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The Accurate Assessment of Muscle Excitation Requires the Detection of Multiple Surface Electromyograms

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VIEIRA, T.M. and A. BOTTER. The accurate assessment of muscle excitation requires the detection of multiple surface electromyograms. *Exerc. Sport Sci. Rev.*, Vol. 49, No. 1, pp. 23–34, 2021. *When sampling electromyograms (EMGs) with one pair of electrodes, it seems implicitly assumed the detected signal reflects the net muscle excitation. However, this assumption is discredited by observations of local muscle excitation. Therefore, we hypothesize that the accurate assessment of muscle excitation requires multiple EMG detection and consideration of electrode-fiber alignment. We advise prudence when drawing inferences from individually collected EMGs.* **Key Words:** electromyography, surface electrodes, skeletal muscle, crosstalk, EMG imaging, high-density EMG, EMG-force assessment

Key points

- Inferences on the degree and timing of muscle excitation are broadly made from surface electromyograms (EMGs) detected from a single, and often small, muscle region.
- These inferences are predicated on the implicit assumption that EMG amplitude scales proportionally with net degree of muscle excitation.
- In this article, we show that the local EMG detection is likely to result in either Type I error, saying a muscle is excited when it is not, or Type II error, saying a muscle is not excited when it is.
- We propose that the probability of making either error can be minimized by using grids of electrode to detect surface EMGs from multiple locations over a target muscle.
- With grids of electrodes, the timing and degree of muscle excitation can be assessed regardless of where it takes place within the muscle.

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INTRODUCTION

Surface electromyography (EMG) has been attracting increasingly greater interest in the field of exercise and sport sciences. The number of EMG articles published per year has almost trebled in the last 30 yr, reaching an average of 3% of all articles published in exercise and sports science. A literature search was conducted in the PubMed database on August 2020, using (Exercise OR Sport) AND (Electromyography OR EMG) anywhere in the article as a search reference. On the one hand, the augmented popularity of surface EMG substantiates the tremendous potential of the technique. On the other hand, it has beget the emergence of initiatives specifically committed to making EMG users aware of the many issues that may invalidate inferences drawn from surface EMGs (1–3). To further this collective, didactic effort, we raise the hypothesis that surface EMGs detected from a single muscle site do not provide accurate estimates of the degree and timing of muscle excitation compared with those detected from multiple sites. This hypothesis is motivated by variations in the amplitude of EMGs detected from different skin locations over a single target muscle, as evidenced by the use of grids of surface electrodes, often termed "high-density recording." With grids of electrodes, the timing and degree of muscle excitation can be assessed regardless of where it takes place within the muscle. More than inviting readers to consider revisiting the concept of muscle function in sport and exercise sciences, we hope this review serves as a reference for whomever would like to start venturing into the growingly popular yet delicate world of high-density surface EMG.

WHAT INFORMATION MAY BE EXTRACTED FROM LOCAL EMG SAMPLING?

Traditionally, surface EMGs are collected with a pair of electrodes positioned at any given point of interest on the skin.

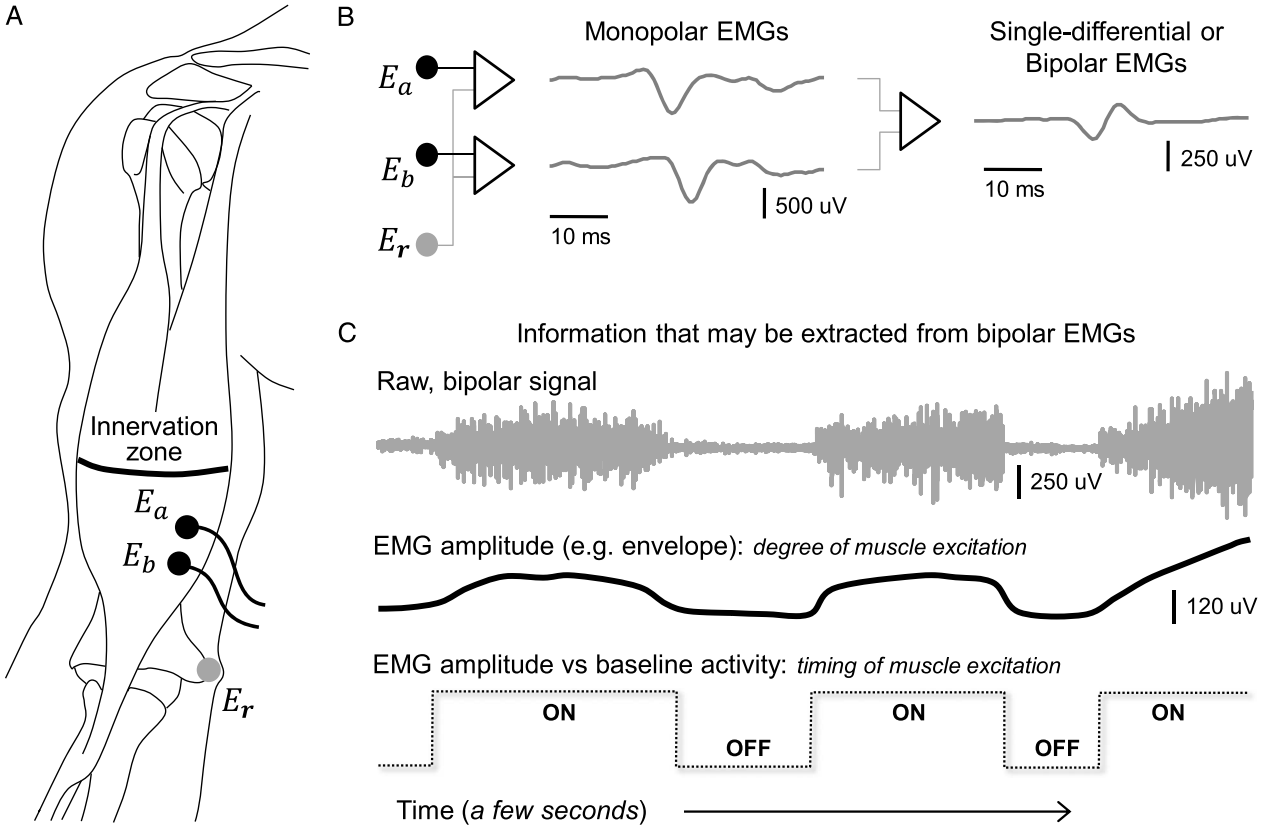

Figure 1. Experimental setup and analyses performed using surface electromyography (EMG). A. Schematic representation of a typical setup for EMG recording. B. The differential procedure considered in most commercially available amplifiers, whereby the algebraic difference between two monopolar EMGs obtained from electrodes E_a and E_b with respect to the reference electrode E_r gives rise to the single-differential or bipolar EMGs. C. The timing and the degree of muscle excitation are the two information of main interest that users may obtain from the bipolar recording.

Figure 1 shows a typical design for the collection of surface EMGs. Even though Figure 1A has been drawn for the biceps brachii muscle during an isometric, submaximal contraction, the underlying concept applies to all recording scenarios. Two electrodes, E_a and E_b, are positioned on the skin region superficial to the target muscle, whereas a reference electrode, E_r, is placed at a point where no electric potential is expected. The potential difference measured between each of the two detecting electrodes and the reference electrode provides what is typically known as a monopolar signal (Fig. 1B) (4). The pair of detecting electrodes is often termed "bipolar electrodes" or "channel," and the algebraic difference between the two monopolar signals provided by the channel gives rise to a single bipolar or single-differential EMG. As the distance between the two detecting electrodes is generally smaller than that between each detecting electrode and the reference electrode, the muscle volume (in the next section) sampled by monopolar EMGs is larger than that sampled by bipolar EMGs. Whereas a single monopolar signal is often affected by excitation of muscles other than that of interest, a single bipolar EMG may sample from a small, unrepresentative fraction of the target muscle. We understand most EMG users feel familiar with the definition of bipolar EMGs, but it is this very differential procedure that may bias the validity of surface EMG as a proxy for muscle excitation.

Bipolar EMGs convey two main pieces of information that are of widespread interest, namely, the timing and degree of muscle excitation. Whenever the degree of muscle contraction changes to a lesser or greater extent, a respective decrease or increase in EMG amplitude is commonly observed. This broad observation advocates a proportional association between contraction level and EMG amplitude, motivating the use of EMG to study when and how much muscles are excited. When the EMG amplitude increases over the level of background noise, the muscle is deemed to be excited, whereas the magnitude of the increase in amplitude indicates how much the muscle has been excited. This concept is illustrated in Figure 1C for the EMG envelope: a low-pass filtered version of the rectified or squared signal. There are a number of situations wherein the information present in surface EMGs may not be unequivocally associated with muscle excitation; presence and displacement of endplates beneath electrodes, cancellation of action potentials, and changes in subcutaneous thickness are examples of factors potentially impairing the interpretation of muscle excitation from EMG (1,5,6). Here, we would like to focus attention on one of the most critical aspects possibly limiting inferences on variations in muscle excitation from variations in surface EMG amplitude: the local sampling of bipolar EMGs or, more specifically, the detection of bipolar EMGs with closely spaced electrodes.

ISSUES WITH LOCAL EMG SAMPLING

Every time bipolar EMGs are used to assess muscle excitation, it seems implicitly assumed that the recorded signal is fully representative of the target muscle and of no other muscles. Referring to Figure 1, this assumption could be formalized by stating that action potentials generated by fibers of nearby muscles

do not contribute to the detected EMG during "on" periods and, furthermore, that all fibers of the target muscle are not excited during "off" periods. Violations of this assumption will lead to characterizing a muscle as "on" when it is actually not excited (Type I error) or classifying it as "off" when it is in fact on (Type II error).

Type I Error

Saying a muscle is excited when it is not (low specificity of surface EMGs)

This error is often due to crosstalk (7,8). Figure 2A illustrates this issue for a superficial (target) and for a deep (contaminating) muscle. In this case, the deep muscle is excited at well-defined periods, whereas the superficial muscle is silent. Activity in the bipolar EMGs is observed when the deep muscle is excited and therefore is said to be contaminated. This crosstalk activity in the surface EMG may be equivocally conceived as indicative of excitation of the target muscle, leading to a Type I error. Surface EMG is free of Type I error when it is specific for the target muscle, that is, when it is not affected by crosstalk. Type I issue may be particularly relevant when assessing thin superficial muscles, as the relative contribution of deeper muscles may outweigh that of the superficial, target muscle (*e.g.*, gluteus), or when assessing muscles small in relation to the size and the center-to-center distance of surface electrodes (*e.g.*, hamstrings).

Type II Error

Saying a muscle is not excited when it is (low sensitivity of surface EMGs)

As illustrated in Figure 2B, this issue is in opposition with the Type I error. Two groups of fibers located in different depths within the target muscle are excited. However, only the most superficial group of fibers contributes to the activity observed in the bipolar EMGs. In this case, excitation of the deep group of fibers in the target muscle is not sampled by the surface EMG, and as a result, a Type II error is likely to occur. Surface EMG is free of Type II error when it is sensitive to the excitation of the target muscle, that is, when it samples from all fibers, regardless of where they are within the target muscle. Type II issue may be critical whenever a single bipolar EMG is collected from large muscles, more so when the center-to-center distance is small relative to the muscle size.

Understanding the specificity and sensitivity issues necessitates an understanding of a key concept in EMG: detection or pick-up volume. A simplistic although practically relevant

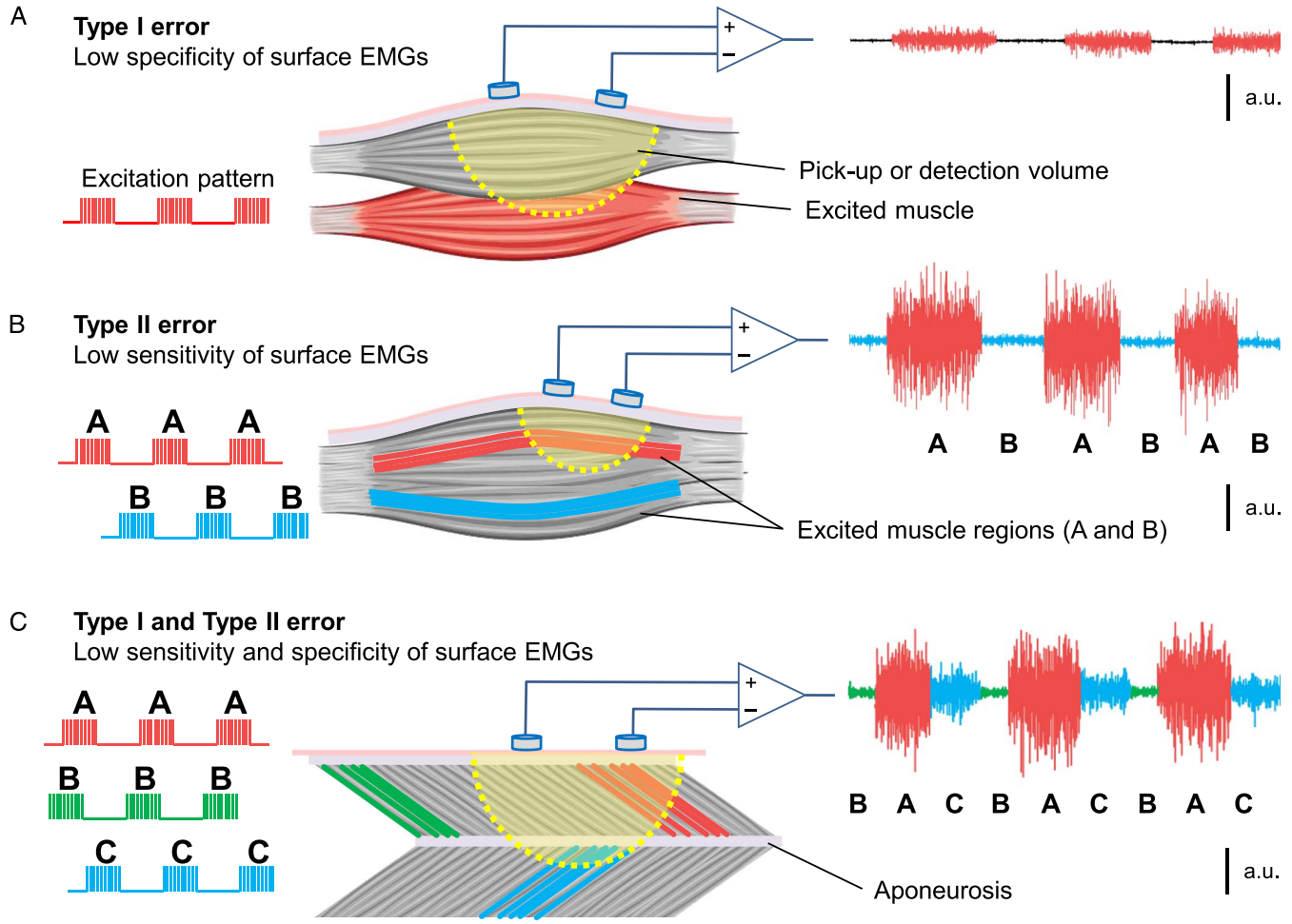

Figure 2. Type I and Type II errors in electromyography (EMG) recordings. A. The activity detected by the bipolar EMG is contaminated by muscles other than the target muscle (crosstalk). This low specificity leads to Type I error. B. The excitation of superficial ("A") although not of deep ("B") regions contributes to the detected EMG. This low sensitivity leads to Type II error. C. Coexistence of Type I and Type II errors: the detection system is not sensitive to all electrical sources within the target muscles but detects the activity generated by the contaminating muscle.

definition for pick-up volume would be that of the region beneath electrodes within which action potentials are detected; for a formal definition of pick-up volume, the reader is referred to Lynn *et al.* (9). For example, the pick-up volume of the bipolar electrodes shown in Figure 2 (dashed lines) is represented as a semicircle in the sagittal plane (semisphere in space). Although the pick-up volume of electrodes in Figure 2A includes fibers of the contaminating muscle, the pick-up volume in Figure 2B does not include all fibers of the target muscle, giving rise to the emergence of Types I and II errors, respectively. In more technical terms, action potentials located outside the pick-up volume would still appear in the surface EMG, but their amplitude would be dramatically smaller than that of action potentials located inside and close to the electrodes. Considering the myriad of combinations of electrode sizes and configurations of muscle architectures, establishing a unique shape and size for the pick-up volume is not possible. It is, however, well accepted that the size of the pick-up volume increases proportionally with the center-to-center distance between electrodes (9,10), motivating the schematic drawings in Figure 2. The shorter the distance between electrodes, the more specific — although the less sensitive — the detected EMG will be.

Type I or Type II errors are extreme cases deriving from equivocal assumptions respectively favoring specificity or sensitivity. Critically, if EMGs are not specific, they overestimate the degree of excitation, whereas if not sensitive, they underestimate the degree of excitation of the target muscle. Moreover, both errors are not mutually exclusive. There are circumstances for which the experimental design may be affected by both errors. As illustrated in Figure 2C, the concurrence of Types I and II errors is more likely to manifest in muscles with pinnate architecture, given that a relatively higher number of fibers may be outside the pick-up volume (in the next section). On the one hand, the reduction in center-to-center distance between bipolar electrodes would generally increase specificity, helping to contend with Type I error. On the other hand, it could critically penalize sensitivity and thus lead to the detection of EMGs representing a very small fraction of the muscle.

In the classic EMG literature, attention mostly has been given to specificity. Although caring for specificity, EMG users may have overlooked the possibility of missing information from the target muscle. The view that surface electrodes have a greater pick-up volume when compared with intramuscular electrodes is presumably the reason for the apparent, general neglection of the sensitivity issue, even though a few classic works have raised concerns regarding the sensitivity of surface EMGs (11,12). The importance and relevance of sensitivity have been recently substantiated by high-density surface EMG, whereby recordings taken from different skin regions covering the same muscle have consistently provided EMGs with different amplitudes (13–16). Before discussing how sensitivity motivates the hypothesis that a single bipolar EMG may not provide accurate estimates of the degree and timing of muscle excitation, we provide readers with a brief but deep overview of high-density surface EMG from a practical perspective.

WHAT INFORMATION MAY BE EXTRACTED FROM HIGH-DENSITY EMG DETECTION?

In general, a multichannel system for surface EMG consists of multiple electrodes and the conditioning electronics. The electrodes can be positioned on skin surfaces covering different target muscles or a single muscle. In the first and traditional case, when activity from several muscles is sampled with pairs of electrodes, one for each muscle, interest is chiefly focused on the understanding of coordinated actions between synergists. In the second case, the use of multiple electrodes to sample EMG activity from a single muscle is expected to provide valuable insights into the muscle physiology and anatomy. Electrodes designed for such a purpose are typically prearranged into grids or positioned individually on a target region and are conceived as high-density electrodes. It is important to note that, although this definition is sufficient for the aims of this review, defining a system of multiple electrodes as "high density" demands establishing specific criteria (*e.g.*, concerning the spatial sampling) that, at the moment, remain to be discussed elsewhere. Here, we are concerned with showing why and how high-density EMGs help contend with Type I and Type II errors. Before doing so, we comment on how the relative arrangement of electrodes and muscle fibers affects the interpretation of high-density recordings obtained with linear arrays and grids of electrodes.

Linear Array Positioned Parallel to Muscle Fibers

Ideally, in this configuration (Fig. 3A), the shortest distance between each electrode and the excited fibers is the same. Owing to the propagation of action potentials, consecutive channels detect the same potentials shifted in time. Because of the bidirectionality of propagation from the endplates to the fibers' endings, time shifts between action potentials detected by consecutive channels on opposite sides of the endplates have different signs, resulting in a "V-shaped" pattern of propagation (Fig. 3A). Importantly, single-differential EMGs obtained from electrodes equidistant from the center of endplates' location may record low EMGs (2). For example, the bipolar EMG in Figure 1 would be almost flat, as both electrodes E_a and E_b would detect similar monopolar signals at the same instant. Because of the extinction of potentials, similarly low EMGs are detected by channels located beyond the fibers' endings. The parallel arrangement between electrodes and fibers therefore allows for the extraction of information about the position of endplates and fibers' endings, in addition to the propagation velocity of detected potentials, computed as the ratio between the interelectrode distance and the estimated time shift between consecutive potentials (17). Concerning the degree and timing of excitation, the propagation of action potentials suggests that not all skin regions provide equivalent estimates. Indeed, the degree of muscle excitation may be underestimated if the bipolar detections are taken near the endplate region (also referred to as innervation zone; [6]). This issue may be more critical in dynamic contractions, whereby changes in muscle length may lead to a displacement of endplates beneath the electrodes. This issue is particularly critical when multiple innervation zones are present (18). Consequently, the amplitude of detected EMGs would decrease not because of a change in the neural input but because of anatomical factors.

Linear Array Positioned Transversely to Muscle Fibers

In this configuration, the dependence of the detected EMG on the distance between the electrode and the intramuscular

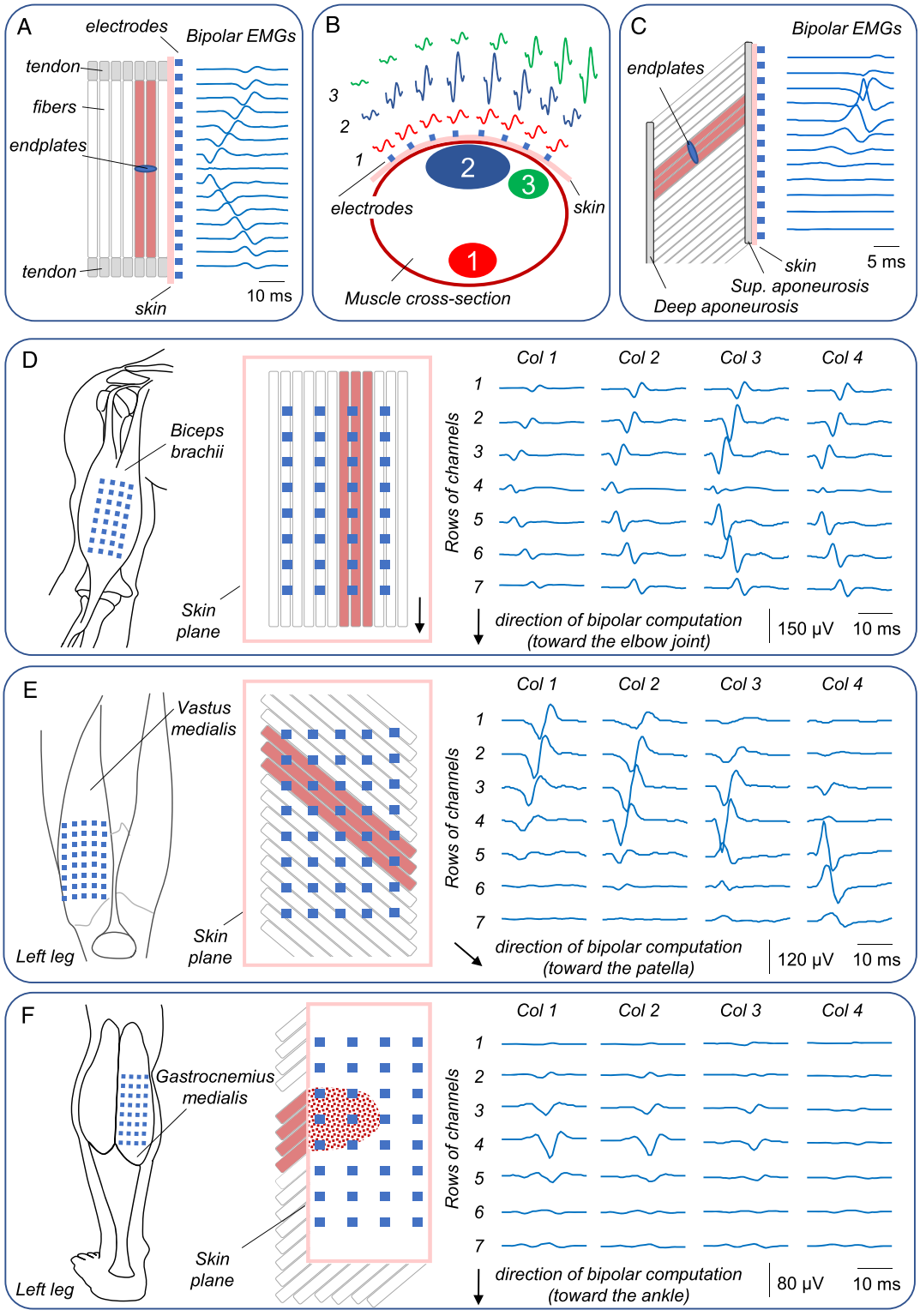

Figure 3. The relationship between electrode-fiber arrangement and bipolar electromyograms (EMGs). The surface representation of intramuscular potentials is shown for linear arrays positioned parallel (A), transversely (B), and in oblique planes (C) with respect to muscle fibers. When using grids positioned parallel to the plane of muscles fibers, columns and fibers may be aligned (D) or not (E) in parallel directions. Finally, (F) reports the case of grids positioned over a muscle with fibers aligned in a plane oblique to the skin. Bipolar EMGs were computed along the proximodistal direction, except for (E) (diagonal direction). Blue squares represent electrodes, and dark rectangles indicate excited muscle regions.

potentials may reveal the location of the excited fibers within the muscle (19,20). This concept is illustrated in Figure 3B. If the excited fibers are deep, their distance to all electrodes in the array is roughly similar (case 1, Fig. 3B). The intramuscular potential appears similarly across the skin and leads to surface EMGs with almost equal amplitude. However, if the excited fibers are superficial, their distance to electrodes varies along the array, leading to the detection of the greatest EMGs at the

electrode closest to the excited fibers. The rate of amplitude decay across the array depends on the distribution of the excited fibers within the muscle in relation to the array size; the larger the excited region, the smoother the decay in EMG amplitude across electrodes (cases 2 and 3, Fig. 3B). The presence of greater EMGs in the array indicates where the excited muscle region is centered, in turn suggesting that inferences on the degree and timing of muscle excitation from a single detection site may be inaccurate.

Linear Array and Muscle Fibers Reside in Oblique Planes

The configuration illustrated in the section *Linear Array Positioned Parallel to Muscle Fibers* applies only to cases where muscle fibers run parallel to the skin surface. In muscles where fibers lay obliquely to the skin surface (*e.g.*, calf muscles), fibers extend from deep to superficial regions. Because a parallel electrode-fiber alignment is not possible, the distance between the electrodes and any single excited fiber changes along the array. For this oblique muscle geometry (Fig. 3C), an action potential originating from the endplate and propagating toward either the superficial or deep fiber ending respectively approaches or moves away from the surface electrodes. It follows that the amplitude of any intramuscular potential is best represented in a subset of electrodes in the array, namely, those that overlie the superficial endings of the excited fibers. The amplitude of EMGs is therefore associated with the location of excited fibers within the muscle (21) and, as in the previous case (in the previous section), bipolar EMGs detected from a single, local site may not be used to draw inferences at the whole-muscle level.

Grids of Electrodes

This approach is an extension of the three previous cases. To highlight the benefits of using grids, here we illustrate three possible cases. In Figure 3D, columns of electrodes are aligned parallel to the fibers, allowing for the assessment of the propagation of action potentials (section *Linear Array Positioned Parallel to Muscle Fibers*) and of the decay of their amplitude in the transverse direction (the section *Linear Array Positioned Transversely to Muscle Fibers*). In muscles with fibers parallel to the skin, the fiber-electrode alignment is not always achievable either because fibers are not consistently aligned throughout the muscle (*e.g.*, vastus medialis, trapezius) or because fiber direction may change during contraction. In the presence of electrode-fiber misalignment (Fig. 3E), propagation along the fibers and the amplitude decay are not exclusively captured by either rows or columns. However, signal processing techniques allow for the reconstruction of the propagation pattern for the excited fibers, at least in isometric or slow, dynamic contractions (22). Finally, Figure 3F shows EMGs sampled with a grid positioned over fibers aligned obliquely to the skin (*e.g.*, gastrocnemius, soleus, tibialis anterior, hamstrings). As grids are an expansion of linear arrays, the propagation of action potential cannot be detected despite how many electrodes are used. Here, the association between the location where greatest EMGs are detected and the superficial ending of excited fibers applies to both the proximodistal and mediolateral directions.

The analysis of the surface representation of intramuscular potentials suggests that EMGs with different amplitudes may be detected across different skin regions over a single target muscle. The interpretation of these spatial inhomogeneities depends on the arrangement between electrodes and fibers. High-density EMGs are therefore expected to provide a more accurate assessment of muscle excitation than a single, bipolar EMG. However, visualizing several tens of EMGs may be cumbersome if represented as interference signals.

REPRESENTING EMGS WITH SCALED IMAGES: *EMG IMAGING*

By simply looking at a bipolar EMG signal, one is readily able to appreciate variations in its amplitude and to attempt drawing conclusions (cf. Fig. 1). However, when multiple EMGs are detected from different skin regions, representing their amplitude by visual inspection becomes an issue. It is therefore possible that using colors or gray scales to depict EMG amplitudes can facilitate their interpretation. Figure 4A illustrates this procedure for one of 56 bipolar EMGs recorded from the gastrocnemius during an isometric ramp contraction. The procedure consists in computing a descriptor for the EMG amplitude and representing it with a colored or gray pixel. The most often known descriptors are the absolute rectified value (ARV) and the root-mean-square (RMS), defined by averaging a portion of the rectified (ARV) or squared (RMS) signal. Establishing a generally valid time window is not possible. However, it is assumed that within these windows, the EMG amplitude is stable or that any changes would be smaller than those one expects to observe. In Figure 4A, ARV values were obtained for 1-s windows of the bipolar EMG. Any variations in amplitude within windows are sufficiently smaller than the variations between windows, as revealed by the ARV time course. The lowest (0 μV) and the highest (90 μV) amplitude values are shown as black and white pixels, respectively, whereas intermediate values are represented from dark-red to bright-yellow pixels.

The colored representation of EMG amplitudes is particularly useful when inspecting multiple EMGs at a time. Figure 4B shows 56 pixels, in which color intensities correspond to the ARV value of each of the 56 bipolar EMGs collected from the gastrocnemius during the 14- to 15-s period, one of which is shown Figure 4A. The combination of high-density EMG recording with the representation of EMG amplitude as a scaled image gives rise to the *EMG imaging* technique. The potential of EMG imaging is not limited to being an appropriate way of representing the amplitude of multiple signals. It may further reveal regions of high EMG amplitude within the target muscle, which may be quantified in terms of size and location (Fig. 4B). Typically, the size is assessed as the number of pixels providing sufficiently high EMG amplitude, whereas location is computed as the center of mass (*i.e.*, the centroid) of the amplitude values across rows and columns of pixels (Fig. 4B) (23–25). Whenever EMG amplitude is concentrated at a small region relative to the size of the grid of electrodes, the distribution of EMG amplitude is said to be localized. The localized EMG distribution has been often reported by our group and by others (13–16,26), providing a basis for the hypothesis we raise in the next section.

EMG IMAGING PROVIDES A MORE ACCURATE ASSESSMENT OF MUSCLE EXCITATION THAN SINGLE BIPOLAR EMGS

In this section, we advance the hypothesis that the localized distribution of EMG amplitude may invalidate the assessment

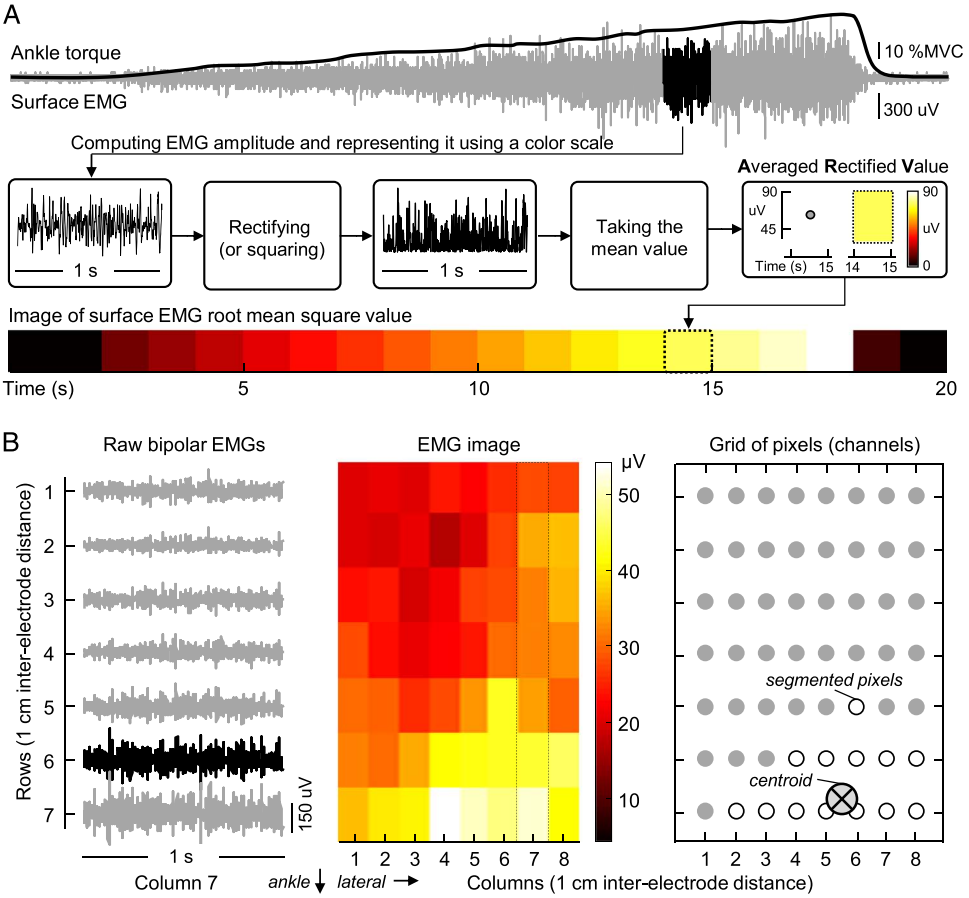

Figure 4. The electromyography (EMG) imaging technique. A. Portions of any raw surface EMG may be rectified or squared, time averaged, and then represented either as a point in an amplitude scale or as pixel intensity. B. This intensity representation provides an image when detecting EMGs with grids of electrodes, facilitating the inspection of where EMGs with greatest amplitude are located. Automated techniques may be applied to reveal where (centroid) and the extent of the skin region (segmented pixels) where greatest EMGs are detected.

of muscle excitation from single bipolar EMGs. Equivalently, we could say different bipolar EMGs in Figure 4B, if considered alone, would provide different indications of the net muscle excitation. Our hypothesis establishes a spatial relation between the local distribution of amplitudes in EMG images and the local excitation of muscles, ultimately implying that surface electrodes are sufficiently selective to detect local variations in muscle excitation. By sufficiently selective, we mean having a pick-up volume sufficiently smaller than the volume of the target muscle.

To make our point clearer, we invite readers to reflect upon the two contrasting hypotheses illustrated in Figure 5: bipolar surface EMG reflects "global" versus "local" information from the underlying muscle. Under the "global hypothesis," regardless of where a single bipolar EMG is collected, its amplitude would be associated with the net muscle excitation. As shown in Figure 5A, this hypothesis would imply either that i) the pick-up volume of bipolar electrodes is sufficiently large to include all fibers of the target muscle, or that ii) regardless of effort demands or conditions, excitation takes place at random locations within the muscle, or that both i) and ii) hold. Conversely, under the "local hypothesis," bipolar surface EMGs would convey information only from the muscle region lying immediately beneath the single pair of electrodes. This possibility would imply both that the pick-up volume of bipolar electrodes is sufficiently small to include only a fraction of the target muscle and that excitation takes place locally within the muscle (Fig. 5B). Clearly, this would result in a less accurate assessment of muscle excitation should EMGs be detected by a single pair of closely spaced electrodes. In terms of EMG imaging, the global hypothesis would result in roughly uniform images (Fig. 5C), whereas the local hypothesis would lead to local groups of pixels with relatively high intensity (Figs. 5D–F).

Documented evidence from our group and from others suggests the two necessary conditions underlying the local hypothesis are likely met. By combining intramuscular and bipolar surface EMGs detected for different interelectrode distances, we systematically assessed the pick-up volume of surface electrodes (10). More specifically, we used intramuscular EMGs to identify action potentials of motor units from the soleus and gastrocnemius, and then quantified the amplitude of these action potentials in the surface EMGs, separately for each muscle. Only for bipolar electrodes spaced by at least 3.5 cm were we able to detect action potentials from soleus motor units with RMS amplitude greater than 10% of that of action potentials from gastrocnemius motor units. At shorter interelectrode distances, action potentials from the soleus were barely visible. These results support the notion that, for gastrocnemius, bipolar electrodes are sufficiently selective. For readers seeking additional, compelling arguments, the selectivity of bipolar electrodes may be well substantiated by visually inspecting the amplitude of action potentials in high-density surface EMGs. Considering

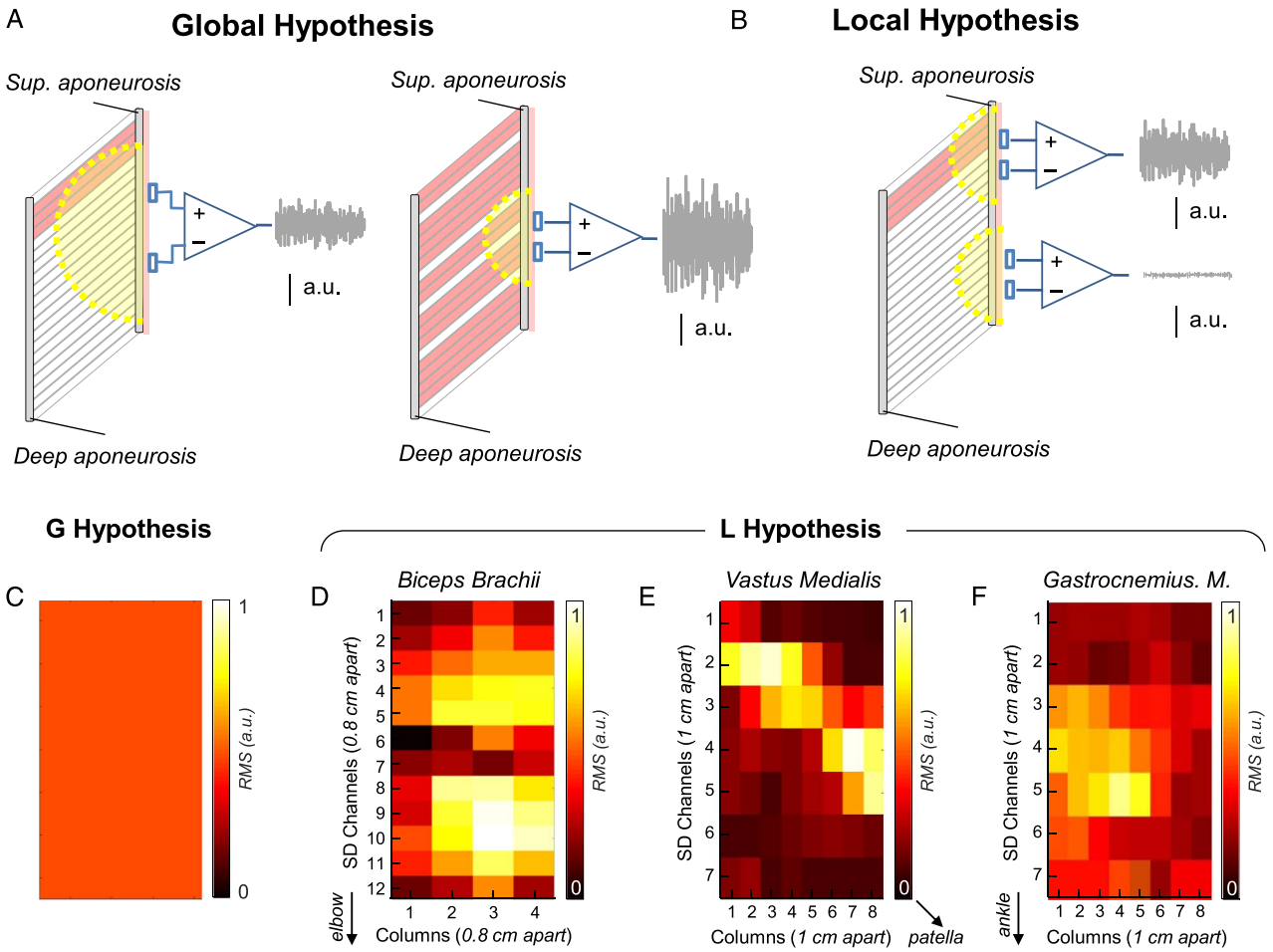

Figure 5. Competing hypotheses for inferring muscle excitation from bipolar electromyograms (EMGs). Global hypothesis (A): the amplitude of a single bipolar EMG is associated with the net muscle excitation regardless of where it is detected. This requires that either its pick-up volume includes all the fibers of the target muscle (left subpanel) or that excitation takes place randomly within the muscle (right subpanel). Local hypothesis (B): spatially localized excitations can only be captured by pairs of electrodes overlying the excited region. This implies that channels positioned elsewhere in the muscle may not be sensitive to the underlying muscle excitation. EMG images would be expected to appear as in (C) if the global hypothesis was verified. D–F. Experimental EMG images of muscle excitation detected from the biceps brachii (D), vastus medialis (E), and gastrocnemius medialis (F), respectively.

Figures 3–5, and those shown by others (27–29), a dramatic decrease in the amplitude of action potential detected by any consecutive channels covering the same target muscle can be observed consistently, if not always, in high-density recordings. Phrasing this statement interrogatively, why should the amplitude of an action potential decrease dramatically between consecutive channels if their pick-up volume was sufficiently large to include the whole target muscle, with all target fibers contributing equally to the surface EMGs? We believe any attempt to address this question would be elusive, at best. The observation of regional variations in the amplitude of high-density EMGs detected from the same target muscle is in itself evidence favoring the sufficiently small pick-up volume of surface electrodes, with the selective excitation of distinct, spatially localized muscle regions appearing as a logical corollary (Fig. 5B). The latter should not be viewed as equivalent to saying the fibers of single motor units are confined to small muscle regions, as one might conceive (30). The point is the number and location of excited fibers within the muscle in relation to the detecting electrodes; excitation of local muscle regions is likely to result in local groups of pixels with high EMG amplitude.

Understanding the geometrical association between muscle architecture and arrangement of electrodes is a prerequisite to inferring local muscle excitation from local EMG amplitudes. From an EMG perspective, whether muscles attach obliquely to the tendinous, connective tissue is irrelevant. What matters is the relative arrangement between fibers and the skin surface occupied by electrodes. This led us to define two specific categories of muscle regions: skin-parallel fibered and in-depth pinnate muscle regions (31). In the former case, fibers and skin reside in parallel planes. Inevitably, there will be channels (pixels) covering different extents of the same group of fibers, lying along one of the two dimensions of the grid (Fig. 5D) (4,31) or oblique to them (Fig. 5E) (15). For in-depth pinnate muscle regions, surface electrodes and fibers reside in nonparallel planes and therefore propagation cannot be appreciated (21). For this muscle region category, variations in EMG amplitude within the grid would be associated with regional differences in muscle excitation (Fig. 5F) (32). The two categories presented here are not mutually exclusive, as both may apply to a single muscle. For example, we have shown that when using a large grid to sample EMGs from the tibialis anterior (33), gastrocnemius (34), and soleus (24), some electrodes

may cover skin-parallel fibered regions, whereas others may cover in-depth pinnate regions (cf. Fig. 1 in [34]). Any attempt to establish recommendations generally valid for the positioning of electrodes over either skin-parallel-fibered or in-depth pinnate regions would be hopeless, considering the inter- and intraindividual differences in muscle size and architecture. Whenever inferences on muscle excitation are to be drawn from high-density EMG, we invite readers to cautiously reflect upon the following key points:

- For skin-parallel fibered muscle regions, regional variations in EMG amplitude (or image) may be conceived as excitations of different muscle regions only if assessed at directions transverse to that of the fibers (Figs. 3 and 5D, E).
- For in-depth pinnate muscle regions, the amplitude of EMG detected from different skin sites convey information on the degree of excitation of different muscle regions (Figs. 3 and 5F).
- Regardless of which target muscle is assessed, electrodes potentially covering regions falling into the two different categories must be identified and treated separately, as their EMGs have different physiological meanings (Fig. 5).

ISSUES TO CARE FOR WITH EMG IMAGING

With the same enthusiasm with which we illustrate the potential of EMG imaging to reveal regional variations in muscle excitation, we need to warn readers about important issues to consider before attempting to draw physiologically meaningful inferences from EMG images. Surface EMG is a relatively easy-to-use technique, if by "*to use*" we mean being able to detect a time-varying signal. The words of wisdom shared by Carlo De Luca, summarized by the statement "To its detriment, electromyography is too easy to use and consequently too easy to abuse" (35), have set the grounds for the emergence of documents focused on highlighting the many factors that influence the interpretation of surface EMGs (1–3). In this section, we discuss how specific, spurious sources of variations in EMG amplitude that may hinder the interpretation of a local group of pixels with high intensity in EMG images (Fig. 6A) as indicating regional muscle excitation.

According to the local hypothesis shown in Figure 5, the excitation of a sufficiently small fraction of any target muscle will lead to grouped pixels with high intensity in EMG images. The opposite however is not necessarily true, that is, the intensity of a local group of pixels may not indicate that excitation takes place locally within the muscle. When compared with electrodes manufactured exclusively for a single bipolar recording per muscle, the electrodes used for high-density recordings are overtly smaller. Typical values range from 5 to 50 mm^2 of skin area covered by gelled or dry electrodes (4). This reduced dimension greatly amplifies the effect resulting from the inappropriate treatment of the skin, with subtle differences in the treatment of skin regions covered by the different electrodes leading to the detection of monopolar EMGs contaminated to different extents by power-line interference, noise, or artifact. Considering the differential procedure shown in Figure 1, any low-quality monopolar signal in the grid will give rise to two consecutive bipolar signals with spuriously high amplitude (Fig. 6B). Although we illustrate a dramatic example of massive power-line contamination, this issue may manifest as spatially grouped pixels with high intensity, resulting from a coarse electrode-skin contact, which could be interpreted as localized muscle excitation. On the other extreme, short-circuit and low-impedance paths between neighbor electrodes would lead to the detection of almost flat bipolar signals, resulting in pixels with unreasonably low intensities (Fig. 6C). Two important notes are necessary here. First, short circuits may be easily avoided in conventional bipolar recordings when large, pregelled electrodes are used, but not in high-density recordings, whereby conductive paste is deposited in closely spaced cavities of a biadhesive foam used to secure the electrode grid to the skin. Second, the issue illustrated in Figure 6C may also manifest whenever low-impedance paths emerge between adjacent electrodes. For unfamiliar readers, these low-impedance paths may be seen as an increase in the electrical conductivity of the tissue interposed between contact points on the skin, resulting from, for example, sweating or the spreading of conductive gel or paste. Sweating or spreading of conductive material around the detection site would lead to bigger electrode-skin contact areas. This artificially induced increase in the electrode area implies a reduction in interelectrode distance and interelectrode impedance, which could lead to a spurious attenuation of the amplitude of bipolar EMGs detected by neighboring channels and thus to equivocal conclusions favoring reduced muscle excitation. At the moment, given there is no objective means of knowing whether spreading of conductive material occurred, if not after the grid has been removed and carefully examined for spreading, it is our opinion that only with experience one may confidently judge any local change in EMG amplitude to be genuine or not.

One final issue we would like to point out is the relative position of electrodes and fibers. The consideration that the intensity of pixels in EMG images may reflect the degree of excitation of a fraction of the target muscle holds if and only if all electrodes are covering muscle regions with the same arrangement between fibers and electrodes, whether it be skin-parallel fibered or in-depth pinnate. Detection volumes depend on both electrode configurations *and* fiber architectures. The surface electric potential associated with any single action potential would therefore have different values depending on whether detected at a skin region parallel or oblique to the fibers (Fig. 6D). Such subtle heterogeneities will likely lead to local differences in intensities of pixels that are not associated with local changes in the degree of muscle excitation.

In an attempt to assist whoever would like to consider using the high-density EMG technique, we recommend the following:

- Cleaning equally well all the skin regions covered by the different electrodes in the grid, minimizing therefore the bad contacts (Fig. 6B).
- Limiting the use of conductive paste to sufficiently filling the electrode cavities, avoiding the emergence of EMGs with spuriously low amplitude (Fig. 6C).
- Controlling for the level of perspiration. Although we anticipate excessive sweating may influence EMGs in a similar way as the spreading of conductive paste, *ad hoc* studies are necessary to systematically assess the influence of sweating on high-density recordings.
- Restricting analysis to EMGs detected by electrodes covering muscle regions with the same electrode-fiber architecture, otherwise local muscle excitation cannot be inferred from local changes in EMG amplitude (Fig. 6D).

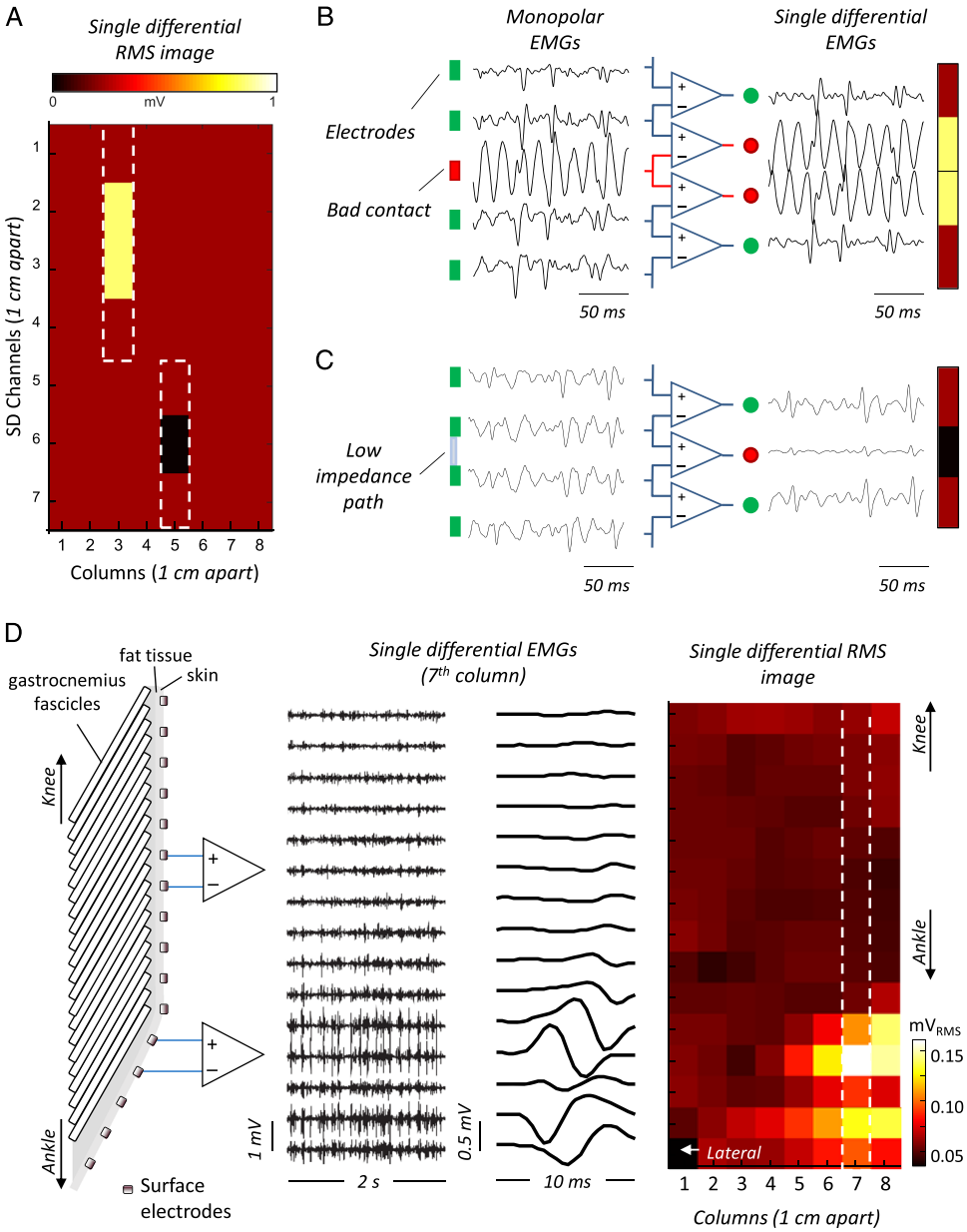

Figure 6. Spurious source of variations in electromyography (EMG) images. A. EMG image with two small areas of spuriously high and low root-mean-square (RMS) amplitude. B. High amplitude is due to low-quality electrode-skin contact, whereby the interference present in the low-quality monopolar signal extends to the two bipolar EMGs (bright pixels in [A] and [B]). C. The spread of conductive gel between electrodes leads to a low-impedance path and thus increases the similarity of monopolar EMGs, spuriously reducing the amplitude of the resulting bipolar EMG (dark pixels in [A] and [C]). D. Regional differences in the arrangement between electrodes and fibers lead to regional differences in EMG amplitude and thus in EMG images.

- Ensuring the integrity of the contact between the grid and the skin, in particular when securing the grid to highly curved skin surfaces; consequences of not doing so are unpredictable.

We further encourage both experienced and new users of high-density recording to carefully inspect signals for all of the issues we have highlighted before interpreting their data. Should this be not possible for whatever reason (*e.g.*, raw signals are not available), users must acknowledge the possibility that localized pixel intensity may not reflect localized muscle excitation.

CONCLUSION AND FUTURE PERSPECTIVES

Surface EMGs are often sampled with a single pair of electrodes. At best, from these bipolar EMGs, the experienced user may draw inferences on the timing and degree of muscle excitation. In this review, we discuss the hypothesis that high-density EMG provides a better picture of muscle excitation across the muscle fibers compared with bipolar configuration. As a consequence, from single bipolar EMGs, users are prone to state that a given muscle is excited when it is not (Type I error) or that it is not excited when it is (Type II error). Even though both errors have critical implications on the inferences derived from any EMG study, only recently has credit been given to the importance and frequency of Type II error. Mainly, bipolar EMGs detected from different skin regions covering the same target muscle reflect the excitation of a fraction of the muscle, and thus, the information provided by any individual EMG cannot be attributed to the whole muscle. The possibility of making

either mistake, in particular Type II, is minimized when detecting EMGs with linear arrays or grids of electrodes; the latter detection systems provide a means of representing surface EMGs as images, allowing exercise and sport scientists to readily appreciate local variations in the amplitude of EMGs. For example, providing local variations in EMG amplitude are genuinely associated with local muscle excitation, we anticipate that the high-density technology may help identify whether different regions of any given muscle or whether a bigger muscle region may be more strongly loaded during different exercises or exercise variations. Finally, we discuss basic concepts and culprits associated with advanced, high-density technologies for the detection of surface EMGs, expecting it to open new fronts for the study of muscle function in sports and exercise.

Although proposing multiple rather than single detection points is likely to provide a more accurate assessment of muscle excitation, we are aware of the difficulties that may emerge when attempting to use the high-density technique in sport and exercise sciences. Difficulties may arise because of the necessity of detecting EMGs in dynamic conditions, whereby cables could greatly hinder movement execution. Recent technical achievements could help circumvent this issue though, as EMG images may be now obtained through miniaturized wireless devices (36). Access to the high-density technology is another limiting factor and by no means do we wish to discredit the validity of studies conducted with the conventional bipolar EMGs. The use of multiple conventional electrodes could be an alternative, to the use of dense grids in attenuating the issues associated with a single bipolar recording. This approach would seem particularly valid for large muscles. For small muscles, the relatively large size of conventional electrodes may not allow a center-to-center distance sufficiently small to avoid Type I error (Fig. 2). It is our view that limitations associated with the use of bipolar EMGs must be acknowledged when designing a study, when the most appropriate way to detect EMGs may be identified and justified. With this purpose, methodological studies using high-density EMG could open new fronts for understanding if and how different regions of a given muscle could be recruited during different activities. It is our hope to encourage studies aimed at guiding users of the conventional EMG technology on how to deal with the limiting issues discussed in this review.

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