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Consensus for experimental design in electromyography (CEDE) project: Terminology matrix

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ABSTRACT

Consensus on the definition of common terms in electromyography (EMG) research promotes consistency in the EMG literature and facilitates the integration of research across the field. This paper presents a matrix developed within the Consensus for Experimental Design in Electromyography (CEDE) project, providing definitions for terms used in the EMG literature. The definitions for physiological and technical terms that are common in EMG research are included in two tables, with key information on each definition provided in a comment section. A brief outline of some basic principles for recording and analyzing EMG is included in an appendix, to provide researchers new to EMG with background and context for understanding the definitions of physiological and technical terms. This terminology matrix can be used as a reference to aid researchers new to EMG in reviewing the EMG literature.

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1. Introduction

Consensus on the definition and use of common terms in electromyography (EMG) research facilitates the clear communication of results from EMG studies across a diverse range of disciplines (physiology, biomechanics, engineering, clinical neuroscience and medical sciences). This paper presents an overview of terminology in the EMG literature and provides definitions for key terms, encompassing both physiological and technical topics. It is one of a series of articles within the Consensus for Experimental Design in Electromyography (CEDE) project, which aims to develop consensus-based matrices to guide decision-making in EMG research (Hodges, 2020). The terminology matrix is designed to be accessible to those with either a clinical or an engineering/technical background. It also serves as a reference to facilitate reviews of the EMG literature and can direct readers to other matrices within the CEDE project which address specific EMG topics (Besomi et al., 2020; Besomi et al., 2019).

2. Methods

The preparation of the terminology matrix followed a three-step process: (1) development of the list of terms and corresponding definitions to be covered in the matrix, (2) refinement of the definitions by the steering committee and (3) implementation of feedback from the CEDE panel of experts using a Delphi process to reach consensus on each definition. Further details on the CEDE project, including the method for expert group selection, and the process for the development of the CEDE matrices, can be found in (Besomi et al., 2020; Besomi et al., 2019; Hodges, 2020). Approval for this project was obtained from the Human Research Ethics Committee of The University of Queensland, Australia.

2.1. Development of draft content

The terminology matrix was drafted by LM and MML and developed for Round 1 review by the coordinator (MB) and the steering committee (KS, LM, MML, RM). The overall format for this matrix was divided into two sections: the definition of each term and general comments on that term. The comments section includes background information needed to provide context for understanding the definition, additional details not covered in the definition, or common misconceptions about the term. Appendix 1, covering some basic principles of EMG, was drafted by LM, MML and RM, and refined by the steering committee. This appendix provides background information on biophysics and signal processing concepts that will help researchers new to EMG to develop a deeper understanding of the origin and meaning of each definition.

2.2. Delphi process to reach consensus on the content

An online Delphi approach was used to reach consensus on each definition and comment among the panel of experts (von der Gracht, 2012). In round one, the entire terminology matrix was sent to every member of the CEDE panel of experts ($n = 18$). Contributors were asked to assess whether the definition was “appropriate” (score 7–9), “uncertain” (score 4–6) or “inappropriate” (score 1–3) and invited to provide comments to highlight aspects of the definition/comment that they did not agree with. Consensus was reached if $> 70\%$ of contributors provided scores between 7 and 9 (appropriate) and $< 15\%$ of contributors provided scores between 1 and 3 (inappropriate), with an interquartile range (IQR) ≤ 2 units (Williamson et al., 2012). For definitions that reached consensus, comments on that term from contributors were considered and implemented as appropriate. The steering committee (KS, MML, RM), coordinator (MB) and lead investigator (LM) did not participate in the rating process.

Questionnaire responses for each round were collected and compiled by the coordinator (MB). Terms that did not reach consensus in the round one questionnaire were revised by the lead investigator (LM) by

integrating feedback from the panel of expert contributors and the updated definitions were further refined and approved by the steering committee. If revisions to a definition were disputed among the CEDE expert panel, the steering committee was consulted before preparing the definition for the next round. The revised terms were re-sent to all experts who had responded the previous round. Changes to the definitions and/or the addition of new information were highlighted in the second-round questionnaire. This process was repeated for rounds two and three. All CEDE panel members reviewed and endorsed the final document and were included as authors.

3. Results

All 18 experts who agreed to participate in the Delphi process replied to the first-round questionnaire (100% response rate). The first version of the terminology matrix was composed of 74 terms in total (31 physiological terms and 43 technical terms). After round one of questionnaires, 14/31 of the physiological terms and 3/43 of the technical terms did not reach consensus (i.e., the criteria that $> 70\%$ of scores were between 7 and 9 and $< 15\%$ of scores were between 1 and 3, with an IQR < 2 , was not satisfied). Based on feedback from the expert panel, the term “Surface EMG bandwidth” was merged with the term “Bandwidth of a signal”; the term “Harmonic” was deleted, and the term “Amplitude of a signal” was split into three separate terms (“EMG instantaneous amplitude”, “EMG peak-to-peak amplitude” and “EMG amplitude”). New terms were also suggested for inclusion in round two (2 new physiological terms and 4 new technical terms). In total, 16 physiological terms and 9 technical terms went through to the second round (1 technical term that reached consensus in round one but was modified substantially was included again in round two).

In the second round, 89% (16/18) of the expert panel responded to the questionnaire. In round two, only 4 terms did not reach consensus (1 physiological term and 3 technical terms). Based on feedback, the term “EMG amplitude” was removed, and the terms “Average rectified value” and “Root mean square value” were renamed as “EMG amplitude: Average rectified value” and “EMG amplitude: Root mean square value”, respectively. Two physiological terms that had previously reached consensus but were modified in the second round to capture reviewer comments were included again in round three. In total, 3 physiological terms and 2 technical terms went through to the third round.

In the third round, there was a response rate of 94% (15/16). All terms reached consensus with minor comments, with the exception of “Signal envelope” which reached consensus but was rated below 7 by four contributors. Following a discussion among the members of the steering committee, the term “Signal envelope” was changed to “EMG signal envelope” and the definition was updated to address some of the concerns raised by the expert panel. The revised definition was sent to the members of the expert panel that had previously rated the definition below 7, and there was a general agreement that the definition was now appropriate. A summary of the results of the three rounds of the Delphi consensus process is presented for both the physiological and technical terms in Appendix 1 and 2, respectively.

The terminology matrices endorsed by the CEDE project team are presented in Table 1 (physiological terms) and Table 2 (technical terms).

4. Discussion

The present study was undertaken to establish consensus on the definitions of common terms used in EMG literature, covering both physiological and technical terms. Previous matrices in the CEDE project have highlighted the need for consensus in the definition and scope of common EMG terminologies (Besomi et al., 2020; Besomi et al., 2019). The definitions and comments on each term have been developed by integrating input from an expert panel with a diverse range of expertise using a Delphi process (Hodges, 2020).

Overall, more concise definitions were preferred by the expert panel.

Table 1
Physiological terms.

#	Term	Definition in words	Comments
1	Action potential (transmembrane action potential)	A transient change in electrical potential across the axonal or muscle fiber membrane, which excites adjacent sections to propagate the change in potential along the nerve or muscle fiber.	Action potentials can also be generated in other types of cells with excitable membranes. The term is also used to refer to the net potential change recorded during the simultaneous discharge of more than one muscle fiber, such as the motor unit action potential and the compound muscle action potential.
2	Agonist muscle	Muscle contributing to the force and/or joint moment required to achieve the task goal, often called a “prime mover”.	Antagonist and agonist muscles often occur in pairs (antagonistic pairs). In anatomy, the role of certain muscles is often defined based solely on their anatomical location. However, this idealized terminology is less applicable in the field of biomechanics, where it is more difficult to ascribe a specific role to a muscle during complex multi-joint motor tasks.
3	Antagonist muscle	Muscle that produces force and/or joint moment in a direction that opposes the action of the agonist muscle.	Agonist and antagonist muscles may be activated together to increase stability in the joint (i.e., increase joint mechanical impedance) to better control a specific task. It is good practice to monitor both.
4	Co-activation (or co-contraction)	The concurrent activation of two or more muscles.	Co-activation can be observed between combinations of agonist, synergist and/or antagonist muscles about a joint. During agonist–antagonist co-activation, the resultant moment of the force is lower than the individual contributions from agonist and antagonist muscles and there is an increase in the mechanical impedance (i.e., resistance to motion) of the joint (beyond what would be expected for similar net moments generated in the absence of co-activation).
5	Doublet or double discharge	Two successive action potentials of the same motor unit close together in time.	Historically, the interspike interval for doublets has been defined as 2.5–20 ms, however, it may be more accurate to define a doublet as an interspike interval that is significantly shorter than the mean interspike interval for a given motoneuron. A doublet is also typically followed by a long interspike interval.
6	Electrode	Sensor made of conductive material that couples the electrical potentials generated within the body to an electronic device.	In EMG, reference electrodes are typically placed over an electrically silent area such as a tendon or bone (surface electrodes) or on the cannula (intramuscular electrode). In monopolar recording configurations, the detected EMG signal is the potential difference between the recording electrode and the reference electrode.
7	Electromyographic signal	The time-varying electrical potential recorded within a muscle, in the surrounding tissue or at the skin surface during muscle activity. It is the summation of the extracellular action potentials generated by muscle fibers within the vicinity of the electrode.	
8	Excitation-contraction coupling	The physiological process by which an electrical stimulus (action potential) initiates a mechanical response in the muscle fiber.	In skeletal muscle contractions, an action potential at the sarcolemma of the muscle cell triggers the release of calcium by the sarcoplasmic reticulum. This initiates the sliding of the myofilaments, resulting in a muscle contraction.
9	Innervation zone (or end-plate region)	A region of a muscle where there is a concentration in the distribution of motor end-plates (neuromuscular junctions).	The characteristics of surface EMG signals are affected by the position of the recording electrode relative to the innervation zone. A term that is often confused with the innervation zone is the “muscle motor point”. The electrical motor point is defined as the location on the skin above the muscle where a muscle contraction is most efficiently generated through electrical stimulation. The anatomical motor point corresponds to the location where the motor branches of the innervating axons enter the muscle belly or where they are most superficial.
10	Instantaneous firing rate	The inverse value of the interspike interval between two successive action potentials discharged by a single motor unit.	Typically measured in discharges per second, pulses per second (PPS) or Hertz (Hz), see Mean Firing Rate.
11	Interspike interval, ISI (also referred to as Interpulse Interval, IPI)	The time between two successive action potentials discharged by a motor unit.	Typically measured in units of seconds or milliseconds.
12	Isometric contraction	A contraction in which a muscle exerts a force with no overall change in muscle–tendon length and no detected change in joint or limb position.	At the beginning of a muscle contraction, muscles can shorten substantially and tendons can lengthen with no change in joint or limb position (quasi-isometric).
13	Isotonic contraction	A contraction in which the muscle tension remains constant.	The term “isotonic” implies constant tension, however, in practice, constant muscle tension is rarely maintained. The term “isotonic” is often used to refer to a constant torque contraction under conditions that can isometric, concentric (muscle shortens) or eccentric (muscle lengthens) and for which the velocity of the movement can vary. This type of contraction is often performed using isokinetic

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Table 1 (continued)

#	Term	Definition in words	Comments
			dynamometers, which measure the torque a subject produces at a single joint.
14	Maximal voluntary contraction (MVC)	Contraction force measured at the greatest level of muscle activation that can be elicited under voluntary conditions (maximal voluntary effort).	The EMG signal is often normalized with respect to the EMG recorded at MVC. Some individuals may not be able to fully activate a muscle during MVC and additional muscle force can be generated through electrical stimulation of the motor nerve supplying the muscle (twitch interpolation).
15	Mean firing rate	The average number of action potentials discharged per second by a single motor unit.	Typically measured in discharges per second, pulses per second (PPS) or Hertz (Hz). Hertz is a unit that measures the number of cycles per second of a periodic, sinusoidal waveform and is thus not strictly applicable to the measurement of aperiodic motor unit firing.
16	Motoneuron or motor neuron	Neurons that integrate information from sources within the nervous system and transmit information to the muscle fibers that they innervate. The alpha motoneuron cell body is located in the spinal cord, or brainstem, and the axon leaves these structures to innervate a group of muscle fibers.	In the context of EMG, the term motoneuron typically refers to alpha motoneurons, which innervate extrafusal muscle fibers, rather than gamma motoneurons, which innervate smaller intrafusal fibers within the muscle spindle. Alpha motoneurons are known as the final common pathway in the processing of motor commands, as all activation signals from the brainstem/spinal cord to muscle are transmitted through them.
17	Motor unit	A motoneuron and all of the muscle fibers it innervates.	All muscle fibers belonging to a motor unit are activated every time the motoneuron discharges (in normal, healthy physiology). The muscle fibers of a motor unit (without the motoneuron) define the muscle unit.
18	Motor unit action potential	The summation of individual muscle fiber action potentials from all the fibers of a motor unit in response to a discharge of its motoneuron.	The motor unit action potential detected by an electrode system will depend on the electrode configuration and the position/orientation of the electrode relative to the muscle fibers.
19	Motor unit action potential train	Sequence of action potentials discharged by a single motor unit.	
20	Motor unit recruitment	Activation of a motor unit to participate in a muscle contraction. Related term: Recruitment threshold of a motor unit	During voluntary muscle contractions where there is a gradual increase in force, motor units are usually recruited in an orderly fashion referred to as "Henneman's size principle". This states that the threshold of motoneuron activation is determined by the size of the neuron, with recruitment occurring in approximate order of size –from the smallest motor units (typically innervated by the smallest motoneurons) to the largest (typically innervated by the largest motoneurons). It should be noted that the size principle may not apply to all types of muscle contractions (e.g., during ballistic or electrically stimulated muscle contractions).
21	Motor unit size	The size of a motor unit is often characterized by the number of muscle fibers innervated by a motoneuron, though different definitions have been used. The number of fibers a motoneuron innervates is generally correlated with the diameter of the innervating motoneuron axon.	Motor unit size is often quantified using the twitch force generated by the motor unit or the amplitude of the motor unit action potential. The twitch force of a motor unit depends on the number of muscle fibers innervated by the motor axon and the cross-sectional area of the muscle fibers. The amplitude of the recorded motor unit action potential depends on the number of muscle fibers innervated by the motor unit, the diameter of the fibers, the distance/orientation of the fibers relative to the recording electrode, and the acquisition parameters of the EMG detection system.
22	Motor unit synchronization	A tendency for two or more motor units to discharge together or within a few milliseconds of one another, with a rate of occurrence above that expected due to chance.	
23	Motor unit territory	The volume within a muscle in which the muscle fibers of a single motor unit are distributed.	
24	Muscle activation	The degree to which a muscle is excited, encompassing both the number of activated muscle fibers and the rate of their discharges.	Muscles are activated by neural drive from the motoneuron pool.
25	Muscle fiber action potential	The extracellular waveform detected from a single muscle fiber as an action potential propagates in both directions away from the neuromuscular junction.	
26	Muscle fiber conduction velocity	The speed at which an action potential propagates or travels along a muscle fiber.	A 'global' estimate of muscle fiber conduction velocity may be obtained from the time taken for a surface EMG signal to travel between two spatially displaced recording electrodes. Conduction velocity is expressed in m/s or mm/ms with values typically centered around a mean of 3–4 m/s
27	M-wave or compound muscle action potential (CMAP)	The summated electrical response of motor units within a muscle, evoked by electrical stimulation of the muscle's motor point.	The M-wave is typically equal to the sum of the motor unit action potentials of all the motor units excited by the stimulation.

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Table 1 (continued)

#	Term	Definition in words	Comments
28	Neural drive	The neural drive to a muscle refers to the net output of all the motoneurons that innervate the muscle.	Neural drive is also used in the context of the neural drive to the motoneuron pool, which refers to the net synaptic input to the motoneurons from different areas of the central nervous system.
29	Neuromuscular junction	The synaptic connection between an axon terminal of a motoneuron and a skeletal muscle fiber.	The neuromuscular junction consists of a presynaptic motor axon terminal, a postsynaptic motor endplate on the muscle fiber and the synaptic cleft between the axon terminal and the motor endplate.
30	Persistent inward currents (PICs)	Slowly inactivating voltage-sensitive Na and Ca currents that amplify and prolong the synaptic input to neurons.	Motoneurons can have strong persistent inward currents, which are dependent on descending monoaminergic drive.
31	Rate modulation or rate coding (for one MU)	A change in the mean firing rate of a motor unit during a voluntary muscle contraction.	Both motor unit recruitment and rate coding can be used to modulate force production.
32	Recruitment threshold of a motor unit	Often defined as the force or torque at which a motor unit begins to discharge action potentials repetitively.	Recruitment threshold has also been estimated from the amplitude of the EMG signal when a motor unit begins to discharge repetitively. The recruitment threshold is sensitive to the task, type of muscle contraction, contributions from other muscles and the history of muscle activation. The force/EMG amplitude at recruitment are indirect approximations of the recruitment threshold of a motor unit. Furthermore, it is often difficult to quantify the force produced by a single muscle in isolation.
33	Synergist muscle	Muscle that supports the work of the agonist and facilitates the completion of the task goal.	Synergist muscles include muscles that contribute to the joint moment of the agonist and/or stabilize the origin of the agonist muscle to enable efficient movement during the task. This “functional” or “biomechanical” definition should not be confused with “muscle synergies” (also called modules or motor primitives). Muscle synergies are coordinated activations of a group of muscles.

In the development of the matrix, it became clear that there were general terms commonly used in the EMG literature that cannot be clearly defined and consequently, required more rounds to reach consensus. One such example was the term “EMG amplitude”, which when used in isolation is non-specific and uninformative. The consensus process for this matrix highlighted the importance of defining the meaning of general EMG terms before use. For example, if “EMG amplitude” was being used in the context of describing the root-mean-square amplitude of the EMG signal, then this should be stated when the term was first used. Other examples of terms that could not be uniquely or precisely defined were “motor unit size” and “motor unit recruitment threshold”. The final definitions for these terms were not strict but describe the most common definition used in the literature, with alternative definitions outlined in the comment section. The consensus on these terms was that no single definition is correct, and the best choice of descriptor depends on the measurement paradigm (although, as noted in the comment section, some descriptions are more accurate than others). In other cases, general terms required more rounds to reach consensus as the common usage of the term has evolved to have a different meaning than when the term was initially defined. For example, “isotonic contraction” was initially used to describe isolated muscle preparations in which there was a constant external load (isotonic – “constant tension”) applied to the muscle. However, the term is now commonly used to describe muscle contractions in humans, in which precisely constant muscle tension is rarely maintained. In these cases, alternative terms may provide a more accurate description of the muscle contraction in human muscle-joint systems (e.g., isoinertial, isokinetic or constant-force).

In general, definitions for physiological terms tended to require more revisions before reaching consensus. In compiling the definitions for the most common physiological terms, often multiple versions of the same definition could be found throughout the literature, occasionally with marked differences that varied according to the specialization of the author. The number of accepted variations on the definition of the same term used through the literature may have contributed to a difficulty

reaching consensus for some terms. For example, experts with a biomechanics background tended to describe muscles or muscle actions more precisely using force/joint moment rather than in terms of “movement” (e.g., isometric contraction, synergist muscle, agonist muscle). Another factor that may have delayed consensus for physiological terms is that often these terms require qualitative definitions, and unlike many of the technical terms, they cannot be directly measured or accurately quantified (e.g., neural drive, muscle activation and excitability, (Kiernan et al., 2020)). Although physiological terms may have been expressed differently by experts on the panel coming from a technical/engineering background, the underlying meaning that the experts wished to convey for each definition tended to be consistent across the panel. The consensus process itself highlighted the importance of this terminology matrix in creating a common language across the range of specializations within EMG research.

EMG is used by researchers and clinicians from a diverse range of specializations, including (but not limited to) physiology, kinesiology, physical therapy, biomechanics, and engineering, in addition to clinical academics, specialist physicians and physiatrists. Combining the knowledge of experts with both technical and physiological backgrounds provides a more comprehensive and accurate definition for each term. The overview of fundamental EMG terminology presented in this matrix will support consistency in EMG terminology across different specializations and facilitate the integration of EMG studies across these different fields of research. Clear definitions of EMG terms can improve the quality of communication both to other specialists and to new researchers and avoid differences in the interpretation or misuse of a term. The overview of EMG terminology and EMG signal recording and analysis in this paper provides a gateway into the EMG literature for non-specialists, a resource for teaching EMG, and a reference from which to access other papers within the CEDE project that provide a more detailed analysis of specific EMG topics.

Table 2
Technical terms.

#	Term	Definition in words	Comments/ common misinterpretation(s)
1	Aliasing	The distortion of a signal and its power spectrum that occurs when the analog signal is sampled at a rate that is too low to create an accurate digital representation of the signal. Related term: Sampling in time	The sampling rate should be greater than twice the highest frequency component contained in the signal to be recorded to avoid aliasing (Nyquist's theorem). In practice, the sampling rate for recording EMG signals should be at least 2.5–3 times higher than the highest frequency component contained within the EMG signal. To avoid aliasing, signals should be low-pass filtered with an anti-aliasing filter with a cut-off frequency less than half the desired sampling frequency before sampling (Nyquist's theorem).
2	Analog-to-digital (A/D) conversion	The process of converting a continuous analog signal into a sequence of discrete (binary) numbers that can be stored and processed. Related terms: Sampling in time, aliasing, A/D quantization error	Choosing an A/D converter with a higher number of bits can reduce quantization errors (the most commonly used A/D converters have resolutions of 8, 12 or 16 bits). The number of bits in an A/D converter determines the number of discrete voltage levels that can be represented by the A/D converter. For example, a 16-bit A/D converter can represent $2^{16} = 65536$ (0 to 65535) distinct voltage levels (i.e., 2^n where n is the number of bits).
3	A/D quantization error	The difference between the value of the analog signal and the closest available discrete value, at each sampling instant, provided by the analogue to digital (A/D) converter. Related term: A/D conversion, A/D resolution	It is reduced by increasing the number of levels of the A/D converter which is given by 2^n where n is the number of bits, e.g., a 4-bit converter has 16 levels (2^4), from 0 to 15.
4	A/D resolution	The smallest incremental change in voltage in a continuous analog signal that will change the discrete binary value detected by an A/D converter by one count. Related term: A/D conversion, A/D quantization error	An n-bit A/D converter produces 2^n discrete binary levels. The resolution is the input voltage range of the A/D converter divided by $2^n - 1$ steps.
5	Auto-correlation	A measure of self-similarity within a signal, i.e., the correlation between the signal and a delayed version of itself. In other words, how much the value of a signal depends on (or is related to) its past and future values. The discrete auto-correlation function, R_{xx} , of a finite, discrete signal, x , can be estimated as: $R_{xx}[m] = \frac{1}{N} \sum_{n=0}^{N- m -1} x_n x_{m+n}, 0 \leq m \leq M-1$ where N is the total number of samples in the signal, m is the lag in samples (i.e., $ m = 0, 1, 2, \dots, M-1$, M is the range of lag values where $M \ll N$), and x_n is the value of the n^{th} sample within the signal. Since $R_{xx}[-m] = R_{xx}[m]$, it is necessary to only to evaluate the auto-correlation function for the nonnegative values of m . This is a biased estimate of R_{xx} , but the bias is small where $M \ll N$.	The equation for R_{xx} in continuous time can also be expressed as (note that below we provide the expression over the entire time axis): $R_{xx}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} x(t)x(t+\tau)dt$ The power spectrum of the signal $x(t)$ can be obtained by taking the Fourier transform of its auto-correlation, R_{xx} (the power spectrum is also the magnitude squared of the Fourier transform of $x(t)$).
6	Bandwidth of a signal	The range of frequencies in which a signal contains power and information. The 3-dB bandwidth is the interval between frequencies at which the power spectral density has dropped to half power, or 3 dB below the peak value.	Surface EMG signals typically contain energy at frequencies from 10 to 500 Hz. Intramuscular EMG signals contain energy at frequencies as high as 5 kHz (due to the rising edges of action potentials from muscle fibers close to the electrode). The bandwidth of the recorded signal may be altered by hardware or software filters applied to the signal.
7	Coherence	Indicator of the linear relationship or dependency between two random (stochastic) processes as a function of frequency (or time and frequency), measured on a scale from 0 to 1 (0 means the processes are uncorrelated, and 1 indicates a perfect linear relationship). The coherence (or magnitude-squared coherence), $C_{xy}(f)$, indicates how much each component of the spectrum of x is related to the same frequency component of the spectrum of y : $C_{xy}(f) = \frac{ S_{xy}(f) ^2}{S_{xx}(f)S_{yy}(f)}$ where $S_{xy}(f)$ is the cross power spectral density between signal x and signal y , and $S_{xx}(f)$ and $S_{yy}(f)$ are the auto-power spectral densities of signals x and y , respectively.	When the coherence between two signals is < 1 , it indicates that there is some independent component contained in one of the signals that is not present in the other and/or there is a nonlinear relationship between the two signals.
8	Common-mode rejection ratio (CMRR)	The ratio of the differential gain of an amplifier (A_d) to the common mode gain (A_{cm}). It quantifies the ability of an amplifier to reject common-mode signals (unwanted signals seen at both input terminals) and amplify differential signals (signals that are different at the input terminals). The ratio is usually measured in decibels (dB). $CMRR = 20 \log_{10} A_d/A_{cm} $	An ideal amplifier would reject all common-mode signals, i.e., CMRR would be infinite.
9	Continuous wavelet transform	The continuous wavelet transform is one of many time–frequency representations used in signal processing. These transforms deconstruct a time domain signal into a sum of	In contrast to the Fourier expansion, the basic waveforms into which the signal is decomposed are not sinusoids but finite

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Table 2 (continued)

#	Term	Definition in words	Comments/ common misinterpretation(s)
		<p>“wavelets” of different scales and time shifts, to produce a time–frequency representation of a time domain signal. It is often applied to signals that exhibit temporal variations in frequency content (i.e., non-stationary signals).</p> <p>The continuous wavelet transform, CWT_x, of a signal x is given by the convolution of the signal with a wavelet function, Ψ:</p> $CWT_x(s, \tau) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t) \Psi^* \left(\frac{t-\tau}{s} \right) dt$ <p>where the $*$ denotes the complex conjugate and Ψ is a function of s and τ, where s is the resolution or scale factor, τ is the time shift factor and t is time. The wavelet function is stretched or compressed by changing the scale factor.</p>	<p>duration waveforms that are concentrated in time. There is a variety of such waveforms with different properties.</p>
10	Cross-correlation	<p>Estimate of the linear relation between two signals (or between two series of samples) as a function of the time displacement of one relative to the other.</p> <p>The cross-correlation function, R_{xy}, of two finite, discrete signals, x and y, can be estimated as:</p> $R_{xy}[m] = \frac{1}{N} \sum_{n=0}^{N- m -1} x_n y_{m+n}, \quad -(M-1) \leq m \leq M-1$ <p>where N is the total number of samples in the signal, m is the lag in samples (i.e., $m = 0, \pm 1, \pm 2, \dots, \pm(M-1)$), M is the range of lag values where $M \ll N$ and x_n and y_n are the values of the n^{th} samples within the signals x and y, respectively. This is a biased estimate of R_{xy}, but the bias is small where $M \ll N$.</p>	<p>Cross-correlation can be used to estimate the delay between similar or identical signals (e.g., for the estimation of conduction velocity). For example, if $y(t) = x(t-\tau)$, the cross-correlation function between $x(t)$ and $y(t)$ is equal to 1 for the time delay τ, i.e., $y(t)$ is a time delayed version of $x(t)$ and the time delay is τ seconds.</p> <p>The equation for R_{xy} in continuous time can also be expressed as (note that below we provide the expression over the entire time axis):</p> $R_{xy}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} x(t) y(t + \tau) dt$ <p>The cross-power spectrum of signals $x(t)$ and $y(t)$ can be obtained by taking the Fourier transform of their cross-correlation, R_{xy}.</p>
11	Crosstalk	EMG signals from muscles other than the muscle of interest.	<p>Crosstalk from surrounding muscles can be detected when recording from small or thin muscles, when muscles are interposed between the muscle of interest and the electrode, or when using electrodes with a large inter-electrode distance due to their large detection volume. Crosstalk is an important consideration for study design and electrode selection (Besomi, Hodges, 2019).</p>
12	Current	<p>The rate of flow of charged particles per unit time (Coulombs per second, C/s, or Amperes, A).</p> <p>$1C = 6.25 \cdot 10^{18}$ electrons</p>	
13	Decomposition of EMG	Process by which the action potential trains of some active motor units are extracted from the EMG signal.	<p>Specialized algorithms can be used to identify motor unit action potential waveforms from the same motor unit contained within the EMG signal.</p>
14	Differential Amplifier Gain	The factor of amplification (A_d) given to the difference in voltage (V_d) between the two input terminals of a differential amplifier.	<p>The output voltage of the amplifier is $V_{out} = A_d V_d$ (in an ideal differential amplifier, where the common-mode voltage gain is zero).</p>
15	Double differential technique	A method of recording EMG using three electrodes and three differential amplifiers, which is used to reduce interference and crosstalk in the EMG signal.	<p>EMG is recorded from three electrodes aligned over the active muscle (typically with equidistant spacing). The signals are passed into two differential amplifiers (with one input common to both amplifiers) to obtain the difference between the first and second signals, and between the second and third signals. The output signals from the two differential amplifiers (i.e., bipolar or single differential EMG signals) are then used as an input to a third differential amplifier to obtain the double differential signal.</p> <p>Performing the differential subtraction twice results in a higher attenuation of signals originating from muscles that are further away (as these signals will appear similar, i.e., as common-mode signals, at all amplifier inputs).</p>
16	Driven Right Leg (DRL)	<p>A technique widely used in electrocardiography, and occasionally in electromyography, whereby the common-mode voltage (primarily due to power line interference) on the body is negatively fed back (i.e., the phase is reversed) to a third electrode, through a feedback amplifier, driving the common mode voltage to a lower level and thereby reducing the power line interference.</p> <p>The additional ECG electrode is typically applied to the right leg (hence, the name).</p>	<p>This technique is occasionally used in surface electromyography where the additional feedback electrode is not necessarily applied to the right leg.</p>
17	Electrocardiographic (ECG) interference	Unwanted voltage fluctuations due to the ECG signal, typically present when EMG electrodes are applied to the chest, back or abdominal muscles.	<p>ECG interference can be attenuated by processing the EMG signal post-recording, as it may not be sufficiently reduced by differential detection or the DRL technique.</p>
18	Electrode impedance	The opposition (impedance) to the flow of the electrical current, as a function of frequency, at the contact point between the electrode and the skin surface.	<p>Lower electrode impedance is generally desired.</p>

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Table 2 (continued)

#	Term	Definition in words	Comments/ common misinterpretation(s)
19	Electrode-Tissue interface	The contact region between the electrode and the skin surface.	The change in the current carrier (from ions to electrons) at the interface between the electrode and the skin generates random noise, the amplitude of which will depend on the contact surface, the electrode used and the skin condition. The impedance at the electrode-tissue interface may be reduced by conductive gel.
20	EMG amplitude: Average rectified value (ARV) or mean absolute value (MAV)	<p>An estimate of the average amplitude of a signal over a given time period. The ARV is defined as the average of the “rectified” (absolute value) signal over an epoch (or window) of duration T (or N samples).</p> <p>The average rectified value for one signal epoch, V_{ARV}, is defined as:</p> $V_{ARV} = \frac{1}{N} \sum_{n=0}^{N-1} V_n $ <p>where N is the total number of samples being averaged (over the epoch of the EMG signal under analysis) and V_n is the value of the n^{th} sample within the epoch.</p>	<p>In practice, the mean value of the signal should be subtracted from the total signal length before rectifying. The epoch/window duration should also be stated when reporting V_{ARV}.</p> <p>The equation for V_{ARV} can also be expressed in continuous time:</p> $V_{ARV} = \frac{1}{T} \int_0^T V(t) dt$ <p>where T is the length of the signal epoch in seconds.</p>
21	EMG amplitude: Root mean square value (RMS)	<p>An estimate of the standard deviation (amplitude) of the signal over a given time window or epoch.</p> <p>The RMS value is the square root of the mean square value estimated over an epoch (or window) of duration T (or N samples). RMS is the square root of the power of the signal.</p> <p>The root mean square value, V_{RMS}, for one signal epoch is defined as:</p> $V_{RMS} = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} V_n^2}$ <p>where N is the total number of samples being averaged (over the epoch of the EMG signal under analysis) and V_n is the value of the n^{th} sample within the epoch. The epoch/window duration must be stated when reporting the V_{RMS}.</p>	<p>The equation for V_{RMS} can also be expressed in continuous time:</p> $V_{RMS} = \sqrt{\frac{1}{T} \int_0^T V^2(t) dt}$ <p>where T is the length of the signal epoch in seconds.</p>
22	EMG instantaneous amplitude	The instantaneous amplitude of the EMG signal is a measure of how far, and in what direction, the signal differs from zero Volts.	The instantaneous amplitude of a signal differs from the magnitude as it can be either positive or negative. It is not recommended as an amplitude indicator for interference EMG signals.
23	EMG peak-to-peak amplitude	The peak-to-peak amplitude refers to the difference between the maximum and minimum values of the recorded waveform observed in a specified time window (epoch).	Can be used to quantify the amplitude of motor unit action potentials and compound muscle action potentials. It is not recommended to use peak-to-peak amplitude as an amplitude indicator for the interference EMG signals that arise from the asynchronous firing of motor units during voluntary contractions.
24	EMG signal envelope	A smooth curve that tracks changes in the amplitude of an EMG signal over time.	The envelope of an EMG signal is usually estimated by rectifying and then low-pass filtering the EMG signal. When reporting the EMG envelope, the filter characteristics (filter type, order, and cut-off frequency) or duration (and overlap) of the moving average window should be specified.
25	Filter	<p>Broadly, a filter is a system (circuit or mathematical algorithm) used to shape the frequency content of a signal to attenuate unwanted frequency components.</p> <p>Related term: Roll-off</p>	<p>A high-pass filter removes or attenuates the frequency components of a signal that are below a certain cut-off frequency, i.e., a high pass filter lets the high frequencies pass.</p> <p>A low-pass filter removes or attenuates the frequency components of a signal that are above a certain cut-off frequency, i.e., a low-pass filter lets the low frequencies pass.</p> <p>A band-pass filter retains frequency components that are within the band-pass range.</p> <p>A notch (band-stop) filter attenuates frequency components within a narrow band of frequencies.</p> <p>Both analog and digital filters are used in EMG. EMG amplifiers contain analog filters to remove low- and high-frequency components prior to digitization. After digitization, digital filters can be used to further adjust the signal characteristics.</p>
26	Fourier transform and Fourier series expansion	<p>Mathematical functions that permit the representation of a signal as the weighted sum of constituent sinusoids of different amplitude, frequency, and phase, enabling a frequency domain representation of the signal. The Fourier series expansion can be derived as special case of the Fourier transform for periodic signals, or for signals of finite length such as a segment of EMG signal.</p> <p>The Fourier transform, $X(f)$, of an infinitely long signal $x(t)$, at each frequency f, can be expressed as:</p> $X(f) = \int_{-\infty}^{\infty} x(t) e^{-i2\pi ft} dt$ <p>The inverse Fourier transform given by:</p>	The Fourier expansion is used to examine the frequency content of EMG signals, e.g., the spectral density of the EMG signal as a function of frequency. Frequency domain analysis of surface EMG signals can provide information on changes in the mean or median frequency of EMG power spectral density (often used in the study of muscle fatigue).

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Table 2 (continued)

#	Term	Definition in words	Comments/ common misinterpretation(s)
		$x(t) = \int_{-\infty}^{\infty} X(f) e^{i2\pi ft} df$ <p>The discrete Fourier transform (DFT) of a sampled signal x_n ($n = 0, 1, 2, \dots, N-1$) is given by X_k:</p> $X_k = \sum_{n=0}^{N-1} x_n e^{-i \left(\frac{2\pi nk}{N} \right)}$ <p>Where x_n is the value of the n^{th} sample, N is the total number of samples, i is the imaginary unit ($i = \sqrt{-1}$), X_k is the value of the k^{th} DFT frequency component ($k = 0, 1, 2, \dots, N-1$).</p> <p>The original signal x may be reconstructed from its Fourier expansion, X, with the inverse transform:</p> $x_n = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{i \left(\frac{2\pi nk}{N} \right)}$	
27	Frequency	<p>The frequency of a sinusoidal signal is the number of repetitions (periods) of the signal per second, measured in Hertz (Hz). Related terms: Fourier transform/Fourier series expansion</p>	<p>The term is often also used, in a less rigorous way, to denote the repetition rate of non-sinusoidal and non-periodic signals, e.g., a square wave or a motor unit firing rate (more precisely defined as pulses/s) and sampling rate (more precisely defined as samples/s).</p> <p>A non-periodic signal such as an EMG signal contains energy at a particular frequency if it has components that change as rapidly as a sinusoid of that frequency.</p>
28	Input impedance	<p>A measure of the opposition to the flow of current into each input terminal of an amplifier, as a function of frequency. Related terms: Resistance, differential amplifier gain</p>	<p>An ideal EMG amplifier has infinite input impedance, i.e., no current flows in or out of the input terminals of the amplifier.</p>
29	Mean spectral frequency or centroid frequency (MNF) or mean power frequency (MPF)	<p>Defines the centroid or barycenter of the power spectrum of the signal that is the frequency around which the frequency components of the spectrum are grouped. Mathematically defined as the normalized, one-sided, first-order spectral moment of the EMG power spectral density.</p> <p>The mean frequency (or mean power frequency), f_{mean}, is defined as:</p> $f_{mean} = \frac{\sum_{j=1}^{k_{max}} f_j P_j}{\sum_{j=1}^{k_{max}} P_j}$ <p>where P_j is the power of the j^{th} frequency component of the EMG power spectrum and k_{max} is the index of the highest frequency component present in the signal (the highest frequency is usually taken as half of the sampling frequency).</p> <p>Related terms: Median spectral frequency, power spectrum, Fourier transform, frequency.</p>	<p>MNF is usually higher than median spectral frequency because of the skewed shape of EMG power spectrum.</p> <p>The equation for f_{mean} can also be expressed in continuous time:</p> $f_{mean} = \frac{\int_0^{f_{max}} f P(f) df}{\int_0^{f_{max}} P(f) df}$ <p>where f_{max} is the highest frequency component present the signal.</p>
30	Median spectral frequency (MDF)	<p>The frequency which divides the EMG power spectrum into two regions, each containing half of the total power within the signal epoch.</p> <p>It is also defined as the 50th percentile of the power spectrum, which means that the frequency components below it contain 50% of the total power and those above it contain 50% of the total power.</p> <p>The median frequency, f_{med}, is defined as follows:</p> $\sum_{j=1}^{k_{fmed}} P_j = \sum_{j=k_{fmed}}^{k_{max}} P_j = \frac{1}{2} \sum_{j=1}^{k_{max}} P_j$ <p>where P_j is the power of the j^{th} frequency component of the EMG power spectrum, k_{fmed} is the index of the median frequency and k_{max} is the index of the highest frequency component present the signal (the highest frequency is usually half of the sampling frequency). Note that $f_{med} = \Delta f k_{fmed}$, where Δf is the frequency resolution.</p> <p>Related terms: Mean spectral frequency, power spectrum, Fourier transform, frequency.</p>	<p>MDF and mean spectral frequency have similar properties.</p> <p>The equation for f_{med} can also be expressed in continuous time:</p> $\int_0^{f_{med}} P(f) df = \int_{f_{med}}^{f_{max}} P(f) df = \frac{1}{2} \int_0^{f_{max}} P(f) df$ <p>where f_{max} is the highest frequency component present in the signal. The value f_{max} is often replaced by half of the sampling frequency ($f_s/2$) since $P(f) = 0$ at frequencies greater than f_{max}.</p>
31	Motion artefact (or movement artefact)	<p>Unwanted voltage fluctuations present in the EMG signal due to movement between the electrode and tissue or the movement of cables connected to the recording electrodes.</p>	<p>Motion artefact at the electrode-tissue interface encompasses both movement of the electrode and the underlying skin and deformation or stretching of the skin underneath the electrode. It can be reduced by careful skin preparation and secure placement of the electrodes.</p> <p>Most of the power in EMG signals occurring due to motion artefact will lie below 20 Hz and can be attenuated by high-pass filtering the signal.</p>
32	Moving average of a rectified (or squared) EMG signal	<p>A simple method to smooth EMG data, that acts as a low-pass filter, reducing random fluctuations in the rectified (absolute value) or squared EMG signal. Each sample of the rectified EMG is replaced by the average of $N + 1$ samples ($N/2$ samples before it and $N/2$ samples after it).</p> <p>Related terms: Filter, EMG signal envelope, EMG amplitude:</p>	<p>It is usually applied to rectified (absolute value) or squared signals. The width of the moving average window selected (and the degree of overlap between windows) should be stated when reporting results. The appropriate length for a moving average window will be shorter when analyzing muscle activity during dynamic contractions than during isometric contractions.</p>

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Table 2 (continued)

#	Term	Definition in words	Comments/ common misinterpretation(s)
		Root mean square value, EMG amplitude: Average rectified value (ARV) or mean absolute value (MAV)	
33	Normalization	The procedure by which a measurement obtained from a particular muscle and subject is expressed as a percentage or proportion of a reference measurement obtained from the same muscle and subject. For example, the amplitude of an EMG signal might be expressed as a fraction of the EMG signal amplitude recorded during an MVC of the same subject.	Normalization of the EMG amplitude to a reference value enables comparisons between subjects/muscles/measurement sessions/electrode positions, etc. To interpret and compare the RMS or ARV amplitude of EMG signals they must be normalized, as a number of factors that are unrelated to muscle activity can influence the recorded voltage (e.g., thickness of subcutaneous layers).
34	Phase	The phase of a signal denotes the delay of a periodic signal relative to a reference time point. As the value of a sinusoidal signal at any point in time is based on circular motion, the phase of a signal is expressed as an angle (start of one period = 0 degrees or 0 rad, end of one period = 360 degrees or 2π radians). The term 'phase' is also used in a different context to refer to regions of an action potential waveform where it deviates in either positive or negative direction.	Phase difference is a measure of relative delay between two signals of the same frequency, Fig. 1(a) in Appendix 1.
35	Power line interference	Unwanted fluctuations in voltage generated by alternating 50/60 Hz voltage in power lines and electrical wiring, which can contaminate or interfere with the detected EMG signal.	Power line interference may also be present at higher harmonics of the 50/60 Hz AC frequency (50 – 100-150...etc. Hz or 60–120-180 etc. Hz). The magnitude of power line interference can be reduced by minimizing any difference in the electrode-tissue impedance between the two EMG amplifier input terminals through adequate skin preparation, by choosing an amplifier with a high input impedance and by moving subject and equipment away from power cables.
36	Power of a signal	The average power, P , in a discrete time signal, x , is defined as the mean of the squares of its sample values: $P = \frac{1}{N} \sum_{n=0}^{N-1} x_n^2$ where N is the total number of samples in the signal and x_n is the value of the n^{th} sample within the signal.	The equation for P can also be expressed in continuous time: $P = \frac{1}{T} \int_0^T x^2(t) dt$ where T is the length of the signal in seconds.
37	Power spectrum/power spectral density of a signal	Distribution of the power contained within a signal at different frequencies. The power spectral density of an EMG signal has the units Volt squared per Hertz (V^2/Hz). Related terms: Fourier transform, frequency.	The integral of the power spectral density of a signal's Fourier transform is equal to the total power of the signal.
38	Pre-amplification or "Front-end stage" amplification	The first stage of EMG amplification process, that is ideally located close to the electrode.	Pre-amplifier should ideally have a high common mode rejection ratio (CMRR), a high input impedance, and be located close to the signal source. The purpose of the pre-amplification stage is to reject noise and interferences close to the signal source and generate a signal with a low-impedance output to help prevent further noise contamination.
39	Rectification	The translation of a signal into a signal with a single polarity (i.e., positive), obtained by taking the absolute value of the signal at each instant in time.	When calculating the RMS or ARV amplitude of an EMG signal, $x(t)$, the mean value of the signal should be subtracted from the total signal length (or the signal should be high-pass filtered) before rectifying (i.e., $x(t)$ should be a zero-mean signal prior to calculating $ x(t) $).
40	Resistance	Resistance is a measure of the opposition to the flow of electric current, measured in Ohm.	DC (direct) current will tend to follow the path of least resistance in a circuit. AC current (alternating sinusoidal current of a given frequency) will tend to follow the path of lowest impedance. Impedance alters both the magnitude and phase of current flow and can vary as a function of frequency.
41	Roll-off	The roll-off of a filter describes the rate of change in signal attenuation between frequencies that pass through the filter unattenuated (passband) and frequencies that are attenuated by the filter (stopband), Fig. 3 (b) in Appendix 1. It is measured in either decibels/decade or decibels/octave, where a decade is a tenfold increase in frequency and an octave is a twofold increase in frequency. Related term: Filter	Higher order filters have higher roll-off values (steeper transitions between passband and stopband frequencies).
42	Sampling in time	An analog EMG signal can be sampled in time by taking instantaneous voltage values at a particular rate or sampling frequency (samples/s or Hz). Related terms: Aliasing, A/D conversion	When converting a signal from analog to digital form, the signal must be sampled at a rate which is greater than twice the highest frequency component in the signal bandwidth (Nyquist's theorem) in order to retain all the information contained within the signal. In practice, the sampling rate should be 2.5 – 3 times higher than the highest frequency component contained within the EMG signal.

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Table 2 (continued)

#	Term	Definition in words	Comments/ common misinterpretation(s)
43	Signal-to-noise ratio (SNR)	The relative power of wanted (EMG) to unwanted signal components (noise, interference etc.) that are contained in the overall signal. It measures the quality of the signal.	SNR is typically measured on logarithmic scale and expressed in decibels (dB).
44	Spatial sampling	An array or grid of electrodes can be used to sample the distribution of the EMG signal in space, e.g., across the skin surface (using a surface electrode array) or within the muscle (with multi-channel intramuscular EMG). Related terms: Filter, aliasing, sampling in time.	
45	Stationarity/ Quasi-stationarity/ Non-stationarity	A signal exhibits stationarity when the statistical properties of the processes that generate the signal do not change over time. A signal exhibits quasi-stationarity when it can be assumed that the processes generating the signal are stationary over short time intervals (time windows or epochs used for estimating the signal properties such as ARV, RMS, power spectrum, MNF, MDF, etc.), but can vary when considered over longer time intervals or across different epochs. A signal exhibits non-stationarity when the statistical properties of the processes that generate the signal, and consequently those of the signal itself, change over time.	Isometric constant force contractions produce surface EMG signals that are quasi-stationary within time epochs of 0.5–1.0 s.
46	Voltage (or potential difference)	The energy required to move an electric charge between two points in an electric field, measured in Volt.	EMG is typically measured in μV or mV.

5. Conclusion

The aim of the terminology matrix is to provide expert consensus from the CEDE project team on the definition and correct usage of common EMG terms. This matrix does not replace formal training or education in EMG practice. Rather, it is intended for use as a reference to aid in the consistent use of terminology when reporting results from EMG studies and clinical applications

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Appendix A. Basic principles of recording and analysis of electromyography data

1. Introduction

This appendix provides a general introduction to electromyography (EMG), and a brief overview of the stages of EMG recording and basic EMG signal analysis. This overview covers some of the biophysics and signal processing concepts underpinning the definitions in the accompanying paper and provides context for the physiological and technical terms included in the two terminology matrices. Terms highlighted in bold in this appendix are defined in the accompanying terminology matrices. A more detailed analysis of the topics covered in the background supporting material can be found in [McManus et al. \(2020\)](#) (in addition to a list of relevant EMG resources), [Merletti and Cerone \(2020\)](#), and [Merletti & Muceli \(2019\)](#). More detail on the procedures for electrode selection ([Besomi et al., 2019](#)) and amplitude normalization of the EMG signal ([Besomi et al., 2020](#)) can be found in other papers from the CEDE project.

2. Fundamentals of EMG

Electromyographic signals or EMG signals provide information on the electrical activity of a contracting muscle, representing the voltage signal generated by the muscle, [Fig. 1 \(e\)](#). **Voltage** (V), measured in Volts, is the difference in electrical potential between two points (e.g., in a bipolar configuration, the potential difference between recordings from two **electrodes**, or in a monopolar configuration, between an electrode and a

reference electrode (sometimes misleadingly referred to as a “ground” electrode¹). The reference electrode is typically placed in a location expected to receive minimal contribution from the active fibers, often over an electrically silent area such as a tendon or bone). In the body, electric charge is carried by ions — the rate of flow of charge is the electrical **current** (I) and is measured in Amperes (coulombs per second). Muscle, subcutaneous tissue, bone, and skin provide an electrical impedance (Z) to the flow of electric current. While this impedance has both capacitive and resistive components, for most EMG applications the resistive component dominates, and the tissue impedance can be represented by the **resistance** (R) quantified in Ohms (Ω) (where $V = IR$).

When a muscle fiber is at rest, there is a potential (or voltage) difference between the inside and outside of the muscle fiber cell (resting membrane potential). This is maintained at a negative value (of approximately -80 mV) due to differences in the concentration of the intracellular and extracellular Na^+ and K^+ ions. During **muscle activation**, **action potentials** travelling along the motoneuron from the spinal cord arrive at the **neuromuscular junction** and cause the release of a neurotransmitter (acetylcholine) which crosses the synapse between the **motoneuron** terminal and muscle fiber membrane. This binds to a receptor on the membrane which opens a channel to allow Na^+ ions flow inwards along the electrical and osmotic gradients to the interior of the cell, causing it to become less negative with respect to the outside of the cell. Once a threshold voltage is reached, voltage sensitive ion channels are activated and open, leading to a rapid influx of Na^+ ions. This depolarization then leads to activation of voltage sensitive Na^+ channels in adjacent regions, in such a way that a wave of depolarization propagates in either direction along the muscle fiber (**muscle fiber action potential**). Opening of the Na^+ channels is followed closely by activation of voltage sensitive K^+ channels, resulting in an efflux of K^+ and repolarization of the cell membrane. Energy-consuming sodium potassium pumps then restore the ionic concentration by exchanging two Na^+ ions for each K^+ ion during each cycle to re-establish the resting membrane potential. Action potentials propagate along the exterior muscle fiber membrane and down into the transverse tubular network that penetrates into the cell, where they induce release of Ca^{2+} ions from the sarcoplasmic reticulum to initiate **excitation–contraction coupling** – the process whereby protein filaments in the muscle fiber (actin and myosin) form bonds and slide relative to each other to generate the force of contraction.

The EMG signal can be more precisely defined as the time-varying extracellular voltage generated as action potentials propagate along the muscle fiber membrane in both directions away from the **neuromuscular junction**. Depending on the electrode type, EMG can be recorded within a muscle (intra-muscular fine wire or needle electrodes), in the surrounding tissue (e.g., subcutaneous electrodes) or at the skin surface (surface electrodes). It is comprised of the summation of individual **motor unit action potentials** – brief electrical potentials generated by the excitation of the muscle fibers of a motor unit. A **motor unit** refers to a **motoneuron** and all of the muscle fibers it innervates. Each **motor unit action potential** will typically have a distinct waveform, Fig. 2 (c), which will depend on the distribution and orientation of the muscle fibers of the motor unit relative to the position of the recording electrode (for details on electrode selection see Besomi, Hodges (2019)). The duration of motor unit action potentials detected at the skin surface, or far from the muscle fibers, is longer than those detected within the muscle, or close to the muscle fibers, due to spatial filtering effects and the distribution of the neuromuscular junctions within the **innervation zone**. At very low levels of muscle activation (typically below 10% of maximum voluntary contraction, MVC), or with intramuscular EMG, it may be possible to distinguish individual motor unit action potentials via direct visual inspection of a recording. At higher contraction levels ($>20\%$ MVC), more motor units become active and a large number of action potentials sum together to generate a pseudorandom signal, Fig. 2 (a). The firing characteristics of individual motor units can be obtained using intramuscular EMG or extracted from surface EMG signals recorded with electrode grids or arrays using **surface EMG decomposition** algorithms.

EMG signals are often examined in the frequency domain to investigate the frequency distribution of the signal power (**power spectrum/power spectral density**), Fig. 2 (b). Signals can be represented in the frequency domain by applying the **Fourier series expansion**, Fig. 1 (d) and (f) (the corresponding time domain signals are shown in Fig. 1 (c) and (e), respectively). The Fourier expansion works on the principle that any signal can be represented as a sum of sinusoidal waves of different amplitudes, frequencies, and phases. The amplitude and phase of each of these sinusoidal components can be examined as a function of frequency, providing the amplitude and phase spectra of the signal, respectively. The power spectrum is obtained by taking the squared magnitude of the Fourier expansion of the signal (square of the amplitude spectrum). As revealed by the power spectrum, the power of the EMG signal is distributed across a range of frequencies, Fig. 2 (b). For an EMG signal segment of length T , its frequency resolution will be $1/T$, with frequency components at $1/T$, $2/T$, $3/T$ Hz, etc., Fig. 2 (b).

Although frequency components up to 5 kHz can be observed in intramuscular EMG signals, most of the power of surface EMG signals is contained between 10 and 500 Hz (this is a result of the spatial filtering of the signal due to the presence of the intervening tissue). Unfortunately, electrical interference (e.g., **power line interference**) also lies within this range (50 or 60 Hz – depending on local power line characteristics) and can contaminate the signal. Frequency components below the 10–500 Hz **bandwidth** are primarily caused by **movement artefact**, noise at the **electrode-tissue interface**, while components above this range can be due to noise in the electronics and in the EMG recording system.

3. EMG recording

The **signal-to-noise ratio** of EMG signals can be maximized by careful choice of equipment (e.g., electrode, differential amplifier, A/D converter), effective grounding and correct placement of the electrode either intramuscularly, subcutaneously or on the skin surface. Detected EMG signals are typically amplified and filtered in order to improve the quality of the recorded signal, and then digitized and stored for further processing, Fig. 3.

3.1. Skin preparation

For surface EMG signals, the skin surface should be adequately prepared before placing the electrode to maximize the signal-to-noise ratio. Noise is generated at the interface between electrode and tissue skin (**electrode-tissue interface**). The amplitude of this noise will depend on the contact surface and the properties of the material used to make the electrodes. Typical preparation involves cleansing and exfoliation of the skin, followed by application of conductive gel, typically placed on the electrode contacts. These steps reduce the **electrode impedance** and noise, improve the quality of the electrode contact, and standardize it across electrode contacts.

3.2 EMG amplification

EMG signals must be amplified by a factor of 1000–1500 to reach the amplitude required for signal sampling and **analog-to-digital** conversion (for example, surface EMG signals are typically in the range of hundreds of microvolts and are amplified to the range of hundreds of millivolts). The amplification required depends on the input range of the A/D converter. Bioelectric amplifiers are usually differential, which means they amplify the voltage difference ($V_d = V_+ - V_-$) between two points (electrodes) by a factor of A_d (**differential amplifier gain** or amplification) to obtain the output voltage, V_{out} , Fig. 3 (c).

¹ The term reference electrode is preferred to avoid confusion with a ground connection (to “earth” or “mains ground”) which is a reference voltage level of zero potential (0 V) for electric and electronic devices.

Fig. 1. (a) A sine wave (solid line) with an amplitude of 1, frequency of 10 Hz and phase of zero, showing the variation of the signal over time. A second sine wave (dashed line) with the same amplitude and frequency but different phase, Φ . (b) A sine wave with an amplitude of 0.5, frequency of 60 Hz and phase of zero. (c) A signal which is the sum of the sine waves shown in (a) and (b). (d) The amplitude spectrum of the signal in (c). (e) A surface EMG signal segment (0.5 s duration) and (f) its amplitude spectrum (with its frequency components spaced 2 Hz apart).

Fig. 2. (a) A surface EMG signal at a low force level (10% of maximum voluntary contraction, MVC) and a higher force level, 40% MVC, in the first dorsal interosseous muscle ($T_r = 0.25$ s). (b) The power spectral density of the surface EMG signal at 40% MVC shown in (a), with most of the power contained in the bandwidth between 10 and 400 Hz. Note that the length of the signal segment or epoch (T_r) determines the “frequency resolution” of the Fourier-transformed signal and the lowest detectable frequency component ($1/T_r$). In the example in (b) the surface EMG recording is 0.25 s in duration, thus it will have a frequency resolution of $1/0.25 \text{ Hz} = 4 \text{ Hz}$ when examined in the frequency domain (i.e., its frequency components will be 4 Hz apart). (c) Samples of single motor unit action potential trains, and an illustration of the increase in action potential duration that can occur with a decline in muscle fibre conduction velocity. (d) **Motor unit action potential trains** with different **inter-spike intervals (ISIs)**, i.e., different **mean firing rates**. The power spectrum of a motor unit spike train firing at 15 Hz (fundamental frequency of the spike train) is also shown, with spectral peaks also present at multiples of the fundamental frequency.

Fig. 3. (a) Schematic of the typical analog electronic filtering stages in recording surface EMG signals. (b) Different types of filters that can be used to keep, remove, or attenuate certain frequencies of the EMG signal + noise. Higher filter orders result in higher roll-off rates (c) A schematic of an ideal differential amplifier with power supply connections (+10 V and -10 V). (d) Front-end differential amplifier with an internal input impedance, Z_i . Note that the input impedance is present at both V_- and V_+ . (e) An example of a voltage signal being “clipped” or “limited” by the amplifier shown in (c). (f) An example of an offset voltage being present in the amplifier output, V_{out} , assuming the gain of the amplifier A_d is equal to 1. (g) Schematic of the electrode and amplifier configuration used to record double differential signals, V_1 , V_2 and V_3 are the voltages recorded at three different electrodes.

Fig. 4. Illustration of sampling an analog (continuous) signal to convert it to a digital or quantized format. During the analog to digital conversion process, the analog signal (grey) is sampled at uniform intervals at a sampling rate of 1000 samples/s (in this case). Each value in the continuous signal is assigned to a discrete level (in this example one of 16 possible levels of a 4-bit A/D converter). The difference between the discrete or digitized value (black line) and the original analog value is known as the quantization error.

Fig. 5. (a) Sample interference surface EMG signal of varying amplitude, (b) the absolute value or rectified surface EMG signal and (c) a 200 ms moving average of the rectified surface EMG signal with 50% overlap (200 ms corresponds to 400 samples as the sampling rate is 2000 Hz). The window length used in the calculation of the moving average can be longer or shorter for a stronger or weaker smoothing effect, respectively. This smoothing procedure on the rectified signal in (b) can also be performed using a low-pass filter, with lower or higher cut-off frequencies used for a stronger or weaker smoothing effect.

Fig. 6. The shape of the power spectral density of a surface EMG signal over 5 s at the start and end of a constant force isometric contraction sustained until task failure. A decrease in the mean frequency (vertical lines) of the surface EMG signal is observed, typically accompanied by an increase in the surface EMG amplitude. These changes in the amplitude and spectral parameters of the surface EMG during sustained muscle contractions are often referred to as “myoelectric manifestations of fatigue” but are only weakly related to changes in the contractile capacity of the activated muscle.

$$V_{out} = A_d V_d$$

(1)

If a signal appears with the same shape and amplitude, and in-phase, at both inputs (V_+ and V_-) of an ideal differential amplifier it will cancel and not be amplified. An example of an unwanted signal that could appear simultaneously at both inputs (a common-mode signal) is electrical interference from power lines (**power line interference**, which occurs at a frequency of 50 or 60 Hz). In practice, differential amplifiers will not exhibit this “ideal” behavior of complete cancellation of simultaneous inputs and the common-mode voltage (V_{cm}) will receive some amplification (A_{cm}), so that:

$$V_{\text{out}} = A_d V_d + V_{\text{cm}} A_{\text{cm}} \quad (2)$$

where V_{cm} is the voltage common to both inputs and A_{cm} is the (very small) common-mode gain of the amplifier. The **Common Mode Rejection Ratio (CMRR)**, expressed in decibels (dB), quantifies the ability of the amplifier to reject noise or interference that is common to both inputs (in an ideal differential amplifier, A_{cm} is zero and the CMRR is infinite, in a real amplifier the CMRR is in the range 80–120 dB).

$$\text{CMRR} = 20 \log \left| \frac{A_d}{A_{\text{cm}}} \right| \quad (3)$$

Real amplifiers also deviate from ideal behavior by exhibiting an “offset voltage” between the two terminals which results in an offset in the output voltage. This means that for zero direct voltage (DC) input there will be a DC output voltage generated by the amplifier, Fig. 3 (f). This offset can be removed by high-pass filtering the signal. Amplifier performance depends on the power supply voltage and the amplifier’s internal **input impedance**. If the amplification is so high that it tries to drive the amplifier output voltage, V_{out} , beyond the power supply voltage (e.g., ± 10 V in Fig. 3 (c)), it will result in the clipping of the signal, see Fig. 3 (e). An amplifier must have a high input impedance to optimally detect EMG signals (reasonable values are $Z_i > 300$ M Ω at 50 Hz), Fig. 3 (d), and minimize contamination from power line interference, see Section 3.3. Random fluctuations in voltage from the amplifier output, “baseline noise”, can be observed when an electrode is placed upon a fully relaxed muscle (generated within the internal stages of the amplifier and its circuit components, as well as at the electrode-tissue interface).

3.3 Power line interference

One of the most common sources of unwanted disturbances in voltage that contaminate or interfere with EMG signals (detected both intramuscularly and on the skin surface) is **power line interference**. Alternating currents (AC) in power lines and electrical wiring/equipment produce electromagnetic fields that fluctuate at the same frequency as the AC power supply (60 Hz in North, Central and some parts of South America and 50 Hz in the rest of the world — Europe, Asia, Africa, Australia, etc.) and its harmonics (100 Hz, 150 Hz, 200 Hz, etc. for 50 Hz sources, and 120 Hz, 180 Hz, 240 Hz, etc. for 60 Hz). The power line waveform is not a perfect sinusoid and will have some distortion, generating harmonics at higher order multiples of 50/60 Hz. These electromagnetic fields can induce currents in the electrode cables and the subject’s body through parasitic capacitive coupling² and electromagnetic induction (mostly in the closed loop formed by the electrode cables, the subject, and the amplifier). These currents produce an interference potential or voltage on the skin (which can reach an amplitude of several volts) that is detected by each recording electrode, appearing as a common-mode input to the differential amplifier (see Section 3.2).

The magnitude of this power line interference can be reduced by minimizing the difference between the electrode-tissue impedances with adequate skin preparation, and by choosing an amplifier with a high input impedance and high common-mode rejection ratio. If the electrode impedances at the two terminals (Z_{e1} and Z_{e2} , respectively) are unequal, the unwanted common-mode interference signal will differ between V_+ and V_- , resulting in a differential signal. This difference will be amplified by the differential gain A_d of the amplifier.

In addition to skin preparation and selection of high-quality equipment, power line interference can be reduced by moving power cables and equipment away from the subject, using wireless electrodes, shielding the electrode leads, keeping electrode cables short and/or twisting the leads together (minimize the closed loop area), turning off fluorescent or LED lighting and using the **driven-right leg** technique. Keeping electrode cables short or twisting long cables together and securing them in place to limit their motion relative to each other also helps to reduce **motion artefact/movement artefact**.

3.4 Signal filtering

Even with well-designed instrumentation using high quality components and careful skin preparation, there will be some noise and/or interference present in the detected EMG signal. Although noise arising from the electronic circuitry is present across a broad frequency range (from 0 Hz to several thousand Hz), electrical signals from other noise sources can have most of their energy contained within specific frequency bands. For example, most of the power in EMG signals due to **motion artefacts** will lie below 20 Hz. To increase the amplitude of the signal relative to the noise (**signal-to-noise ratio**), different types of **filters** (low-pass, high-pass, band-pass and notch filters) can be used to shape the power spectrum and to remove or attenuate frequency components that are likely due to noise, Fig. 3 (b). Surface EMG signals are typically band-pass filtered between 20 and 500 Hz (using at least second order filters with a roll-off of 40 dB/decade) to remove the electrical noise at frequencies below 20 Hz (e.g., **motion artefact**, drift, and noise from the **electrode-tissue interface**) and above 500 Hz. Intramuscular or fine-wire EMG is typically low-pass filtered with a cut-off frequency of between 1000 and 5000 Hz, depending on the application. EMG signals must be filtered prior to sampling to remove high frequency noise and prevent **aliasing**.

3.5 Analog-to-digital conversion (A/D conversion)

The EMG signal detected by the amplifier is a continuous signal, and at any given time point may take on an infinite number of voltage values (analog signal). In order to be stored and later processed, an analog signal must be first sampled in time by taking instantaneous voltage values at a particular **sampling** rate. To retain all the information contained within the signal, it must be sampled at a rate that is greater than twice the highest frequency component contained in the signal (Nyquist’s theorem). If lower sampling rates are chosen, the signal (and its spectral representations) may not be accurately represented and cannot be interpolated. To prevent **aliasing**, before sampling the analog EMG signal, the signal should be low-pass filtered with a cut-off frequency of less than half the desired sampling frequency. The highest frequency components contained within EMG signals lie below approximately 400–500 Hz for surface EMG and 1000–5000 Hz for intramuscular EMG, though this will depend on the muscle and electrode configuration used.

Sampling converts the analog signal into a time series consisting of a sequence of distinct voltage values, Fig. 4. Each discrete voltage value is converted into a binary number consisting of a number (N) of bits³. For example, a two-bit binary number can represent four discrete, equally spaced values (bit patterns 00, 01, 10, 11). A 12-bit analog-to-digital converter with an input voltage range of ± 5 V provides 4096 (2^{12}) discrete voltage values (**A/D resolution**) between -5 V and $+5$ V, hence equally spaced by 2.44 mV (10 V/4096). At each sampling point, the signal is given the discrete value which is closest to the true signal level. The difference between the true value of the analog signal and the closest available discrete value

² The unwanted transfer of electrical current from one current-carrying conductor (e.g., electrical wiring) to another conductor that is physically close (e.g., the human body), due to the interaction of the electric fields surrounding the conductors. This interaction is also called “electrostatic induction”.

³ A bit (or binary digit) is a single unit of information representing one of two possible values, 1 or 0. Binary numbering systems use combinations of 1s and 0s to represent values.

at each sampling instant is called the **quantization error**, Fig. 4. Choosing an analog-to-digital converter with a higher number of bits reduces quantization errors. The most commonly used A/D converters have resolutions of between 12 and 24 bits.

4. Signal analysis techniques

The properties of the EMG signal can be used to infer information about the behavior of the underlying motor unit population. An increase in the amplitude of the surface EMG signal can indicate an increase in **motor unit recruitment** (number of motor units that are activated) and/or **discharge rate modulation** (the frequency of discharge of the motor units). Changes in the amplitude of an EMG signal can be used to assess the timing of **muscle activation**, for example, to provide information on the activation and relaxation of muscles during different phases of a movement. Alterations in the frequency content of the EMG can also provide insight into changes occurring within the muscle and EMG spectral features are often used in the assessment of adjustments during fatiguing contractions (see Section 4.2).

4.1 EMG amplitude features

To quantify the amplitude of an EMG signal, the **average rectified value** (ARV) (or mean absolute value, MAV) and the **root mean square value** (RMS) of the EMG signal can be calculated. The latter is an optimal estimate of the standard deviation (square root of the signal power) when the signal has zero mean and is Gaussian distributed. **Instantaneous** and **peak-to-peak amplitudes** of EMG during voluntary contractions are unreliable and should not be used to quantify signal magnitude. EMG signals can be assumed to be **quasi-stationary** during constant force, isometric muscle contractions, i.e., approximately stationary over short time periods (0.5–1 s), meaning that the statistical properties of the signal do not change during this period. EMG signal amplitude is thus typically estimated over short time intervals or windows (epochs). The time window can be shifted forward in time, incrementally, to obtain an average for each sequential epoch. This is the **moving average** of the rectified signal (see definition of **rectification**). The moving average is a simple method to smooth EMG data, acting as a low-pass filter to reduce random fluctuations in the EMG signal. Short duration windows or epochs allow rapid changes in muscle activity to be detected, whereas longer epochs produce a stronger smoothing effect but attenuate rapid changes in muscle activity. The longer the window the stronger the low-pass effect, and the more the amplitude fluctuations are reduced. Calculating the moving average with epochs that overlap in time (50% overlap or more between successive windows) can improve the detection of rapid changes in EMG amplitude, while improving the statistical precision or reliability of the EMG peak amplitude, Fig. 5 (c). It should be noted that the ARV and RMS of the EMG signal are sensitive to several factors that are unrelated to the physiological characteristics of the muscle (e.g., the electrode type and orientation/location of the electrode). **Normalization** of the EMG amplitude to a reference value is typically required to enable comparisons between subjects/muscles/measurement sessions/electrode positions — further details on amplitude normalization can be found in Besomi, Hodges (2020).

4.2 EMG spectral features

The distribution of the frequency content of the EMG signal is described in the shape of the EMG power spectrum (measured in Volts squared, V^2) or power spectral density (measured in Volts squared per Hertz, V^2/Hz), Fig. 2 (b). A reduction in the **mean frequency** or the **median frequency** of the EMG power spectral density is often used as an indicator of compression of the frequency spectrum during fatiguing contractions, primarily due to changes within the muscle that slow **muscle fiber conduction velocity**. As muscle fiber conduction velocity decreases, recorded action potentials have a longer duration and a lower frequency content, Fig. 2 (c). This results in a compression of the EMG power spectrum towards lower frequencies, Fig. 6. The mean and median frequency of the EMG power spectral density are also sensitive to **motor unit synchronization**. More advanced time–frequency transforms can be applied to investigate non-stationary EMG signals that exhibit rapid temporal variations in frequency content (i.e., during dynamic muscle contractions, see definition of **continuous wavelet transform**). The correlation between two signals in the frequency domain can be examined by estimating **coherence**, which can be used to examine coupling between simultaneously recorded EMG signals, or EMG and EEG signals, at specific frequencies. A wide range of analysis methods based on both amplitude and spectral features can also be used to examine the characteristics of EMG signals (e.g., signal entropy, EMG amplitude thresholding, short-time Fourier transform, etc.).

Appendix 2. Rating scores for physiological terms

Rating Scores for each of the physiological terms. Each cell provides median score and (in parenthesis) IQR in the first row, then % appropriate (scores 7–9) followed by inappropriate (scores 1–3) in the second row. Note that some terms were added to the list after Round 1 and are first rated in Round 2.

#	Term	Round 1	Round 2	Round 3
1	Action potential (transmembrane action potential)	8 (1) 83.3%, 5.6%		
2	Agonist muscle	6 (3) 50%, 11.1%	8 (1) 82.4%, 0%	
3	Antagonist muscle	8 (3) 66.7%, 11.1%	8 (1) 94.1%, 0%	
4	Co-activation (or co-contraction)		7 (3) 58.8%, 6.3%	8 (1) 100%, 0%
5	Doublet or double discharge	8 (2) 94.1%, 0%		
6	Electrode	8 (2.8) 72.2%, 5.6%	8 (1) 93.8%, 0%	
7	Electromyographic signal	6 (3) 44.4%, 23.5%	8 (1) 100%, 0%	
8	Excitation-contraction coupling		8 (1) 100%, 0%	
9	Innervation zone (or end-plate region)	8.5 (2.7) 72.2%, 5.6%	9 (1) 100%, 0%	
10	Instantaneous firing rate	8.5 (1) 88.9%, 5.6%		

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#	Term	Round 1	Round 2	Round 3
11	Interspike interval, ISI (also referred to as Interpulse Interval, IPI)	9 (0.8) 88.9%, 5.6%		
12	Isometric contraction	9 (3) 66.7%, 5.6%	8 (1) 100%, 0%	
13	Isotonic contraction	7.5 (3.8) 55.6%, 5.6%	8 (2) 76.5%, 6.3%	9 (1) 86.7%, 6.7%
14	Maximal voluntary contraction (MVC)	8 (1) 82.4%, 11.8%		
15	Mean firing rate	9 (1) 100%, 0%		
16	Motoneuron or motor neuron	8.5 (2) 83.3%, 11.1%		
17	Motor unit	7.5 (2.8) 72.1%, 11.1%	9 (1) 100%, 0%	
18	Motor unit action potential	9 (1.8) 94.4%, 0%		
19	Motor unit action potential train	8.5 (1) 88.9%, 5.6%		
20	Motor unit recruitment	7 (3) 66.7%, 11.1%	8 (1) 94.1%, 6.3%	
21	Motor unit size	7 (3) 61.1%, 22.2%	8 (1) 88.2%, 6.3%	
22	Motor unit synchronization	8 (1.8) 88.9%, 5.6%		
23	Motor unit territory	9 (1.8) 77.8%, 11.1%		
24	Muscle activation	7 (2.8) 61.1%, 16.7%	8 (1) 88.2%, 0%	
25	Muscle fiber action potential	8 (2) 94.4%, 5.6%		
26	Muscle fiber conduction velocity	8 (1.8) 88.9%, 5.6%		
27	M-wave or compound muscle action potential (CMAP)	8 (2) 88.2%, 5.9%		
28	Neural drive	8.5 (3) 66.7%, 22.2%	8 (1) 88.2%, 6.3%	8 (1) 100%, 0%
29	Neuromuscular junction	9 (1) 100%, 0%		
30	Persistent inward currents (PICs)	8 (1) 88.9%, 5.6%		
31	Rate modulation or rate coding	8 (2) 77.8%, 11.1%		
32	Recruitment threshold of a motor unit	7 (2.8) 72.2%, 16.7%	8 (1) 94.1%, 6.3%	
33	Synergist muscle	7 (3) 61.1%, 5.6%	8 (2) 76.5%, 11.8%	

Appendix 3. Rating scores for technical terms

Rating Scores for each of the technical terms. Each cell provides the median score and (in parenthesis) IQR in first row, then % appropriate (scores 7–9) followed by inappropriate (scores 1–3) in the second row. Note that some terms were added to the list after Round 1 and are first rated in Round 2.

#	Term	Round 1	Round 2	Round 3
1	Aliasing	8 (2.8) 72.2%, 5.6%	8 (1) 100%, 0%	
–	Amplitude of a signal (removed)	7.5 (2) 83.3%, 22.2%		
2	Analog-to-digital (A/D) conversion	8.5 (2) 72.2%, 5.6%		
3	A/D Quantization error	8 (2) 83.3%, 0%		
4	A/D resolution		9 (1) 100%, 0%	
5	Auto-correlation		8 (2) 94.1%, 0%	
6	Bandwidth of a signal		8 (2) 77.8%, 11.1%	
7	Coherence	8 (1.8) 94.4%, 0%		
8	Common-mode rejection ratio (CMRR)			

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#	Term	Round 1	Round 2	Round 3
9	Continuous wavelet transform	8 (1.8) 83.3%, 0% 8 (1) 100%, 0%		
10	Cross-correlation	8 (1.3) 81.3, 0%		
11	Crosstalk	9 (1) 100%, 0%		
12	Current	8 (2) 83.3%, 0%		
13	Decomposition of EMG	9 (1) 100%, 0%		
14	Differential Amplifier Gain	8 (2) 83.3%, 5.6%		
15	Double differential technique		8 (2) 88.2%, 0%	
16	Driven Right Leg (DRL)	8 (2) 88.9%, 0%		
17	Electrocardiographic (ECG) interference	8 (1.8) 94.4%, 0%		
18	Electrode impedance	9 (1.8) 83.3%, 0%		
19	Electrode-Tissue interface	8 (1) 94.4%, 0%		
–	EMG amplitude (removed)		8 (4) 64.7%, 11.8%	
20	EMG amplitude: Average rectified value (ARV) or mean absolute value (MAV)	9 (1.8) 94.4%, 0%		
21	EMG amplitude: Root mean square value (RMS)	9 (1) 94.4%, 0%		
22	EMG instantaneous amplitude		8 (3) 70.6%, 12.5%	8 (1) 86.7%, 6.7%
23	EMG peak-to-peak amplitude		9 (1) 100%, 0%	
24	EMG signal envelope		8 (3) 70.6%, 17.5%	8 (2) 73.3%, 13.3%
25	Filter	8 (2) 77.8%, 5.6%		
26	Fourier Transform/ Fourier series expansion	8 (2) 83.3%, 5.6%		
27	Frequency	9 (2) 94.4%, 5.6%		
–	Harmonic (removed)	8 (2) 94.4%, 5.6%		
28	Input impedance	8 (2) 94.4%, 0%		
29	Mean spectral frequency or centroid frequency (MNF) or mean power frequency (MPF)	8 (0) 100%, 0%		
30	Median spectral frequency (MDF)	8 (2) 94.4%, 0%		
31	Motion artefact (or movement artefact)	8 (1) 94.1%, 0%		
32	Moving average of a rectified (or squared) EMG signal	8 (2) 94.4%, 5.6%		
33	Normalization	9 (2) 88.9%, 0%		
34	Phase	8 (2) 77.8%, 5.6%		
35	Power line interference	8 (1) 88.9%, 0%		
36	Power of a signal	8 (2) 83.3%, 0%		
37	Power spectrum/power spectral density of a signal	9 (2) 88.9%, 5.6%		
38	Pre-amplification or “Front-end stage” amplification	8 (1) 100%, 0%		
39	Rectification	9 (1) 94.4% (17), 0%		
40	Resistance	9 (1.8) 83.3%, 11.1%		
41	Roll-off	8 (1) 88.9%, 0%		
42	Sampling in time	8 (2) 83.3%, 5.6%		
43	Signal-to-noise ratio (SNR)	9 (1) 94.4%, 0%		

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(continued)

#	Term	Round 1	Round 2	Round 3
44	Spatial sampling	7 (2) 77.8%, 0%		
45	Stationarity/Quasi-stationarity	8 (1.8) 88.9%, 0%		
–	Surface EMG bandwidth (removed)	8 (3) 66.7%, 5.6%		
46	Voltage (or potential difference)	8 (1.8) 83.3%, 0%		

References

- Besomi, M., Hodges, P., Clancy, E.A., van Dieën, J., Hug, F., Lowery, M.M., et al., 2020. Consensus for experimental design in electromyography (CEDE) project: Amplitude normalization matrix. *J. Electromyogr. Kinesiol.*
- Besomi, M., Hodges, P.W., van Dieën, J., Carson, R.G., Clancy, E.A., Disselhorst-Klug, C., et al., 2019. Consensus for experimental design in electromyography (CEDE) project: Electrode selection matrix. *J. Electromyogr. Kinesiol.* 48, 128–144.
- Hodges, P.W., 2020. Editorial: Consensus for Experimental Design in Electromyography (CEDE) project. *J. Electromyography and Kinesiology.* 50:102343.
- Kiernan, M.C., Bostock, H., Park, S.B., Kaji, R., Krarup, C., Krishnan, A.V., et al., 2020. Measurement of axonal excitability: consensus guidelines. *Clin. Neurophysiol.* 131, 308–323.
- McManus, L., De Vito, G., Lowery, M. Analysis and biophysics of surface EMG for physiotherapists and kinesiologists: toward a common language with rehabilitation engineers. *Front Neurol.* 11: 576729 doi: 103389/fneur. 2020.
- Merletti, R., Tutorial, Cerone G., 2020. Surface EMG detection, conditioning and pre-processing: best practices. *J. Electromyogr. Kinesiol.* 102440.
- Merletti, R., Muceli, S., 2019. Tutorial. Surface EMG detection in space and time: Best practices. *J. Electromyography and Kinesiology* 49:102363.
- von der Gracht, H.A., 2012. Consensus measurement in Delphi studies: review and implications for future quality assurance. *Technol. Forecast. Soc. Chang.* 79, 1525–1536.
- Williamson, P.R., Altman, D.G., Blazeby, J.M., Clarke, M., Devane, D., Gargon, E., et al., 2012. Developing core outcome sets for clinical trials: issues to consider. *Trials* 13, 132.