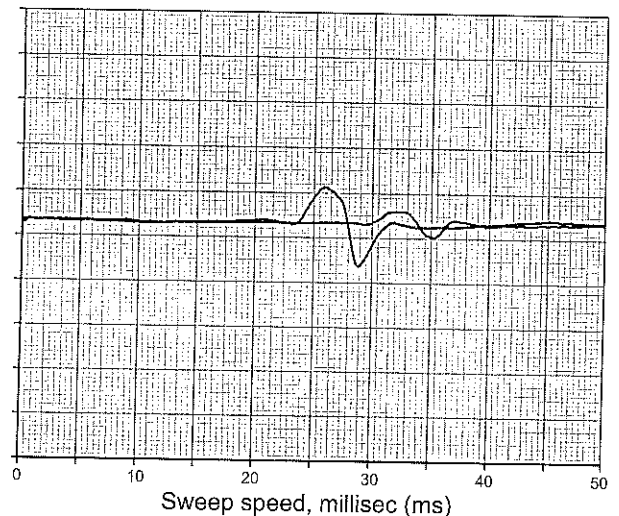


Fig. 5. Electrical activity recorded from gastrocnemius muscle activated by triggering the ankle jerk reflex (striking the Achilles tendon with a hammer coupled to an electrical switch), which initiates recording. The larger-amplitude trace is from an ankle jerk elicited while the subject performed Jendrassik's maneuver.

Measurement of latency of activation of the ankle jerk reflex and demonstration of the Jendrassik effect. A trace from this experiment is shown at Fig. 5. The reflex activation of the gastrocnemius muscle on striking the Achilles tendon has a latency of 30 ms. Also shown is a trace from the same reflex elicited while the subject performed the Jendrassik maneuver. It has a greater amplitude but similar latency and shape as the basic Achilles tendon reflex.

Demonstration of the Hoffman reflex and investigation of the anatomic and physiological properties of mixed nerves. Experimental traces for electrical activation of the gastrocnemius muscle by stimulating the tibial nerve in the popliteal fossa are shown in Fig. 6. At low stimulation voltages, a long-latency muscle response (with similar latency to the stretch reflex) is

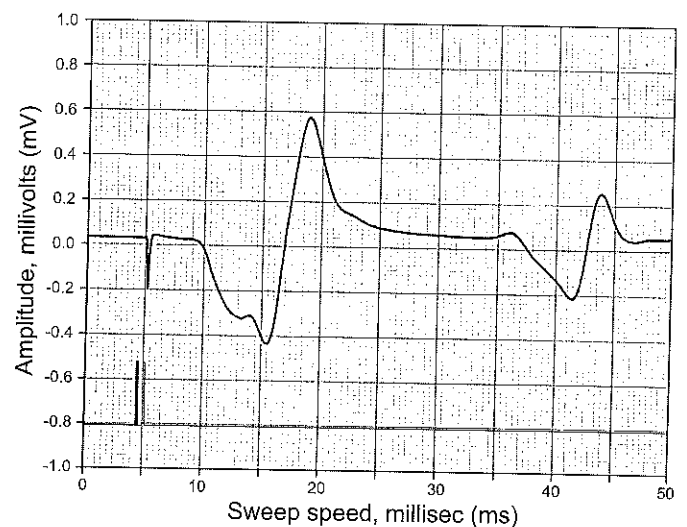


Fig. 6. Electrical activity recorded from the gastrocnemius muscle activated by stimulating the tibial nerve in the popliteal fossa using a bipolar prong electrode. The long-latency response is due to activation of Ia sensory fibers in the nerve and is termed the Hoffman (H) response, whereas the shorter-latency response results from directly activating the motor nerve (M response).

evident (the H response). This is due to activation of Ia fibers that innervate gastrocnemius muscle spindles. As stimulation voltage increases, the H response becomes smaller, and a shorter-latency response caused by directly activating the motor nerve appears (the M response). These responses are shown in Fig. 6. As voltage increases further and this M response gets larger, the H response disappears (11).

Misconceptions

Students may have some confusion regarding the difference between the erratic waveforms observed on activation of the muscle in *experiment i* and those they see from intracellular recordings in textbooks. This may be explained to students by describing EMG as a compound action potential recorded from potentially thousands of motor units in the ADM, whereas intracellular recordings generally come from one muscle fiber. In *experiment ii*, values for conduction velocity of the ulnar nerve are low compared with published data for motor nerves. This is due to an underestimation of distance travelled by the stimulus in this experiment (if measurement is made straight between the two points of stimulation). This is because the ulnar nerve doesn't travel directly between the two points of stimulation; it follows an erratic course, around muscles and bones. Also, nerves follow a zig-zag course to allow for stretch with muscle movement.

Students are often surprised to learn that nerves are not just motor or sensory but that many nerves contain both sensory and motor fibers and that each nerve may carry fibers to many motor units, allowing graded stimulation of a muscle. Addressing this misconception can be the basis of a tutorial on fine control of muscle force (see below).

Students may also be curious about why there are both positive and negative deflections in the EMG traces from *experiments ii-iv*, a phenomenon that may be explained by the nature of muscle recordings from bipolar electrodes, with current first passing one electrode and then another of opposite polarity.

Evaluation of Student Work

Students should present traces from each of their experiments, similar to those shown in Figs. 3-6, calculate ulnar nerve conduction velocity, and give the latencies for the Achilles tendon reflex and both the M and H waves of the Hoffman reflex experiment.

Inquiry Applications

As we use it in second-year medical and first-year science classes, this experiment is at the "methods" level of inquiry, in which staff design the experiment and the questions to be answered to illustrate the basic physiologic properties of muscles and nerves. Results from the Hoffman reflex experiment can form the basis of a problem-based learning session on neuromuscular anatomy and physiology (see *Wider Educational Applications*).

Wider Educational Applications

A number of questions may be asked about the results from the Hoffman reflex experiment to form the basis of a problem-

based tutorial on anatomic and physiological properties of muscles and nerves. These are as follows:

Question 1. How can stimulation of one nerve on one occasion at one stimulation site cause two separate muscle activations with two different latencies?

ANSWER. The answer requires an appreciation of the composition of mixed nerve, composed as it is of many motor fibers that can stimulate the muscle directly and a similar number of sensory fibers coming from muscle spindles that stimulate motor nerves via the stretch reflex pathway. Students should appreciate that the M response comes from $A\alpha$ fibers activating muscle motor units directly, with the H response due to the activation of muscles via Ia afferents synapsing on motor fibers. At certain voltages, some of the gastrocnemius motor units are activated directly and some via the reflex pathway, giving two responses (11).

Question 2. Why does the indirect reflex (H) response appear at lower stimulation voltages?

ANSWER. The answer to this question requires an understanding that nerve fibers within nerves have different stimulation thresholds. In the case of the tibial nerve, the sensory fibers are easier to stimulate, having a greater diameter within the nerve than motor fibers and a lower stimulation threshold. When stimulation voltages are increased, some of the motor nerves are stimulated directly, with the proportion directly stimulated increasing as voltage is raised.

Question 3. Why, as the stimulation voltage is increased, does the indirect response reduce and eventually disappear?

ANSWER. As stimulation voltage increases and more motor units are directly stimulated, current travelling antidromically in $A\alpha$ fibers renders them refractory. They are thus unable to transmit the signal coming from Ia fibers. Individual motor units can therefore be activated either by direct stimulation of $A\alpha$ fibers or indirectly via stimulation of the Ia sensory fiber from the muscle spindle, but not by both.

This problem-based learning session using the results from the activities is a useful way of illustrating the properties of mixed nerves, illustrating, as it does, the multifiber composition of mixed nerves, which contain fibers with different stimulation thresholds. The results also allow for discussion of the nerve refractory period and antidromic conduction. The results also pose interesting questions on the nature of motor control. Enquiries about its reflex nature stem from the results as well as how force may be precisely regulated by activating different proportions of motor units within the same muscle (recruitment).

Additional Information

While a separate inquiry-based learning session stems from the results as described above, discussion within the practical may focus on the real-world uses for the techniques.

1. The results from *experiment i* promote discussion on the use of EMG in research where quantifying muscle activity is appropriate but measuring muscle force is impractical (e.g., studies on the activation of upper airway muscles during sleep or waking and gait analysis). How the asynchronous EMG pattern from maximal muscle activation may differ with upper and lower motor neuron lesions can also be detailed (3, 11, 12).

2. The results from *experiment ii* may focus attention on diseases that compromise conduction velocity in nerves and

give an indication of the usefulness of EMG as a tool in diagnosing and assessing the progress of these diseases (11).

3. The results of *experiment iii* promote discussion on reflexes, reflex delay, and synaptic transmission. The phenomena underlying the Jendrassik effect can illustrate the role of the reticular core in setting the tone of stretch reflex through the body and how this is controlled.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: S.M.R., C.D.J., and E.A.T. conception and design of research; S.M.R. interpreted results of experiments; S.M.R. prepared figures; S.M.R. drafted manuscript; S.M.R., C.D.J., and E.A.T. edited and revised manuscript; S.M.R., C.D.J., and E.A.T. approved final version of manuscript.

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