# Electromyograms Are Repeatable: Precautions and Limitations

Abstract. *Electromyograms recorded by bipolar, fine wire electrodes placed into anatomically equivalent sites in skeletal muscles of vertebrates are repeatable when the animals use the muscles in a similar way. Repeatability applies to the number of spikes recorded from a given site and to their average amplitude as well as to the root-mean-square value, though the values obtained for these descriptors differ among muscles, and perhaps fascicles, of particular animals even when the animals are performing equivalent actions. Tests suggest that these results are not affected by the nature of most kinds of recording equipment. Also, substantial differences in electrode tip configuration and wire diameter induce relatively minor, less than 8 percent, differences in electrode resistance and impedance. Doubling the length of the fine wire leads produces less than an 8 percent (15 percent when the length is tripled) effect; however, the effect of electrode material may be as much as 85 percent in resistance and 20 percent in impedance. Reports of nonreproducibility or variability of electromyograms apparently result mainly from anatomically inexact placement into physiologically and histochemically different fascicles of compound muscles, from recordings of muscles that are active at very low levels, and perhaps from comparison among recordings of muscles that really differ in their activity level.*

Electromyograms (EMG's) are extracellular recordings of voltage changes taken from within or from the surface of muscles of active animals. Since the introduction of bipolar, fine wire electrodes (*1*), EMG's have been widely used to study the functional morphology and physiology of freely moving vertebrates. Because the literature continues to state that the signals are not repeatable and that electrodes placed in adjacent sites of a muscle of a particular animal give markedly different results, many studies compare only the onset and cutoff of EMG signals. For quantitative comparisons, investigators analyze the changes in the output of a single array of electrodes (muscles) while the animal is performing a sequence of different functions.

Observations have suggested that EMG's are actually repeatable; we tested this using digitized rather than analog records of the major descriptors of the EMG (*2*). A series of experiments, in which electrodes were placed in well-defined areas, now suggest that the EMG recordings are indeed repeatable. For instance, three electrodes were placed into a small area (2 by 2 cm) of the deep temporalis muscle on each side of each of four cats that were then fed standard food (*3*). None of the means for sequences of 15 consecutive chewing movements (that is, bites) obtained with any one electrode was significantly different from those obtained for any other one of the set of 24 (Table 1). The EMG's clearly predicted on which side of the cat's mouth the food was being chewed, and these predictions were confirmed from synchronized film records; the EMG's on the working side agreed with each other and differed significantly from those on the balancing side. In contrast, the EMG's differed markedly from bite to bite within any sequence. Tests do show significant differences among the EMG's recorded from the several masticatory muscles (*4*), perhaps correlating to histological aspects at the site (*5*).

Clearly, EMG's recorded from particular sites in diverse muscles of multiple animals produce repeatable results. Does the "variability" noted in other studies reflect variability of the recording equipment and the nature of the electrodes or does it reflect the events being sampled?

The action potential of a single motor unit, that is, the physical event that must be detected and recorded, proceeds within approximately 0.3 to 1.0 msec (*6*). Commonly used high-input impedance differential preamplifiers (we tested the Tektronix 122 and 26A2, with input impedance increased to 100 megohms, and the Grass P-15), adequately separate such events without significant amplitude attenuation until spike duration becomes less than 0.05 msec. Such signals can be photographed off of the screen of an ordinary oscilloscope. Substantial fusion of EMG signals and a decrease in spike number and spike amplitude occurs for many chart recorders, but even poor recorders would adequately represent the onset and cutoff of trains of signals.

To determine the effect of electrode characteristics, we made multiple, bipolar, fine wire electrodes to identical configurations (*7*) from each of several types of wire. We then tested the resistance across each electrode pair (free end to free end), while the tips were placed into lactated Ringer solution (NDC 0074-7953, Abbott). Next we determined the effect of electrode impedance within the standard recording arrangement by plac-

Table 1. Muscular activities of the deep temporales of both sides when four different cats chew standard-sized pieces of cooked beef. Each value gives the output from one electrode placement for 15 bites. In all cases the mean number of spikes and mean spike amplitude (peak to peak in millivolts) per bite are given ± the standard error.

| Cat | Electrode | Right | | | | Left | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Working | | Balancing | | Working | | Balancing | |
| | | Number | Amplitude | Number | Amplitude | Number | Amplitude | Number | Amplitude |
| 1 | A | 34.1 ± 1.5 | 2.21 ± 0.25 | 26.2 ± 1.6 | 1.78 ± 0.17 | 30.9 ± 3.1 | 2.15 ± 0.21 | 24.9 ± 2.2 | 1.77 ± 0.15 |
| | B | 31.5 ± 1.7 | 2.07 ± 0.16 | 22.6 ± 1.7 | 1.74 ± 0.12 | 29.5 ± 1.8 | 2.18 ± 0.22 | 23.4 ± 1.9 | 1.71 ± 0.10 |
| | C | 34.3 ± 1.4 | 2.17 ± 0.26 | 22.1 ± 1.3 | 1.82 ± 0.13 | | | | |
| 2 | A | 32.4 ± 3.7 | 2.71 ± 0.21 | 21.0 ± 2.2 | 1.85 ± 0.17 | 33.1 ± 2.1 | 2.17 ± 0.16 | 23.2 ± 2.5 | 1.79 ± 0.17 |
| | B | 34.6 ± 1.8 | 2.27 ± 0.17 | 22.8 ± 1.9 | 1.82 ± 0.11 | 31.6 ± 2.5 | 2.10 ± 0.10 | 22.1 ± 2.3 | 1.68 ± 0.09 |
| | C | 30.5 ± 2.7 | 2.20 ± 0.15 | 23.3 ± 1.9 | 1.80 ± 0.12 | 33.0 ± 2.5 | 1.98 ± 0.12 | 22.9 ± 2.1 | 1.65 ± 0.10 |
| 3 | A | 35.1 ± 3.1 | 1.94 ± 0.20 | 24.8 ± 1.3 | 1.68 ± 0.12 | 31.9 ± 2.9 | 2.06 ± 0.23 | 22.8 ± 1.4 | 1.61 ± 0.11 |
| | B | 32.8 ± 3.2 | 2.18 ± 0.19 | 20.3 ± 2.3 | 1.81 ± 0.17 | 35.7 ± 2.8 | 2.12 ± 0.26 | 20.8 ± 2.1 | 1.66 ± 0.17 |
| | C | 32.5 ± 1.4 | 2.22 ± 0.23 | 23.5 ± 1.5 | 1.72 ± 0.22 | 34.2 ± 1.8 | 2.24 ± 0.19 | 22.6 ± 1.7 | 1.76 ± 0.11 |
| 4 | A | 31.4 ± 2.3 | 2.01 ± 0.19 | 25.1 ± 1.5 | 1.69 ± 0.14 | 34.8 ± 2.1 | 1.88 ± 0.14 | 24.5 ± 2.1 | 1.67 ± 0.16 |
| | B* | 32.6 ± 1.9 | 2.14 ± 0.20 | 22.2 ± 1.9 | 1.76 ± 0.10 | | | | |
| | C | 33.3 ± 2.1 | 2.03 ± 0.26 | 21.0 ± 1.2 | 1.67 ± 0.12 | 38.8 ± 1.9 | 1.93 ± 0.17 | 21.9 ± 1.5 | 1.65 ± 0.14 |

*This electrode broke on this cat.

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Table 2. Change in resistance (R) and impedance (I) of bipolar electrodes formed from different metals and different total lengths and tip lengths (+, an increase; −, a decrease).

| Electrode | Metal* | | Length of electrode† | | | | Length of tip† | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Increase (50 %) | | Decrease (50 %) | | Increase (50 %) | | Decrease (50 %) | |
| | R | I | R | I | R | I | R | I | R | I |
| Copper‡ (0.05 mm, solid; Pope, Venlo Holland) | +12 | +4 | +5 | +4 | −4 | −5 | −6 | −5 | +5 | +5 |
| Silver§ (0.076 mm, solid; Medwire) | +15 | +7 | +8 | +5 | −8 | −3 | −4 | −3 | +6 | +5 |
| Silver chloride§ (0.076 mm, solid; Medwire) | +33 | +4 | +6 | +5 | −7 | −4 | −4 | −4 | +3 | +8 |
| "Karma" stainless steel‖ (0.02 mm, solid; Driver-Harris) | +71 | +8 | +4 | +5 | −4 | −3 | −3 | −5 | +6 | +7 |
| Stainless steel§ (0.076 mm, solid; Medwire) | +78 | +12 | +7 | +5 | −8 | −5 | −3 | −5 | +2 | +7 |
| Stainless steel¶ (0.05 mm, solid; California Fine Wire) | +85 | +18 | +4 | +6 | −5 | −5 | −4 | −3 | +3 | +4 |
| Stainless steel‖ (0.076 mm, stranded; Cooner) | +80 | +20 | +6 | +6 | −6 | −6 | −3 | −6 | +3 | +7 |

*Percent change in reference to a platinum-iridium electrode, 15 cm long, 2-mm bared tip. †Percent change in reference to electrode of the same metal, 30 cm long, 2-mm bared tip. ‡Enamel coated. §Teflon coated. ‖Polyurethane coated. ¶H-ML coated.

ing groups of different electrodes, selected from the set, into a conductive gel (agar with distilled water) and by comparing their responses to various signals (*8*). The rapid events make a change of electrode impedance or recorded spike height (peak voltage) the critical factor. The variants evaluated were the length of electrode wire, the length of the bared tips, and the diameter of the wire. The most marked effect was that due to the nature of the metal of the electrode (*7, 9*) (Table 2).

Among all metals tested, the maximum change, relative to platinum-iridium, was an increase of 85 percent in resistance, but only 20 percent in impedance, both shown by stainless steel. Also, our copper electrodes were the only ones that showed a marked thermoelectric effect from the alternating current at the solder junctions (*10*). This raises further questions about the problems associated with the use of toxic metals such as silver and copper in long-term applications (*11*). However, interelectrode differences are relatively insignificant when EMG's are first passed to high-impedance differential preamplifiers.

With respect to the events being sampled, variability could be (i) spatial, in which case adjacent electrodes would perceive distinctly different signals, or (ii) temporal, in which case the signals at an electrode would differ during successive contractions. Spatial variability is clearly a source of error. Many muscles show regional differences in the distribution of fiber types; the fibers of some motor units are clumped, others are distributed. This is particularly true in multipinnate muscles and those subdivided by internal tendons; in these muscles, portions may differ in activity during one behavioral sequence or among behaviors (*12*). Consequently, electrodes must be placed into identical heads of muscles or identical fiber layers of complex muscles in order to sample equivalent biological events. Commonly used bipolar electrodes sample events that occur in multiple adjacent muscle fibers. If the muscle, or a subsection of it, is very small, has relatively few motor units, and is active at a low level, adjacent electrodes may produce different signals (*13*); however, as the activity level rises, adjacent electrodes acquire more similar signals. Another potential source of variability may be the movement of freshly inserted electrodes as the muscle acts. In short, EMG signals should be repeatable only if they reflect equivalent events. If the electrode records muscular activity during a series of bites that differ, due to the changing nature and size of the food, the "nonrepeatability" documents only that the recording system is functioning properly.

Perhaps, the argument for nonrepeatability derives from our inability simply to correlate EMG's with the forces produced by a muscle. Electromyography will not yet differentiate among the contributions of different types of fibers, nor indicate whether contraction is isometric or whether the muscles are shortening or lengthening during the active period. As such factors obviously affect the force generated, they must be taken into account in analysis (*14*).

Our results should leave no question that EMG's, obtained from reasonably standardized fine wire electrodes and standardized recording equipment and placed into well-defined sites in major subdivisions of muscles, do yield repeatable observations and do permit predictions for equivalent events on the same muscle in other specimens. Not all parts of any muscle will be equivalently active, nor can we, in the absence of other data, readily predict the force generated by a muscle from the localized EMG. We can often predict the force from EMG's of portions of muscles that are constrained to particular displacement patterns by joints of limited degrees of freedom. However, the remaining levels of uncertainty among EMG's reflect unresolved biological phenomena rather than random results of the recording procedure.

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**References and Notes**

1. J. V. Basmajian and G. Stecko, *J. Appl. Physiol.* **17**, 849 (1967).
2. The system used for our analyses records the positive or negative number of spikes (zero crossings) as well as the mean spike amplitude per (adjustable) interval. The system treats each spike as a single event and does separate spikes with smooth rise and fall from those with shoulders, which indicate that two or more discrete signals have (partially) fused. Our approach cannot differentiate between a pair of spikes produced by a single motor unit firing repeatedly and two spikes each of which is produced by a different motor unit. After this study was completed, we passed the stored signals through a root-mean-square module and obtained similarly repeatable values.
3. All equipment was freshly calibrated by passing a 1 mV signal from a Grass S44 stimulator to the connecting site of the electrodes, through Tektronix 122 preamplifiers (set at 1000 gain) and into a Honeywell 5600 FM intermediate bandpass

tape recorder (center frequency of 3.12 kHz ± 1 percent) at 1⅞ inch per second. The output of the tape recorder was monitored on a Tektronix 565 oscilloscope. Forty bipolar electrodes [dimensions determined after preparation: 31.05 ± 1.56 cm long (mean ± 1 standard deviation) with bared tips 2.16 ± 0.16 mm long] were formed from Teflon-coated stainless steel wire (Medwire), 0.076 mm in diameter. Each electrode pair was passed through the shaft of a hypodermic needle (14 cm long, 22 gauge) with an interdermal point. The insertion depth was marked by a gauge 1.5 cm from the tip of the needle. Cats were anesthetized by an intramuscular injection of ketamine hydrochloride (Vetalar). Three electrodes were inserted into the deep temporalis muscle on both sides through a 1-cm skin incision over the middorsal origin of each muscle. The first needle and its electrode were directed straight downward for 1.5 cm along the bony cranial wall. The needle was left in place while a second and third were inserted to the same depth anteriorly and posteriorly to the first. Then all three needles were removed. The electrode wire was kinked at the incision site and passed subdermally to the dorsum of the neck where it was soldered to a connector. The shoulder was then wrapped with an elastic bandage to minimize intramuscular movement of the electrode tips due to displacement of the connecting wires. Tests occurred 24 hours after electrode implantation. The EMG signals were stored on tape. Synchronized 16-mm motion pictures and voice records indicated the chewing side as well as the start and end of each reduction sequence. Cats were fed pieces of cooked beef (2 by 2 by 1 cm). The taped records of 33 reduction sequences were then processed by a computer that sampled four channels of EMG's for sequential 30-msec intervals.
4. G. C. Gorniak and C. Gans, *J. Morphol.* **163**, 252 (1980).
5. ———, J. A. Faulkner, *Science* **204**, 1085 (1979).
6. The actual durations of electrical events will differ depending on the site from which the signal is recorded—within one muscle fiber, among fibers of a motor unit, or outside the field of a motor unit [F. Buchthal and H. Schmalbruch, *Physiol. Rev.* **60**, 90 (1980)]; C. J. LeLuca, *IEEE Trans. Biomed. Eng.* **26**, 313 (1979).
7. Three electrodes were tested for each of the nine possible configurations of the seven wire types (Table 2). All electrodes were formed under a dissecting microscope by G.C.G. by a variation of the method of R. G. Scott and G. B. Thompson [*Med. Biol. Eng.* **7**, 677 (1969)]. Reference electrodes were formed from Teflon-coated platinum-iridium wire (Medwire), 0.03 mm in diameter. The middle of a length of wire was lifted off the working surface, forming a loop that was placed on a hook mounted in a drill chuck. The two sides were pinched tightly together, approximately 2 cm from the top of the loop and twisted about each other by manual rotation of the chuck. The loop was then removed from the hook, and the required length of insulation (as measured with a millimeter scale) was stripped from the wire on one side, close to the twisted portion facing the top of the loop. Twisting continued until half of the bared area was within the twisted part. The loop was then cut at the junction between the bared and insulated area; this produced one tip of the bipolar electrode. Next, an equal length of insulation was removed from the other side, starting across from the end of the first tip. The second tip was then cut where bared and insulated sections met. Both tips of the electrode were bent back toward the twisted zone, forming a double hook and leaving the bared stretch of one tip opposite an insulated zone on the second tip; this made contact between the bared zones unlikely. The insulation was always removed by scraping the wire between the tips of fine forceps. This lessened the possibility that the properties of the wire might be altered, as when insulation is removed by chemicals or flame. Teflon, polyurethane, and H-ML insulation are removed easily; however, enamel insulation adheres to the wire.
8. Each electrode was soldered directly to an Amphenol MS 3101A connector. Signals to be monitored were generated by a Grass S44 stimulator and transmitted to two 0.115 mm solid stainless steel wires placed into the gel. Signals from the test electrodes were amplified 1000 times through Tektronix 26A2 preamplifiers and stored on a Sony TC-788-4 four-channel tape recorder at a tape speed of 7.5 inches per second. Stimulator settings were 1- or 5-mV amplitude, frequencies 100, 500, or 1000 Hz, and signal durations 0.01, 0.1 or 1 msec. The system was calibrated at different signal frequencies and magnitudes by placing an electrode pair on a plate of conductive gel, preamplifying the signal received, and monitoring it from the output channel of the tape recorder. The signal of the electrode was passed to three tape channels and preamplifiers and amplifiers adjusted to obtain equal outputs. For each test, the bared tips of three electrodes were placed on the surface of a circular plate of gel (9.5 cm in diameter) that was subdivided into quadrants. Each quadrant was used for only one test, and the gel was covered between tests to minimize desiccation, which might affect the conductance of a signal through the medium. The electrode tips were arranged horizontally to fit a rectangle (3 by 1 cm) and were held steady by a weighted glass plate. Positions of recording electrodes were set so that the signal displayed did not change more than 1 percent when the stimulating electrode was moved 1 cm in any direction. Change of impedance was estimated from the change in the peak to peak voltages noted on a Tektronix 564B storage oscilloscope.
9. Major sources of information on electrodes, their impedance, difference among metals, and electrode-electrolytic interaction include J. M. R. Delgado, in *Physical Techniques in Biological Research*, W. L. Nastuk, Ed. (Academic Press, London, 1964), vol. 5, p. 88; C. D. Ferris, *Introduction to Bioelectrodes* (Plenum, New York, 1974); L. A. Geddes, *Electrodes and the Measurement of Biolectric Events* (Wiley, New York, 1972); N. A. Miller and D. C. Harrison, Eds., *Biomedical Electrode Technology* (Academic Press, London, 1974). We tested fine wire electrodes directly in an arrangement with preamplifiers with a high-input impedance. Most investigators now use such a recording arrangement to obtain EMG records. The question is whether differences in the type or material of the electrodes can induce sufficient differences in such a system to justify the claim of nonrepeatability.
10. This effect (producing a drop in amplitude) was easily demonstrated by temporarily cooling the junction between the electrode wire and the cables with a compressed air spray during recording sessions.
11. Copper is very toxic to living tissue, as are both bare and chloride-coated silver. Both copper and silver progressively destroy the surrounding tissue from the time they are introduced until they are removed; severe tissue destruction can occur in a few days. Thus, EMG's recorded from copper or silver electrodes may differ sequentially from day to day. In contrast, stainless steel produces only a temporary inflammatory response in the tissue, but there is no progressive tissue destruction. It seems useful to emphasize that the insulating material, as well as the metal should be biologically inert [J. M. R. Delgado, in (*9*); P. L. Blanton, R. P. Lehr, J. H. Martin, N. L. Biggs, *Electromyography* **11**, 475 (1971)].
12. S. W. Herring, A. F. Grimm, B. R. Grimm, *Am. J. Anat.* **154**, 563 (1979); L. C. Maxwell, D. S. Carlson, J. A. McNamara, Jr., J. A. Faulkner, *Anat. Rec.* **193**, 389 (1979).
13. Orientation of bipolar electrodes may also affect the recorded voltage as the resistivity of muscle is greater across than along muscle fibers. The durations of recorded muscle action potentials are shorter and their amplitudes greater when the tips of a bipolar electrode are parallel to the fibers than when they are perpendicular to them [F. Buchthal, C. Guld, P. Rosenfalck, *Acta Physiol. Scand.* **38**, 331 (1957); F. Buchthal, F. Ermino, P. Rosenfalck, *ibid.* **45**, 72 (1959); W. Waring, in *Biomedical Electrode Technology*, N. A. Miller and D. C. Harrison, Eds. (Academic Press, London, 1974), p. 215].
14. This implies among other things that muscles that fire twice during a jaw movement or limb rotation cycle may show different correlations between the EMG amplitude and the force generated for each activity phase [B. Walmsley, J. A. Hodgson, R. E. Burke, *J. Neurophysiol.* **41**, 1203 (1978); M. C. Wetzel and D. G. Stuart, in *Mechanics and Energetics of Animal Locomotion*, R. McN. Alexander and G. Goldspink, Eds. (Chapman & Hall, London, 1977), p. 115].
15. We thank K. Guthe, R. A. Nussbaum, R. J. Lowry, and T. Scanlon for discussion; A. English for the gift of the Cooner wire; and J. V. Basmajian, D. Cundall, C. J. De Luca, A. English, A. S. Gaunt, G. E. Goslow, F. C. Kallen, S. Kashin, G. E. Loeb, T. Scanlon, and D. Stuart for their perceptive and helpful criticisms of early versions of this manuscript. Supported by NSF grant DEB 77-02605 and NIH grant DHEW-PHS-G 1R01DE052112-01.

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## Bandwidth Requirements for Video Transmission of American Sign Language and Finger Spelling

Abstract. *Although current video communication schemes use a bandwidth on the order of 1 megahertz, the bandwidth required for video communication of American Sign Language by a simple raster scan is only approximately 20 kilohertz.*

Alexander Graham Bell invented the telephone in the course of his research on a hearing aid for the deaf (*1*), but the telephone has primarily served the hearing community. With more than 2 million severely deaf Americans who are unable to understand speech even with a hearing aid (*2*), it is appropriate for current research to find a means of adapting the transmission facilities already established for voice communication by telephone to the needs and habits of the deaf community. The most common methods of linguistic interaction among the congenitally deaf are American Sign Language (ASL), finger spelling (used where no sign exists in ASL, such as for proper names or technical terms), and speech reading (*3*).

Two existing devices that provide telecommunication for the deaf are the teletypewriter and the video telephone. Teletypewriters (*4*) enable a sender to transmit a typewriter message to a receiver, who sees the characters displayed on a screen or produced on another teletypewriter. The teletypewriter is useful for communication between deaf and hearing people, perhaps in conjunction with a voice channel for those deaf who retain intelligible speech. But the teletypewriter has a practical disadvantage: communication is slow and effortful compared with voice or ASL communication, which is about as fast as voice (*5*). The video telephone is far more attractive than the teletypewriter to many deaf persons for communication among themselves (*6*).

The American video telephone [Picturephone (*7*)] and the British version [Viewphone (*8*)] both transmit a picture


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