Electromyography in sports and occupational settings: an update of its limits and possibilities

JAN PIETER CLARYS*
Experimental Anatomy, Faculty of Physical Education and Physiotherapy, Vrije Universiteit Brussel, Brussels, Belgium

Keywords: History and bibliometry; Raw EMG; Rectified EMG; Surface-integrated electromyography; Normalization; Detection hazards.

The detection of the electrical signal from human and animal muscle dates from long before L. Galvani who took credit for it. J. Swammerdam had already shown the Duke of Tuscany in 1658 the mechanics of muscular contraction. Even if 'electrology or localised electrisation' — the original terminology for electromyography (EMG) — contained the oldest biological scientific detection and measuring techniques, EMG remained a 'supporting' measurement with limited discriminating use, except in conjunction with other methods. All this changed when EMG became a diagnostic tool for studies of muscle weakness, fatigue, pareses, paralysis, and nerve conduction velocities, lesions of the motor unit or for neurogenic and myogenic problems. In addition to the measurement qualities, the electrical signal could be induced as functional electrical stimulation (FES), which developed as a specific rehabilitation tool. Almost in parallel and within the expanding area of EMG, a speciality developed wherein the aim was to use EMG for the study of muscular function and coordination of muscles in different movements and postures. Kinesiological EMG and therewith surface EMG can be applied in studies of normal muscle function during selected movements and postures; muscle activity in complex sports; occupational and rehabilitation movements; isometric contraction with increasing tension up to the maximal voluntary contraction, evaluation of functional anatomical muscle activity (validation of classical anatomical functions); coordination and synchronization studies (kinematic chain); specificity and efficiency of training methods; fatigue; the relationship between EMG and force; the human–machine interaction; the influence of material on muscle activity, occupational loading in relation to lower back pain and joint kinematics. Within these various applications the recording system (e.g. the signal detection, the volume conduction, signal amplification, impedance and frequency responses, the signal characteristics) and the data-processing system (e.g. rectification, linear envelope and normalization methods) go hand in hand with a critical appraisal of choices, limits and possibilities.

1. Introduction
Recent developments in electromyographic signal processing, especially systems for analysing data, have upgraded electromyography (EMG), in particular surface electromyography (SEMG), into a data acquisition method for solving, detecting and discriminating ergonomic problems. The reason why it took so long for EMG to

*e-mail: jclarys@exan.vub.ac.be
Electromyography in sports and occupational settings

reach this status is because EMG took three distinct different directions in the course of its development, each with various approaches and analytical techniques.

Clinical EMG is largely a diagnostic tool whereas kinesiological EMG is merely a means to study function and coordination. The fundamental EMG itself deals with single motor unit action potentials and the related time–frequency domain. Depending on the user, whether a physician, anatomist, ergonomist, physiologist, engineer, physiotherapist or neurologist, one encounters independent improvements in registration technology, different approaches to data acquisition and various but specific graphic representations, modelling techniques and software for treatment of the signal.

All these have facilitated a great number of applications in neurology, neurophysiology, neurosurgery, bioengineering, functional electrostimulation (FES), orthopaedics, zoology, ergonomics, occupational biomechanics and medicine, rehabilitation and physical therapy, sports medicine and sports science, and other areas. This dissemination of knowledge about the neuromuscular system, both in the normal and the disabled person, was already predicted (and in part described) by Duchene de Boulogne in 1855, 1862, 1867, 1872 and 1885. As movement is the prime sign of animal life, scientists have shown a perpetual curiosity about the origins of locomotion in human and other creatures. Among the oldest scientific experiments known are those concerned with the detection of electricity and function of muscle (Basmajian and de Luca 1985, Clarys and Lewillie 1992, Clarys 1994).

Von Humboldt (1797), especially in the correspondence supplements in their translation into French (Jadelot 1799), alluded on several occasions to the fact that he had been experimenting with the irritation of muscles and nerves for many years. He claimed he was unable to publish his results because of his other scientific interests or his long and frequent travels or because he felt the experiments needed more time, more repetition and more analysis under different circumstances. It is known, however, that he was working on this topic in 1792 (the year Galvani published De Viribus Electricitatis in motu Musculari). He handed a written manuscript on the matter to Professors Soemering and Blumenbach in 1795. The same year Pfaff (cited in von Humboldt 1797) published his book on the electricity and irritation of animal muscular tissue. He was already working in this field before Galvani’s publication. Pierson and Sperling (1893) confirmed both statements. From the earlier works and especially from the correspondence published in them, it is clear that electricity generated by skeletal muscle had become an important research area for many scientists. Their experiments and discussions were to be found in Le Journal de Physique (France), Journal der Physic (Germany), Journal Encyclopédique de Bologne (Italy) and Le Journal de Grenoble (Switzerland). Several scientists studied the electrical phenomena of muscular and nervous tissue after Galvani’s publications but we are led to believe that some of them studied these phenomena independently before Galvani in 1786 (cited by Trouvé 1893) and/or 1792 (Clarys 1994). This explains in part the early discussion of terminology such as: ‘metallic irritation’, ‘animal electricity’, ‘Galvanic irritation’, ‘human electrology’ and ‘vital action’. It explains also the methodology used by those who stated that ‘muscular irritation (or electricity) is not possible without metal or carbon excitators’ and the findings of those scientists who confirmed that muscular electricity could be produced through irritation of humid animal tissue. According to von Humboldt (1797) and Jadelot (1799), it was Cotugno in 1786 and Vassali (1789) who investigated and suggested that soft animal tissue irritated muscle. It was their work that was the basis of the experiments of Galvani.
At the beginning of 1793, Volta wrote to Vassali that he believed Galvani’s experiments were faulty and that they proved nothing (Jadelot 1799). Von Humboldt repeated and completed these experiments with success (figure 1) and convinced Volta that, in fact, the contrary was true (von Humboldt 1797 and letter of van Humboldt to Blumenbach 1795 cited by Jadelot 1799). Apparently nobody corresponded with Galvani informing him of these findings (Clarys 1994).

Looking at other sources, one encounters different names, periods and stories in addition to different experiments and observations. According to Basmajian and de Luca (1985), Francesco Redi in 1666 was the first scientist to make the logical deduction that muscles generate electricity since he suspected that the shock of an electric-ray fish was muscular in origin. From Trouvé (1893), it is known that Du Fay in 1698 stated that all living bodies, including the human body, have electrical properties. The most spectacular discovery was the giant sized book (~60 × 40 cm) on the ‘Biological experiments of Jan Swammerdam’ written by Boerhaave et al. (1737) in Old Dutch and Latin (and of which a very limited amount of copies were printed) (Clarys 1994) (figure 2). Here Swammerdam described various experiments on the irritation of nerves, on the mechanism of muscle contraction and on the relation between stimulation and contraction. He showed the results of these experiments to the Duke of Tuscany in 1658, about 130 years and more before the works of Galvani and von Humboldt who were arguing to get credited with the original findings. For a good understanding of the developments of EMG in the 20th

Figure 1. Von Humboldt’s experiments (1795).
century, a series of historical landmarks in clinical, kinesiological and fundamental EMG are identified in table 1.

2. Technical and bibliometric considerations
Within EMG, in particular within the sports sciences and ergonomics, a speciality has been developed wherein EMG is used for studying muscular function and coordination. This area of research is usually called kinesiological EMG. The general aims are to analyse the function and coordination of muscles in different movements and postures, in healthy subjects as well as in the disabled, in skilled actions as well as during training, in humans as well as in animals, under laboratory conditions as well as during daily or vocational activities. Combining electromyographical, kinesiological, kinanthropometric, psychosocial and epidemiological data acquisition techniques often do this.

The research areas of kinesiological EMG can be summarized as follows. Areas incorporate studies of normal muscle function during selected movements and postures; studies of muscle activity in complex sports; occupational activity and rehabilitation movements; studies of isometric contraction with increasing tension up to the relative maximal voluntary contraction; evaluation of functional anatomical muscle activity (validation of classical anatomical functions); coordination and synchronization studies (kinematic chain); specificity and efficiency of training.
<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Contribution</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swammerdam (1658)</td>
<td>Described different experiments on muscle and nerve irritation, depolarization and contraction</td>
<td>Boerhaave et al. (1737), Clarys (1994)</td>
</tr>
<tr>
<td>Redi (1666)</td>
<td>Made deduction that muscles generate electricity since he suspected the shock of a ray-fish was muscular in origin‡</td>
<td>Biederman (1898), cited in Basmajian and de Luca (1985)</td>
</tr>
<tr>
<td>Vuverney (1679)</td>
<td>Described the function of muscles through the electricity (spirits) coming from the brain</td>
<td>Duverney (1761), Trouvé (1893)</td>
</tr>
<tr>
<td>Du Fay (1698)</td>
<td>Stated that all living bodies including humans have electric properties‡</td>
<td>Trouvé (1893)</td>
</tr>
<tr>
<td>Musschenbroek (1746)</td>
<td>Invented the Bottle of Leyden, the first electricity machine (improved by many since)</td>
<td>von Humboldt (1797), Trouvé (1893)</td>
</tr>
<tr>
<td>Jallabert (1750)</td>
<td>Described electrical stimulation of muscles for the purposes of medical re-education</td>
<td>Duchenne (de Boulogne) (1867)</td>
</tr>
<tr>
<td>Cotugno (1786)</td>
<td>Experimented with muscular contraction without metal or carbon contact—the basis of Galvani’s work</td>
<td>Pierson and Sperling (1893)</td>
</tr>
<tr>
<td>Vassal (1789)</td>
<td></td>
<td>von Humboldt (1797), Jadelot (1799)</td>
</tr>
<tr>
<td>Galvani (1792)</td>
<td>Published <em>De Viribus Electricitatis in Motu Musculari</em></td>
<td>Galvani (1792)</td>
</tr>
<tr>
<td>von Humboldt (1795)</td>
<td>Made primitive electrodes and experimented with many forms of stimulation</td>
<td>von Humboldt (1797)</td>
</tr>
<tr>
<td>Jadelot (1799)</td>
<td>Translated the work of van Humboldt (1797) and commented on correspondence of 18th-century neurophysiologists</td>
<td>Jadelot (1799)</td>
</tr>
<tr>
<td>Matteucci (1838, 1844)</td>
<td>Stated that electrical currents originate in muscle and that they are related to voluntary contraction</td>
<td>Matteucci (1844)</td>
</tr>
<tr>
<td>Du Bois Reymond (1849)</td>
<td>Redesigned and improved the electricity machines and detected voluntary contraction in vivo</td>
<td>Du Bois Reymond (1849)</td>
</tr>
<tr>
<td>Duchenne (de Boulogne)</td>
<td>Described techniques and developed equipment for both registration and stimulation; described mapping of all motorpoints in segments and made the first myoelectric-powered orthosis. Author of the first EMG bestseller</td>
<td>Pierson and Sperling (1893)</td>
</tr>
<tr>
<td>Pierson and Sperling (1893)</td>
<td>Century literature up-date</td>
<td>Trouvé (1893)</td>
</tr>
<tr>
<td>Trouvé (1893)</td>
<td>Century literature up-date</td>
<td>Wedenski (1884)</td>
</tr>
<tr>
<td>Wedenski (1884)</td>
<td>Discovered that muscle becomes inhibited by high-frequency stimulation—the Wedenski block. Nobel prize for Medicine</td>
<td>Marey (1890)</td>
</tr>
<tr>
<td>Marey (1890)</td>
<td>Introduced the word 'electromyography'; made the first myograph and may be considered as the pioneer of biomechanics</td>
<td>Marey (1890)</td>
</tr>
</tbody>
</table>

†Revised and complete version of Clarys (1994).
‡No second supporting reference found and/or no original, nor copy.
Electromyography in sports and occupational settings

methods; fatigue studies; the relationship between EMG and force; the human–machine interaction; the influence of equipment on muscle activity, and so on.

Since there are over 400 skeletal muscles in the human body and both irregular and complex involvement of the muscles may occur in neuromuscular diseases and in occupational or sports movements, it is impossible to sample all of the muscles of the entire body during the performance of complex motor skills. In addition, the EMG and the choice of integrated electromyography (iEMG) measurement, including the choice of the best normalization technique, depend on the specific demands on the type of subjects (e.g. athletes, manual handling workers, sedentary professions) and the specific demands of the field circumstances (e.g. swimming pool, office, alpine ski slope, hospital room, etc. whether in a vocational setting or in a simulation).

It is not within the scope of this review to discuss the instrumentation for recording electromyograms, nor to discuss functional anatomy. There is a wealth of literature concerned with the neuromuscular system, the recording system, the processing system and the information feedback system, which outlines the kinesiological and experimental data that should be reported (figure 3). Important dissemination roles have been fulfilled by:


2. The European SENIAM's (Surface EMG for Non-Invasive Assessment of Muscles) concerted action of the Biomedical and Health Research Program, as part of Biomed II. The SENIAM project has two objectives. First,
SENIAM enables scientists and clinicians working with surface EMG (SEMG) to exchange knowledge and experience on both basic and applied aspects of SEMG. The SENIAM project brings different disciplines together for the first time, enabling exchange and discussion and the creation of a common European body of knowledge on SEMG (e.g. by annual conferences 1996–99). The second objective of SENIAM is to develop recommendations for key items that presently prevent a useful exchange of clinical data and knowledge and a further maturation of SEMG. These items concern sensors, sensor placement, signal processing and modelling. The development of recommendations is essential to bring SEMG a major step forward as a general tool to be used in many applications focused on the assessment of the status and functioning of the neuromuscular system (Hermens et al. 1996a, 1997, 1998a,b, Hermens and Freriks 1997). Unfortunately, some of the contributions in these proceedings (1998a,b) report the mistakes/errors this author is cautioning against.

3. The Journal of Electromyography and Kinesiology (JEK) (edited by Solomonow, Maton and Moritani) spanning key topic areas such as muscle and nerve properties, motor units, physiological modelling, control of movement, motion analysis, posture, joint biomechanics, muscle fatigue, sports and exercise, measures of human performance, neuromuscular and musculoskeletal diseases, rehabilitation and functional electrostimulation. Important here is that the ‘Units, Terms and Standards in Reporting EMG’ (Winter et al. 1980) were rewritten and updated as the ‘Standards and Guidelines of Reporting EMG Research’ (Solomonow et al. 1996).

4. The journal Ergonomics, that was and remains the cradle of interdisciplinary applications in a range of vocational, simulation and work circumstances.

Whatever is not included in the above is to be found in the associated publications of biomechanics, neuroscience, sports science and orthopaedic societies respectively.

3. Critical appraisal of EMG studies, its limitations and hazards

The majority of activities in sport and occupational settings involve complex movement patterns often complicated by external forces, impacts and the equipment used during the movement. An electromyogram (or its derivatives) is the expression of the dynamic involvement of specific muscles within a determined range of that movement. The integrated EMG of that same pattern is the expression of its muscular intensity. However, intensity is not always related to force. For a review of EMG and force related to voluntary effort and isometric conditions, the reader is referred to the various literature sources. Mostly SEMG is used to investigate the activity of a series of muscles, seldom just one or two. The choice of these muscles is (based either on practical knowledge of the skill or on the basic anatomy literature. The functional EMG literature and early specific EMG work are rarely referred to.

The majority of scientists working in sport and occupational contexts measure EMG using surface electrodes. Skeletal muscles do not always stay in the same place during complex dynamic (sometimes ballistic) movements and the entire muscle belly may not be fully under the skin, but covered by parts of other bellies or tendons and subcutaneous adipose tissue (that is very variable both in composition and volume). It needs to be emphasized that the selection of muscles for EMG measurement
Electromyography in sports and occupational settings

requires careful consideration. Some of these choices can lead to erroneous registration, sometimes without being noticed by peer reviewers.

Despires (1974) placed his surface electrodes on M. sartorius, Broer and Houtz (1967) placed theirs on M. gracilis, and Strass (1990) and Toyoshima et al. (1971) on M. teres major. Measuring the EMG of these muscles under static conditions creates little or no problems, but under complex dynamic conditions the sartorius and gracilis muscles disappear from under the electrodes as does M. teres major, especially during arm motion above 90° abduction. It is therefore uncertain which muscles have contributed to the EMG patterns presented. Yoshizawa et al. (1978, 1987, 1989) and Oka et al. (1976, 1989) selected for their studies M. extensor carpi radialis brevis. This muscle has a very small superficial 'strip' accessible under the skin. The EMGs of this muscle are dubious and may give more information about M. extensor digitorum. The same problem arises when measuring M. semimembranosus (under M. semitendinosus) (Brandel 1973, Asang 1974, Elliot and Blanksby 1979, Gregor et al. 1981, 1985, Jorge and Hull 1983, 1986, Hull and Jorge 1985, Simonsen et al. 1985, de Proft et al. 1988), although the superficial muscle belly parts are greater in size than is the case with M. extensor carpi radialis brevis, the combination of displacement of the superficial M. semitendinosus with a lack of functional surface again gives different information from that which is expected (e.g. the cross-talk phenomenon).

Those authors who use wire electrodes do not necessarily have this problem, although measuring M. subscapularis in this way (Nuber et al. 1986, and others)—especially during front crawl in swimming and during golf movements—is questionable. This point of view of the anatomist who is confronted with these situations in the dissection room and palpation classes should not be discounted. That same anatomist will never measure M. sacrospinalis (Broer and Houtz 1967, Tokuyama et al. 1976, Yoshizawa et al. 1978, Oka et al. 1989), but instead chooses M. erector spinae. One group, however, reported measuring the EMG of M. tibialis posterior during skiing with unipolar active surface electrodes (Louie et al. 1984). It is assumed that this was a printing error.

In localizing the site of detection of the electrode on the skin, a variety of approaches has been applied: (1) over the motor point; (2) equidistant from the motor point; (3) near the motor point; (4) on the mid-point of the muscle belly; (5) on the visual part of the muscle belly; (6) at standard distances of osteological reference points (anthropometric landmarks); and (7) with no precision at all with respect to its placement.

The effects of electrode location on muscle fibre conduction velocity and median frequency estimates have been discussed in the SENIAM publications. The most reliable and most stable EMG values are to be obtained from the muscle belly area between the motor point and the most distal tendon. It follows that the position of the detection electrode must be chosen very carefully to minimize errors. Motor points are often located at the borders of muscles if projected to the skin, because other muscles or tendons cover part of those muscles.

As the motor point moves according to the level of contraction and the complexity of the movement, localizing the detection electrode over, near or equidistant from the motor point must be avoided. The motor point can in certain muscles disappear under another muscle. In other words, the region has to be large enough to accommodate the electrode. For complex skills in sport and occupational contexts, the muscle belly shortens in the proximal direction during concentric
contractions and the electrode on the skin finds itself over the distal tendon. It is therefore proposed to place the electrodes over the visual midpoint of the 'contracted' muscle (Clarys et al. 1983, Clarys 1985).

In addition to localizing the electrode in its proper place on the skin over a muscle, it is also important to pay attention to the orientation of the electrode with respect to the muscle fibres. Bipolar surface electrodes have two detection surfaces. For optimal results, the two detection surfaces should be oriented so that the line between them is parallel to the muscle fibres. To accomplish this arrangement, it is assumed that the muscle fibres act along a line and that the muscles have a single arrangement of unipennate fibres. In some muscles, neither of these conditions is satisfied; in such cases it is advisable to place the electrode so that the line between the detection surfaces points to the origin and the insertion of the muscle. This orientation provides for consistent landmarks, so that the future placement of the electrode will have near-similar orientations and reduce the variation in EMG signal among the myoelectric measurements obtained from different contractions (de Luca and Knaflitz 1990).

Following the ISEK, SENIAM and JEK criteria, it is recommended to report the upper cut-off frequency, the lower cut-off frequency and the type of filter used in the amplifiers. If a DC-coupled amplifier is used, the input impedance and input current should also be reported. The type and material of the electrodes, the space between the contacts, the site and the preparation of the skin should also be documented (Solomonow et al. 1996). As to the processing of data, it is important to mention the use of raw EMG, iEMG, linear envelope, mean rectified EMG (MREMG), but also average EMG or ensemble average, together with the synchronization system and the normalization technique used, such as normalized to MVC or to 50% of the average of three MVCs, or to the highest peak (per movement or per subject) or to the mean of the subject ensemble average.

The linear envelope is the qualitative expression of the rectified and eventually averaged signal. Within a window choice this linear envelope can be smoothed, independent of its purpose. It should equally be clear once one starts smoothing, one cannot integrate anymore and it is unwise to use 'intensity' or 'activity level' in this case. Integration refers to the surface under the non-smoothed but rectified signal, to express the 'muscular intensity' phenomenon.

Because of the known variability of the EMG signal, not only between subjects, but also between different trials, these different normalization techniques have been developed to reduce variability. Generally, the EMG of maximum effort or the highest EMG value has been selected as the normalizing factor. In the main, the subject is asked to perform a maximal voluntary contraction (MVC) of the muscle (groups) being studied. This amplitude, either raw or rectified, is then used as a reference value (e.g. 100%). The use of the MVC reference is perfect in all static applications. For all dynamic activities the use of an isometric reference is debatable (Clarys et al. 1983, Yang and Winter 1984). Recently, the discussion about this normalization technique has been resurrected, because several investigators have found dynamic activities that exceeded the maximal isometric effort. Therefore, other normalization techniques have been developed in kinesiological EMG, e.g. normalization to the highest peak activity in dynamic conditions, to mean integrated EMG (ensemble average), to EMG per unit of measured force (net moment), and so on.

In an extensive review of sport specific and ergonomic studies using EMG, the missing information mostly concerned the normalization. In the majority of both
Electromyography in sports and occupational settings

sport and occupational studies in which a normalization technique is mentioned, the MVC technique has been used. This approach, however, is unreliable for several reasons:

- different maxima may be observed within the same subject repeating at different moments the same 'maximal' but isometric effort;
- different maxima will be observed at different angles of movement, both in the eccentric and concentric movement mode; and
- in addition, the question of linearity may arise when the values measured during isotonic dynamic-ballistic-complex sports movements exceed the 100% MVC. For example, Clarys et al. (1983) found dynamic percentages in swimming up to 160%, while Jobe et al. (1984) found up to 226% of MVC in baseball pitching.

Reason suggests that a statically obtained EMG cannot be a reference for dynamic EMG.

4. Closing remarks

To understand the nature and the development of EMG it is important, if not imperative, to have knowledge of its spectacular development in the previous millennium. Nevertheless it has taken about 300 years for EMG to emerge as an independent discriminating research methodology. Parallel to the technical hardware and signal-processing progression (not discussed in this review) is a requirement to be aware of problems with respect to the EMG acquisition and analysis methods. Users of EMG should possess a basic understanding of both fundamental electrophysiology and anatomical kinesiology before they start working with the tool. Valid conclusions have to be based on the assumption that the researcher knows exactly from which muscles the signals are being recorded.

To decide whether this condition has been met, different test procedures have been developed for collecting information, which will indicate temporal phases of the movement. These procedures assume knowledge of muscle function, and in the case of complex sports and occupational movements, a thorough knowledge of the sport and skill is concerned. ISEK and SENIAM have strongly suggested that some explicit standards should be met in reporting EMG research. A detailed description of the results of the test procedures and the circumstances under which the test procedures and the recording took place should be a requirement. This prerequisite has not always been met in the past. Another common mistake occurs when two independent EMGs from different muscles are available. It is not possible to state, as some investigators have implied, that because the amplitude, integral or some other measure of muscle A is greater than the corresponding measure from muscle B, muscle A is producing more force than muscle B. This comparison is complicated by many factors ranging from the size of the muscle fibres to the nature of the interface between the skin and electrodes (Cavanagh 1974, de Luca and Knaflitz 1990, Hermens et al. 1996, 1997, 1998).

Twenty-five years ago (Cavanagh 1974) the first warnings were given about use and misuse of EMG in physical education and the misuse still exists. These warnings stay valid today and apply to all movement studies, in both sport and occupational contexts.
References


Duchenne, G. B. (de Boulogne) 1885, Physiologie der Bewegungen (Cassel: Theodor Fischer).


Galvani, L. 1792, De Viribus Electricitatis in Motu Musculari (Bologna: Università di Bologna).


Electromyography in sports and occupational settings


WEDENSKI, N. 1884, Wie rasch ermydet nerveder, Zeitschrift für die Medicinische Wissenschaft, 65–68.


