Electromyography

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INTRODUCTION

Electromyography is the evaluation of muscles based on detection of the muscle’s electrical activity (electromyogram or EMG) and its study (EMG signal processing and interpretation of the results). The electrical activity that precedes the muscle contraction is detectable using simple sensors and is painless for the majority of sensors used. In the case of voluntary muscle contractions, study of the EMG signal assesses the correct operation of the motor ways from the motor cortex to the muscle fiber itself. Thus, electromyography is a powerful method used in several investigative domains, including medical research (as functional neurology, gait and posture analysis), rehabilitation (as neurological rehabilitation, physical therapy), ergonomics (as risk prevention), and sports science (as biomechanics, movement analysis, training control).

Understanding of EMG signal composition is based on the anatomic and functional knowledge of the neuromuscular system. Skeletal muscle is made up of a large number of mostly parallel muscle cells called muscle fibers. Each fiber, as with all excitable cells, has electrical activity. However, to understand how an EMG signal is generated from the electrical activity of the muscle fiber, it is important to consider not only the muscle but also the nerve that transmits the motor command. Thus, the neuromuscular system must be considered an association of several functional units, called motor units.

The review is organized as follows: The motor unit is described in the first section. In the second section, genesis of an EMG signal from motor unit activity is presented. Electromyographic signal processing is described in the third section, including EMG detection, signal conditioning and recording, and data processing. At the output of processing chain, the EMG signal may be represented by several graphic models and characterized by several quantifiers in the time and frequency domain. The study of EMG signals and their changes, presented in the fourth section, is valuable to the understanding of physiological phenomena such as muscle fatigue, as well as to the discovery and diagnosis of abnormalities in nerve and muscle. However, EMG signal study must take into account the test conditions resulting from measurements of other signals (for example, mechanical signals) in order to obtain reliable and repeatable results, as described in the fifth section. Lastly, in the sixth section, some examples of EMG signal changes are described, notably during muscle contraction and after electrical stimulations as used in clinical EMG.

MOTOR UNIT (MU)

The MU is the functional unit of the muscle (Fig. 1A). The MU is defined as the association of a motoneuron α (nervous cell) and the muscle fibers it innervates.[1]

The MU has the ability to contract itself (motor action or contraction) following a driving order (neuronal excitation) because of excitation–contraction coupling.[24]

Nervous and muscular cells (muscle fibers) are excitable cells. These cells react to all external events (named excitation) that are mechanical, chemical or electrical in nature. As is the case for all live cells, these cells have electrical polarity on both sides of their cytoplasmic membrane (membrane potential or resting potential). Using microelectrodes (typical sensors in the cell electrophysiological domain) with a very thin tip, it is possible to measure the difference in potential between the outside (taken as an electric reference) and the inside of the cell (this detection type is qualified as intracellular detection). The measured membrane potential is stable with time and ranges between −70 and −90 mV according to cell type. After excitation, cells react with a transitory variation of the electrical polarity of the membrane, called the action potential (AP). The AP (Fig. 2) is identical in amplitude and in duration and is characteristic of the cell type (nervous or muscle). Moreover, AP is propagated along the membrane of these cells (axonal membrane for nervous cells, fiber membrane for muscle fibers). The cell parts considered are long extensions: the axon of the nervous cell whose cell body is located in the ventral horn of the spinal cord or a long cylindrical cell (muscle cell).
The AP is transmitted from an axon (nervous AP) to a cell muscle (muscle AP fiber) through the neuromuscular junction (NMJ), also called the motor end plate, a chemical synapse whose neurotransmitter is acetylcholine. The single axon is subdivided at its end into several branches or collaterals. Thus, axonal AP is reproduced on each collateral ending with an NMJ and innervates several muscle fibers.

A muscle associated with its motor nerve is described as a set of MUs, from ten MUs for small muscles to several thousands of MUs for large muscles. The muscle fibers of one MU are distributed in the muscle. This distribution determines the concept of MU territory defined by Buchthal et al. In the first approximation, the MU territory corresponds to the muscle surface (in the muscle cross-section view).
delimited by the most distant fibers. The spatial scattering of fibers is regarded as a uniform or a Gaussian distribution. In the muscle cross-section, MU territories overlap each other. The rate of innervation of a MU is defined as the number of muscle fibers belonging to it. Muscles that must provide a coarse effort (for example, in limb muscles) are constituted by MU with a large rate of innervation, whereas muscles that need to ensure a precious and discriminative activity (for example, face muscles) have MUs with a larger number of fibers, but each has a low rate of innervation.
The entire set of MU axons corresponds to the motor component of the mixed nerve that innervates the muscle. The other nervous component is sensitive and drives sensitive information from muscle spindles. The nervous endings on the muscle are a privileged area (identifiable by cutaneous electric stimulation) called the innervation zone, or motor point (MP). The MPs are located at different places on the muscle. Tables of MP localization were constructed previously.\textsuperscript{[5]}

**Type of MU**

The type of MU is related to the type of fiber that composes it.\textsuperscript{[2]} Several types of muscle fibers exist and are classified into two main categories: slow fibers (type I) and rapid fibers (type II). The fast fibers are divided into three groups, IIa, IIb, and IIc. The various fiber classes are determined from criteria or characteristics dependent on their structural, contractile, metabolic, and functional properties. For example, fiber diameter, AP amplitude, and generated force are larger in type II fibers, whereas the excitability threshold, fatigue resistance, and time of twitch contraction are larger for type I fibers. In one MU, the type of muscle fibers that composes it is the same. Categories of MU type are determined based on fiber type, such as slow or fast MU.

In a given muscle, the proportion of different types of MU assigns the properties of the muscle: slow muscle (98\% slow MU; for example, soleus muscle), fast muscle (90\% fast MU; for example, extracocular muscle), and mixed muscles (slow and fast MU; for example, biceps brachii muscle). During a progressive increase in the intensity of muscle contraction, Henneman\textsuperscript{[6]} determined that the larger the cell body of the motoneuron, the higher the threshold of excitability will be and consequently the motoneuron will be activated late; this result is called the size principle. Then, consequently, slow MUs are recruited before the fast MUs.

**GENESIS OF THE EMG SIGNAL**

**Muscle Fiber Potential**

In electromyography, independent of the method used, electrical activity detection is realized extracellularly. The changes in detected potential are collected outside the cell. The relation between intracellular and extracellular AP is a second derivative with respect to time.\textsuperscript{[7]} The activity of just one cell can be picked up (Fig. 1B) and represents the muscle fiber action potential (MFAP). The propagation velocity of the MFAP along the muscle fiber is about 2 to 5 m/sec. The propagation velocity is smaller than that of axons, which is about 45 to 65 m/sec. The propagation velocity in the axons is increased because of saltatory conduction, which is conduction resulting from the presence of a sheath of myelin (Fig. 1A) that surrounds and electrically insulates the axon in small sections. Each myelin section corresponds to a Schwann cell in the case of peripheral nerves.

**Motor Unit Action Potential**

When a motoneuron is activated, an AP is generated and propagated along the axon and its collaterals. These AP are transmitted by NMJ to muscle fibers and then each muscle fiber generates MFAP. The motor unit action potential (MUAP) is the algebraic sum of MFAP (Fig. 1B). These potentials, detected using intramuscular electrodes, have amplitudes and shapes that depend on the following parameters: electrode–fiber distance, fiber conduction velocity, density of fibers at the site of detection, and length of collateral.

**Elementary EMG**

Elementary EMG is an intramuscular EMG constituted from algebraic summation of a restricted number of MUAP (from 1 to 4–5 MUs; Fig. 2). If a needle electrode with one wire is used, MFAP may be detected.\textsuperscript{[8]}

**Surface EMG**

Surface EMG (SEMG) is a global EMG because a large number of MUAP are detected (Fig. 2). Surface EMG is picked up on the surface of the skin (Fig. 1B) and thus the electromyographic evaluation is reduced to the most external muscles. The potentials then cross various media such as the fat layer (via adipocytes) and the skin layers (via keratocytes). The detected EMG signals are altered in amplitude and frequency by the cell layers. Signals with the greatest amplitudes come from the muscle fibers closest to the electrodes.

**EMG Characteristics**

Electromyographic signals have different characteristics according to the modalities used to generate them. The two kinds of modalities are stimulation and voluntary contraction performed by the subject. Using electric stimulation (applied to the motor nerve or the muscle itself) or mechanical stimulation (impact on one of the muscle tendons by a hammer), EMG signal is deterministic. At the occurrence of stimulation or
excitation, activation of each MU is synchronous, i.e., all are active at the same time. Using electric stimulation (adjustable in intensity and duration), the size principle is reversed: type II MU are initially excited. During voluntary activity, the EMG signal presents characteristics of a random signal; the activities of MUs are asynchronous. The EMG signal in bipolar detection and collected on the skin is called interferential EMG and is centered on electrical zero (baseline). In some cases of muscle contraction, such as fast or explosive contractions, MUs tend to have synchronous activity.

**EMG SIGNAL PROCESSING CHAIN**

A typical EMG signal measurement chain\(^9\)\(^{11}\) consists of three basic units: detection, signal conditioning, and signal acquisition and processing. Because an EMG signal is extremely weak, ranging from microvolts to millivolts, it is easily contaminated by undesirable noise. Thus, the higher the performance of each unit, the better the quality of EMG in terms of signal-to-noise ratio. The Surface Electromyography Not Invasive for the Assessment of Muscles (SENIAM) research group,\(^5\) supported by the European Union in the biomedical research program (BIOMEDII) proposed in 1999, made recommendations based on practical methods for the use of SEMG in clinical diagnostics. These recommendations help users standardize measurement methods, analysis, and modeling of SEMG.

**Detection**

The detection of EMG is performed by specific sensor electrodes. These electrodes, which come in direct contact with the muscle or skin, are made of different metals that must be non-toxic for the subject and do not polarize with an electrical current across the electrode (unpolarizable electrode). The interface, or the contact surface, between a metal and the biological environment produces long-lasting polarization effects. In order to minimize polarization, the metal must be covered with a layer of salt of the same metal. Generally, silver chloride (Ag/AgCl) is used for sensor electrodes. The most important characteristics of the interface of the electrode–biological medium are their electric impedance (in ohms) and their filtering effect (in particular the low-pass filter) on the detected signal. The EMG signal depends on these electrical characteristics but also on the electrode position. The detected electrical activity is a signal under high impedance.

This high electric impedance is lowered using an impedance transformer (preamplification circuit). Three electrodes must be used: two electrodes (active electrodes) are connected to the high impedance inputs (one input for each electrode). The third electrode (the reference electrode) is connected to the low-input impedance (placed in a region without electro-physiological activity that is linked to the ground).

Special care must be taken to realize EMG detection; the amplifier requires electric insulation in order to protect the subject electrically (subject safety) because devices in the acquisition system are linked to the AC power line.

Two modes of detection (monopolar and bipolar) are usually used. The monopolar mode involves only one active electrode and gives information regarding changes in potential under the detection place. The second electrode must be placed on an electrically inactive zone (wrist, ankle, or ear lobe). In the bipolar mode, which is most generally used, two electrodes are placed with a gap between them. Because of the difference in potential, the undesirable remote potentials (parasitic or noise) are eliminated, thus improving the signal-to-noise ratio. A bipolar EMG signal obtained is very different in shape from the monopolar EMG signal; this must be taken into account in the conditioning and treatment of the signal. The bipolar EMG is dependent on the interelectrode distance. A pair of electrodes will detect more or less remote electric activity with a large or small interelectrode distance, respectively. Then active muscle volume (or conductor volume) will be larger or smaller depending on the interelectrode distance. When the interelectrode distance is small, the conducting volume is low and the electrodes have high selectivity. The distance between electrodes must be chosen in such a way that the conductor volume receives no activity from neighboring muscles (concept of “cross-talk”).

**KINDS OF ELECTRODES**

Two kinds of electrodes are used (Fig. 3): invasive electrodes cross the skin (intramuscular electrodes) and noninvasive electrodes are attached to the skin surface (surface electrodes). Invasive electrodes have electrode needles with one or more Ag wire of detection (coaxial, multiple) and wire electrodes (with or without hooks) allowing detection of the electrical activity during motion with low amplitude and low speed. The first electrodes are mostly for neurophysiological evaluation, whereas the second electrodes are generally dedicated to biomedical research. Non-invasive electrodes, or cutaneous surface electrodes, are widespread in the fields of kinesiology and sport. They consist of a round metal plate a few millimeters in diameter or a rectangular plate of Ag/AgCl (about 2 × 10 mm). Moreover, special kinds of electrodes can be constructed in relation to the
Electromyography electrodes are called dry electrodes. The advantage of wet gel electrodes compared with dry electrodes is their insensitivity to the movements of wire-linked electrodes to amplifiers during the evaluation.

Electrode Placement in Surface EMG

Skin preparation

When surface electrodes are used, contact impedance with the skin is higher because the skin may be fatty and dirty, have a large cutaneous keratinization, or be senile skin. In such cases, before electrode placement it is necessary to eliminate fatty impregnation of the skin, scaled cells, and abnormally high pilosity as much as possible. The reduction techniques for cutaneous impedance consist of shaving and then abrading the zone on which the electrodes will be fixed using an abrasive paste or an equivalent mixture of alcohol and acetone. Once the electrodes are correctly positioned, inter-electrode resistance is measured. Interelectrode resistance must be lower than 5 kΩ.

Electrode placement

The electrodes are placed in parallel to the orientation of muscle fibers and one of the two sides of the MP. The best placement is in the position the muscle will have during its contraction phase, which does not necessarily coincide with the resting position. The electrodes are fixed using double-face adhesive tape. For most muscles, surface electrodes of 10 mm in diameter and a distance of 20 mm intercenter is recommended by the SENIAM[5], but for small muscles the size of the electrodes and their distance must be adapted.

Electrode Placement in Elementary Electromyography

The use of intramuscular electrodes is a medical act and requires initial asepsis of the electrode. After the skin is cleaned with alcohol, the skin is locally anesthetized (by spray cooling or local analgesic) before needle puncture.

Electromyographic Multidetection (Fig. 3)

In some elementary EMG uses, the needle contains several detection wires constituting a multielectrode bundle, which makes it possible to detect several channels of signals simultaneously. For SEMG, several electrodes can be arranged, either online with equivalent interelectrode distances or matrix built for mapping EMG investigations.
In these cases, the associated signal processing is specifically developed. As an example, an electrode device called a laplacian electrode made with five electrodes is used to perform space filtering. Laplacian detection enhances the depth of detection with high selectivity. A second example is n-electrodes in line with constant interelectrode distances in order to compute the velocity of propagation of muscle potential.

At the present time, the needle and cutaneous electrodes are manufactured industrially and ready for use. The disposable electrodes available for SEMG are wet gel or adhesive gel electrodes.

**SIGNAL CONDITIONING AND DATA RECORDING (FIG. 4)**

The primary purpose for analog signal conditioning circuitry is to modify sensor output into a form that can be optimally converted to a discrete time digital data stream by data acquisition. The conditioning circuit consists of three consecutive stages: preamplification, filtering, and amplification. The accuracy of the data recording relies on the precision of these three units.\(^9,10\)

**Preamplification**

The preamplification stage boosts the scaled electrical signal received from the electrodes. The most important circuit configuration for amplifying sensor output is the instrumentation amplifier. The EMG preamplifiers are typically built around an instrumentation amplifier with the following requirements: accurate and stable weak gain (usually between 2 and 10), extremely high input impedance (about 101MΩ), extremely low output impedance (about 100 ohms), and an extremely high common mode rejection ration (more than 110 dB). Because signals received from the electrodes have high impedance and low amplitude, the preamplification stage operates as an impedance transformer. Usually, it is located as close as possible to the detection site.
Filtering

The filter section will comb out irrelevant frequencies, electrical noise, and other unwanted interference from the signal, leaving only the part of the converted bio-potential signal one wishes to measure and record. To reduce the undesirable signals (noises) as best as possible, the filtering unit uses both low- and high-pass filters. Noise has an extrinsic origin (electromagnetic disturbances of 50 or 60 Hz, engine in action, wire movements) or an intrinsic origin (other biopotential signals, such as ECG, the amplitude of which is larger than that of an EMG). The high-pass filter removes unbalanced components of half-cell potentials and movement artifacts of the cables, i.e., spurious changes in the signal resulting from movements of the leads and slipping during gesticulation or motion. Low-pass filtering limits the spectral characteristic of the EMG signal to the known bandwidth so the signal can be sampled at the required rate. The filters are analog devices and are tunable according to frequency bandwidth. A notch filter (which ideally attenuates the frequency for which the filter was built) is currently added to enhance the suppression of electromagnetic disturbance. The bandwidth of each filter is set according to the frequency band of the EMG signal, the value of which depends on the type of EMG (elementary or surface), on electrodes placement, and also on muscle size and type. Typical amplitudes and frequency bands are 1–10 mV and 5–500 Hz for surface EMG and 200–250 μV and 30–3000 Hz for intramuscular EMG, respectively.

Amplification

Before the signal is sent to the last unit (visualization or processing devices), the EMG signal passes through a final amplification with a very high gain. By placing high-gain amplification at the filter output unit, selective increase in the desired signal is ensured without noise amplification because the majority of the electrical interference has already been filtered. The high gain significantly increases the amplitude of the EMG signal, making it easily detectable and manageable by visualization or numerical acquisition devices. To avoid distortion or saturation, the output signal must not exceed the specific range of the device (example of voltage range: ±1.4 V, ±5 V, ±10 V).

The active sensor is a specific system use for SEMG detection, and includes a preamplification circuit and a filtering circuit placed nearest the two active electrodes. Thus it generates a low self-impedance signal that is ready to be amplified. In some cases, the signal must be brought far from the detection site and be transmitted by radiotelemetry.

Signal Insulation

For human safety, it is necessary to isolate the sensor from the power supply of the conditioning units. The EMG preamplification unit includes electric insulation in order to protect the subject. This occurs in one of two ways: magnetic isolation or optical isolation. Magnetic isolation is primarily used for coupling power from the computer or the wall outlet to the sensor. This is performed through the use of a transformer. Optical isolation is used for coupling the sensor signal to the data acquisition input. This is usually performed through the use of a light-emitting diode and a photodetector.

Recording

Some devices are used for visualization or acquisition of the conditioned EMG. Using an oscilloscope (analog or digital), the amplitude in time variation of the EMG signal can be investigated.

In order to permanently record the signal, tape or graphic recorders are used to produce a trace paper. Tape recorders, which are less used nowadays, make it possible to reread the recorded signal. Graphic recorders using ink jet or thermic paper are commonly used, as for ECG or EEG. In choosing a recorder, particular care must be given to the value of the recorder’s bandwidth because it is dependent on technical considerations. During an examination or a test using elementary EMG, it is common to listen to EMG signals via a loudspeaker. The EMG is transformed into a signal compatible with that of loudspeakers.

Hearing the activity allows the investigator to have a “third hand”: it enables him to position the needle without having to see the signal.

All contemporary analyses and applications of EMG signals are accomplished using algorithms implemented on computers, and necessitates that the signals be expressed as numerical sequences. The process by which the detected signals are converted into these numerical sequences is called analog-to-digital conversion. Analog signals are voltage signals that are analogous to the physical signal they represent. The amplitude of these signals typically varies continuously throughout their range. The analog-to-digital conversion process generates a sequence of numbers. Each number represents the amplitude of the analog signal at a specific point in time. The resulting number sequence is called a digital signal, and the analog signal is said to be sampled. Numerical recording for upcoming EMG signal processing requires devices with an analog-to-digital converter (ADC). Their use is highly varied and widespread. Each application must be
assessed with consideration of the advantages and limitations of the specified ADC.

Knowledge of the signal ranges is strongly recommended—both amplitude and frequency—in order to match the dynamic of the signal as well as the sampling rate as much as possible. It is advisable to sufficiently but not excessively (to avoid an overload) amplify the signal with regard with the voltage range of the AD boards (typical ranges for ADCs are $\pm 1.25$, $\pm 2.5$, $\pm 5$, and $\pm 10$ V) and to choose a sampling rate at least twice the maximum frequency of the signal (according to Shannon’s theorem).

**DATA PROCESSING—EMG QUANTIFICATION**

Data processing and computation of EMG depend on the type of electrode, the type of detection, and the type of study that justifies the use of electromyography.\(^{[9,11,14]}\)

Data processing is applied to numerical signals, which are then sampled. Pretreatment may be carried out to enhance the signal-to-noise ratio. For example, a numerical filtering may be applied to the signal in the temporal domain (e.g., filter of Butterworth or Tchebysheff) or in the spectral domain to eliminate one frequency, where after the frequency component is reset (zero value) the signal is rebuilt. Another technique is signal averaging, and requires three conditions. The first is the existence of a trigger event, which will correlate with the signal; the second is that the time between the trigger event and the signal is invariable; and the third condition is that it is possible to repeat several times the generation of the signal without changes in the two first conditions. By summation of sampling epochs, only the signal generated at the same time will appear and thus its amplitude will increase, whereas the existing signals not generated by the starting signal will decrease in amplitude. This method, often used in EEG to extract evoked potentials, makes it possible to extract a signal from a composite signal. For example, it is possible to extract the force generated by one MU from the force signal during contraction; the trigger event is the MU potential itself.\(^{[15]}\)

Finally, the use of adaptive filtering eliminates undesirable signal but the signal must be recorded independently. For example, if the SEMG of back muscle is contaminated by an ECG signal, to delete the ECG in the SEMG it is necessary to record the subject’s ECG on an additional channel in order to apply adaptive filtering.

After pretreatment, the signals can be quantified using numerical parameters. In the case of elementary EMG, MUAP are analyzed individually or in the entire activity during a defined duration. Individually, the shape of the MUAP is characterized by this duration and number of phases, amplitude, and area. In a defined time interval, the firing rate of the potentials, the mean interpotential interval (IPI), the instantaneous frequencies (inverse of IPI), and the jitter (mean variation in IPI between single-fiber action potential of the same MU) will be studied.

In the case of SEMG, the signal may be studied in the temporal domain (according to time) and in the spectral domain (according to the frequencies which it contains). In the temporal domain, common processing involves wave rectification (absolute value of the signal, knowing the signal is centered on a level mean, generally zero), counting the number of passages to zero, integration (calculation of the signal area with respect to the baseline), and calculation of the signal envelope (the total shape of the signal). Moreover, the envelope may be estimated using a moving average of rectified EMG (average of the amplitude in the moving time window).

In the spectral domain, characterization is carried out on the power density spectrum of the signal. Using a fast calculation algorithm (fast Fourier transform or FFT), the temporal signal is transformed into the spectral domain. Using a calculation associated with FFT, the signal is then represented as a power density spectrum. The signal is graphically represented by a continuous curve (power density) according to frequencies the signal contains. The power density spectrum is characterized by quantifiers such as the root mean square (RMS), corresponding to total power of the signal computed as the spectrum surface, the mean power frequency (frequency corresponding to the barycenter of all the frequencies according to their power), and the median frequency (the frequency that divides the power spectrum into two equal RMS parts). Using the most common parameters, other parameters such as the symmetry of the power density spectrum or flatness with respect to a normal Gaussian curve can be calculated.

If, by calculation of these parameters, it is possible to quantify the EMG signal, interpretation of the results and their changes during the time course must take into account the test set-up in which the signal is generated. For example, according to the level of contraction (maximal or submaximal) or during muscle fatigue the parameters may be different, thus leading to different interpretations.

**Specific Computation of EMG Signal**

Data computation\(^{[12,14,16]}\) can be used to improve the detected EMG signal or to seek particular information regarding the signal using specific algorithms. For example, new algorithms in filtering methods are elaborated upon to improve the preprocessing step, such as the removal of artifacts in the electrical signal. The methods most used to extract information from the
EMG signal are decomposition of the EMG signal into MUAP trains and classification of MUAP parameters using wavelet transform or neural network methods. Following the application of extraction methods, data are analyzed using statistical analysis (such as mean, variance, or correlation analysis to evaluate the relevance of a given parameter) or multivariate methods (such as principal component analysis or discriminant analysis to classify data and to take a decision from many parameters).

**Graphical Representation of EMG Signals**

Other characterizations of the EMG signal, such as graphic modes of representation, provide information on the shape, duration, and intensity of the electric activity of the muscle during contraction.

In the monodimensional mode (1-D), observation of the signal (one channel) as a function of time provides information regarding the signal amplitude. However, another representation called graphical superposition of signal epochs provides information regarding shape changes. Graphical superposition is made from a characteristic in each signal (such as trigger event or maximal amplitude). For example, by triggering the visualization of multiphasic MUAP (Fig. 2) in the first phase, it is possible to identify changes in the other phases. The jitter is defined as the delay in propagation on the branches of collateral of the motor nerve. In the same way, the superposition of power density spectra may identify spectral changes in EMG, such as in the case of muscle fatigue processes.

In the two-dimensional mode (2-D), according to the axes (abscissa and ordinate) the parameters used may be homogeneous or heterogeneous. For example, the time (abscissa)–frequency (ordinate) representation called a periodogram demonstrates power spectra for each segment of the raw signal. The possible spectrum change appears upon visual examination of the graph. When several channels of EMG are recorded, one image can be built pixel by pixel using an interpolation between the signals and by transforming the amplitude to color according to a color chart. This corresponds to a 2-D representation or a pseudo 3-D representation. The most current application concerns the EMG mapping (position of electrode in abscissa and in ordinate), or a pixel has a determined color (amplitude), which illustrates the distribution of EMG activity on the surface of the skin. More recently, by using an n-electrode line array (electrode positioned in the abscissa and time in the ordinate with color as amplitude), it is possible to estimate the propagation velocity of electric activity by computing the slope of the colored lines, which appear on the image.

**PRINCIPAL FACTORS LEADING TO EMG SIGNAL CHANGE**

The principal factors implied in EMG signal changes for a healthy subject[13,14,16] are as follows:

1. Methodological factors such as those linked to the sensors (chemical properties of the detection surface, size and shape of the electrodes) and sensor placement (orientation of the electrodes compared with the direction of muscle fibers, sensor placement with respect to the motor point, distance and impedance between electrodes);
2. Structural physiological factors such as the space distribution of MUs, the diameter of fibers constituting the MU, and the filter properties of muscle tissue and skin; and
3. Functional physiological factors such as the kind and the level of contraction, the degree of synchronization in MU behavior, muscle metabolism (ionic disorder; pH, balance in release–production of lactate), intramuscular pressure, blood flow, and muscle temperature.

In addition to these factors, it is necessary to consider the age of the subject and the various neuromuscular pathologies[17,18]

1. Structural factors such as diseases of the central nervous pathways (e.g., brain motor area) or peripheral diseases (neuropathies), structural changes in the neuromuscular junction (such as myasthenia gravis) and in muscle fibers (myopathies); and
2. Functional factors such as those associated with diabetes and obesity or muscle fiber function such as McArdle’s syndrome (abnormal glycogen accumulation in muscle tissue).

Finally, electromyography characterizes specific changes in the neuromuscular system that have led to a specialization of this system as this is identified after endurance or pliometric training, after reduced muscle activity (limb immobilization), and during exposition in extreme environments such as space flights of long duration. These neuromuscular changes, which are generally reversible, illustrate the neuromuscular plasticity.

**ASSOCIATION OF EMG SIGNALS TO OTHER ELECTROPHYSIOLOGICAL SIGNALS**

The study of EMG signal and its changes is dependent on the conditions of signal generation. The EMG signal is evoked from a muscle activity (muscle contraction), which requires voluntary motor control or involuntary solicitation (external stimulation, e.g., the
electromyographical component in the study of reflexes).

Using experimental devices called ergometers, it is possible to normalize or standardize muscle contractions according to a fixed protocol. The detected EMG signal is associated with other signals (such as force, power, position, and speed for mechanical signals) or related to the stimulation parameters (e.g., intensity and duration for electric stimulations).

Two kinds of contractions exist: isometric contractions (the muscle does not modify its length and thus a force torque is measured) and dynamic or anisometric contractions (the muscle works with variable length). The interest in using mechanical devices or ergometers that are more or less complex lies in seeking the most reliable, reproducible, and even standard experimental conditions. Moreover, specific protocols such as the research of maximum (e.g. maximal voluntary force, maximal RMS) are generally proposed and leads to standardization of the instructions given to the subject or to normalization of the calculated parameters values to this reference value. Under test conditions, it is possible to identify changes in the EMG signal in comparison to standard signals or characteristic signals obtained from healthy subjects.

According to the properties of the SEMG signal, the signal is not reproducible but the quantifier values and evolution are (e.g., total energy, mean frequency during muscle fatigue) if test conditions are repeatable. Changes in EMG signal are then perceived by its parameters rather than the signal waveform variations.

**Muscle Fatigue**

Muscle fatigue is a reversible physiological phenomenon that is studied during isometric contractions (with maximal or submaximal level). During the submaximal level, which is maintained until exhaustion, the SEMG is altered and RMS and mean power frequency changes are observed. The increase in RMS is associated with a decrease in the mean power frequency of the signal. The interpretation is that increased MU activity is required to maintain the force and mean power frequency changes are associated with biochemical disorders such as muscle acidification.

In maximal contraction, the number of active MU cannot be increased and the muscle activity is close to the maximal activity. Fatigue is identified by a fall in mean power frequency and force produced.

**Body Motion in Cycling, Walking, and Jumping**

Using an ergometer (for cycling), EMG signals (Fig. 2) can be detected with multiple channels and demonstrate patterns of activity that are quantified during body motion. For example, the beginning and end of activities may be quantified in duration and in magnitude with signal RMS. Each motion, such as walking, jumping, or exercising on a bicycle, is associated with mechanical variables (such as position, speed, and acceleration). Interrelations between the EMG quantifiers and the mechanical parameters are studied and may describe anomalies in motor coordination.

**EXAMPLES OF PHYSIOLOGICAL CHANGES IN EMG SIGNAL**

**Level of Contraction**

Under isometric conditions of contraction, when a subject increases the intensity of a voluntary contraction in arm flexion, the SEMG of the biceps brachii muscle increases gradually in amplitude, as characterized by an increase in the EMG RMS. The muscle activity is dependent on the number of recruited MU (by spatial recruitment according to the size principle) and on the activity of each MU by their firing rate (temporal recruitment). For various levels of contraction, the MU firing rates differ with respect to MU type; the firing rate of MU ranges from 4–5 to 25–30 Hz for slow MU and up to 60 Hz for fast MU. For small muscles, all the MU are recruited before the intensity of contraction reaches 50% of the maximal voluntary force, whereas for large muscles the entire MU recruitment is obtained when contraction levels range between 70 and 80%.

**CLINICAL ELECTROMYOGRAPHY**

Elementary EMG with needles is currently used in clinical electromyography.

Neuromuscular evaluation using electromyography corresponds to the evaluation of the most distal organ (muscle) and, consequently, leads to the identification of signs of suspicious pathologies at various places from the cerebral motor area to the muscle (localization of the excitation–contraction coupling). Electromyography is used to assess the effect of medicinal therapy or to follow up with rehabilitation (e.g., in the case of muscle reinnervation: the MU territories decrease, whereas the rate of innervation increases).

In practice, an EMG signal is generated following a verbal instruction to the subject and signal anomalies with respect to reference signals may be identified. Another manner of generating EMG signal consists of evoking EMG responses following stimulations that are electric (electrodiagnostic) or mechanical (tendinous stimulation or disruption of posture). The
method, which is most often used in the study of reflexes, is called reflexology.

For example, electrostimulation of the sciatic nerve applied to the hollow popliteal (area located behind the knee) generates various muscle responses (Fig. 2) according to the intensity of stimulation. With low intensities, the sensitive nervous fibers (Ia fibers from muscle spindles) are the only ones to be excited and by the monosynaptic loop reflex of the homonymous muscle will produce the slow type of MU contraction. The EMG response is called Hoffman's reflex (H reflex). With stronger stimulation intensities, the H reflex gradually decreases and the direct response of the muscle, called the M wave, appears. The evoked EMG response to abrupt percussion on the Achilles' tendon is called tendinosus reflex (T reflex). The T reflex occurs later than the H reflex because of the coupling between tendinosus mechanical stimulation and the response of the spindles.

CONCLUSION

Electromyography, or the study of EMG signal, provides information on nerve and muscle functionality. First, after drawing up a protocol and deciding whether an ergometer should be used, special care must be given to the choice of muscle investigated, kinds of electrodes, and their placement. Second, when the EMG signal processing chain is constructed, each unit of the chain must be adjusted according to the modality of the EMG signal generation (voluntary contraction or stimulation) and the signal kind (intramuscular or surface). In the third step, the kind of data analysis must be chosen to extract the researched information. In comparison with “normal” waveforms or changes, the EMG signal may reveal abnormalities in nerve or muscle function.

At the present time, new methods for EMG signal processing are in progress. The study of EMG is also associated with other means (for example, Nuclear Magnetic Resonance or NMR) used to investigate nerve and muscle function.

ARTICLE OF FURTHER INTEREST

Biopotential Amplifiers

REFERENCES


