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Development of recommendations for SEMG sensors and sensor placement procedures

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Abstract

The knowledge of surface electromyography (SEMG) and the number of applications have increased considerably during the past ten years. However, most methodological developments have taken place locally, resulting in different methodologies among the different groups of users.

A specific objective of the European concerted action SENIAM (surface EMG for a non-invasive assessment of muscles) was, besides creating more collaboration among the various European groups, to develop recommendations on sensors, sensor placement, signal processing and modeling. This paper will present the process and the results of the development of the recommendations for the SEMG sensors and sensor placement procedures.

Execution of the SENIAM sensor tasks, in the period 1996–1999, has been handled in a number of partly parallel and partly sequential activities. A literature scan was carried out on the use of sensors and sensor placement procedures in European laboratories. In total, 144 peer-reviewed papers were scanned on the applied SEMG sensor properties and sensor placement procedures. This showed a large variability of methodology as well as a rather insufficient description. A special workshop provided an overview on the scientific and clinical knowledge of the effects of sensor properties and sensor placement procedures on the SEMG characteristics.

Based on the inventory, the results of the topical workshop and generally accepted state-of-the-art knowledge, a first proposal for sensors and sensor placement procedures was defined. Besides containing a general procedure and recommendations for sensor placement, this was worked out in detail for 27 different muscles. This proposal was evaluated in several European laboratories with respect to technical and practical aspects and also sent to all members of the SENIAM club (>100 members) together with a questionnaire to obtain their comments. Based on this evaluation the final recommendations of SENIAM were made and published (SENIAM 8: European recommendations for surface electromyography, 1999), both as a booklet and as a CD-ROM. In this way a common body of knowledge has been created on SEMG sensors and sensor placement properties as well as practical guidelines for the proper use of SEMG.

Keywords: Surface EMG; Sensor; Electrodes

1. Introduction

The knowledge of surface electromyography (SEMG) has increased considerably during the past ten years. This concerns a better understanding of the physiological processes that contribute to the generation of this signal, more adequate signal processing techniques and a growing knowledge on how it can be applied in various clinical applications. In particular, the rapid growth of the number of applications underlines the high potential of SEMG as a non-invasive tool for the assessment of the neuromuscular system. On the other hand, however, most methodological developments have taken place locally, resulting in different methodologies among the different groups of users. This hinders the further growth of SEMG into a mature well-accepted tool by the users as well as industrial efforts on a large scale. A standardization effort is required to make the results more comparable and to create a large common body of knowledge on the use of SEMG in the various fields of application.

With this in mind, the European concerted action SENIAM (surface EMG for a non-invasive assessment of muscles) was started in 1996. Besides having the general goal of creating more collaboration among the vari-

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ous European groups [14,15,17,19], the specific goal was formulated to develop recommendations on key items to enable a more useful exchange of data obtained with SEMG, including sensors, sensor placement, signal processing [20] and modeling [18]. Two of these key items involved sensors and the placement of sensors on the muscle. In this context the sensor is defined as the arrangement of electrodes put on the skin surface to pick up the EMG signal from the underlying muscle. As it is clear that these two items are very much interrelated it was decided to combine them into one set of sensor tasks.

This paper will present the process and the results of the development of the recommendations for the SEMG sensors and sensor placement procedures.

2. Methods

Execution of the SENIAM sensor tasks, in the period 1996–1999, has been handled in a number of partly parallel and partly sequential activities. The interactions between these activities are shown in Fig. 1.

First, an inventory was carried out on the use of sensors and sensor placement procedures in European laboratories. The inventory consisted of a questionnaire circulated among the SENIAM partners and a literature scan of 144 SEMG publications by European authors.

In parallel, an overview was obtained on the scientific and clinical knowledge of the effects of sensor properties and sensor placement procedures on SEMG signal characteristics. This was done by organizing a topical workshop, with experts in this field, to discuss these various effects and to produce a consensus on relevant guidelines. In addition, some specific experimental studies have been carried out in European laboratories combining the knowledge and facilities of the partners [19].

Based on the inventory, the results of the topical workshop and generally accepted state-of-the-art knowledge, a first proposal for sensors and sensor placement procedures was defined [16]. Besides containing a general procedure and recommendations for sensor placement, this was worked out in detail for 27 different muscles. This proposal was evaluated in several European laboratories with respect to technical and practical aspects. The proposal was also sent to all members of the SENIAM club (>100 members) together with a questionnaire to obtain their comments. Based on this evaluation the final recommendations of SENIAM were made and published, both as a booklet [21] and as a CD-ROM [10]. In this way a European common body of knowledge has been created on SEMG sensors and sensor placement procedures as well as practical guidelines for applications.

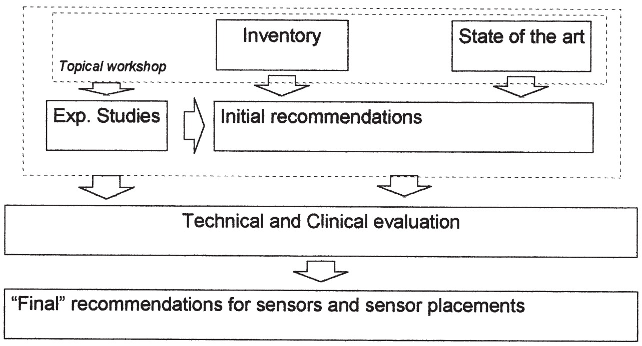

Fig. 1. Sequence and interrelations between the SENIAM sensor tasks.

2.1. The inventory

The inventory on sensors and sensor placement procedures consisted of two parts:

1. A questionnaire among the 16 SENIAM partners;
2. A literature scan of a large number of European publications on SEMG.

The questionnaire should be regarded as a pilot study for the literature scan. It was designed to obtain a first impression about the sensors, sensor placement procedures and equipment used in the European laboratories. It was sent to the 16 SENIAM partners and they all returned the form. A main conclusion [9] was that a large variety of sensors and equipment is being used in these laboratories. The high variability in this limited amount of data justified a larger-scale effort.

The literature scan was based on seven journals in which publications about SEMG can be found regularly. Table 1 shows an overview of the selected journals. The selection covers most of the application areas of SEMG as well as the more basic research-related activities. In the available volumes of the last 5–7 years (1991–1997) all publications from European first authors have been scanned with respect to the following subjects:

1. General: author, title of the publication, journal, volume.
2. Sensor properties: manufacturer type, number of contact points, shape, size, material, inter-electrode distance.
3. Sensor placement procedure: skin preparation technique, paste, muscles, location on muscles, location of reference electrode.
4. Equipment; Signal processing; Comments.

All data were entered in a database and then checked for completeness. In case of incompleteness, the captured information was put in a form and then sent to the first author with a request to complete the information. The additional information was then entered into the database.

Table 1
Numbers and years of SEMG publications scanned for the inventory

Journal	Scanned volumes	Number of publications
The Journal of Electromyography and Kinesiology	1991, 1992, 1993, 1994, 1995, 1996	34
Electromyography in Clinical Neurophysiology	1993, 1995, 1996	20
Electroencephalography in Clinical Neurophysiology	1992, 1993, 1994, 1995, 1996	38
The Journal of Biomechanics	1992, 1993, 1994, 1995, 1996, 1997	13
Ergonomics	1994	6
Muscle and Nerve	1992, 1993, 1994, 1996	9
The European Journal of Applied Physiology	1995, 1996	24
		Total: 144

3. Results

3.1. The inventory

3.1.1. Number of papers scanned and verified by first authors

In total, 144 peer-reviewed papers were scanned. The number of publications on SEMG that was found in each journal is shown in Table 1. This table also shows which volumes of the journals have been scanned. Because not all volumes were available in the libraries visited, it was not possible to scan at least five complete volumes of each journal.

In 101 of the 144 papers the address of the author was known so a request for completion could be sent. Of these, 33 (32%) were returned and the information obtained was added to the database.

3.1.2. Sensor configuration

Initially, in 40% of the publications the applied sensor configuration was not mentioned properly. After feedback from the authors the sensor configuration in 126 (88%) of the publications was known. This resulted in the following overview:

- monopolar reported in 5 publications
- bipolar reported in 115 publications
- array/line electrodes reported in 6 publications

It is very clear that a bipolar sensor configuration was used most frequently. Most references to monopolar configurations were found in ElectroEncephaloGraphy and Clinical Neurophysiology while most array/line configurations were found in the Journal of Electromyography and Kinesiology.

3.1.3. Trademark

In 81 of the 144 publications (56%) the trademark of the electrodes used was not mentioned. After feedback from the authors this amount reduced to 63 (44%) which means that the trademark of the electrodes in 81 (56%) publications was known. These were:

- Medicotest (child ECG-electrodes) reported in 18 publications
- Beckmann (miniature size) reported in 14 publications
- Own/custom-made reported in 8 publications
- DISA 13Lxx reported in 5 publications
- Meditrace reported in 4 publications
- Dantec reported in 4 publications
- Other reported in 25 publications

The inventory shows a large variety in electrodes used: in total, 24 trademarks have been counted (the 6 trademarks mentioned above together with 18 other trademarks which have been counted less than four times and make up the ‘other’ category). This variety is even larger when taking into account that within trademark categories a large variety in shape and size can be discerned.

The inventory shows that there is a preference for Medicotest and Beckmann electrodes, which is not surprising as they are easily available and are small enough to be used for SEMG recordings.

3.1.4. Material

In 82 (57%) of the publications the material of which the electrode was made was not mentioned. After feedback from the authors this amount has been reduced to 62 (43%). In the remaining 82 (57%) publications the electrodes were made of the following material:

- Ag/AgCl reported in 57 publications
- Ag reported in 11 publications
- AgCl reported in 6 publications
- Au reported in 3 publications
- Other materials reported in 5 publications

In total, seven types of electrode materials have been discerned (the four types mentioned plus three types in the ‘other materials’ category: tin, metal, stainless steel, each mentioned less then three times). For bipolar or monopolar electrodes, it is obvious that Ag/AgCl was the preferred electrode material. Although reported separately, it makes no sense to distinguish between AgCl and Ag/AgCl electrodes since in the presence of an electrical potential an AgCl electrode immediately becomes an Ag/AgCl electrode. For array or line electrodes Ag or Au was used.

3.1.5. *Electrode shape and size*

Initially, in 88 (61%) of the scanned publications the shape of the electrodes used was not mentioned. After feedback from the authors this amount was reduced to 69 (48%). In the 75 publications (52%) the following shapes were used:

- circular reported in 59 publications
- rectangular/bar reported in 13 publications
- square reported in 2 publications
- oval reported in 1 publication

Thus, in the literature both rectangular (bars) and circular electrodes are being used for SEMG recordings of which circular electrode are by far the most used.

When discussing electrode size, we have to discriminate between circular and rectangular/bar electrodes. In 52 (88%) of the 59 scanned publications in which circular electrodes were reported, the size of the electrodes was mentioned. In some papers several electrode sizes were used which contributes to the fact that, in total, 57 sizes were found. Fig. 2 shows the occurrence of the different electrode diameters that were found.

From Fig. 2 it becomes clear that there is a slight preference to use circular electrodes with a diameter ranging from 8 to 10 mm. It can also be concluded that an almost continuous range of electrode diameters was used. Only two occurrences relate to array electrodes (1 mm diameter (once), 2 mm diameter (once)). All other occurrences relate to the electrodes used in mono- or bipolar recordings.

With respect to the square/rectangular/bar electrodes it is not possible to detect any particular preference. The size of 12 of the 15 electrodes found in the literature was mentioned, usually expressed as width (mm)×length (mm). Although the orientation of an electrode with respect to the fibers is of importance (which side—longest or shortest side—is placed perpendicular to the muscle fibers), this was badly described. As such, the definition of ‘width’ in this chapter means nothing else but the shortest length of the electrode. The following overview shows that a large variety in sizes was used.

- 1×5 mm (1× array)
- 1×10 mm (1× array, 2× bipolar)
- 2×10 mm (1× array)
- 3×5 mm (1×)
- 4×7 mm (1×)
- 5×10 mm (1×)
- 5×12 mm (1× array)
- 6×12 mm (1×)
- 11×11 mm (1×)
- 20×40 mm (1×)

3.1.6. *Inter-electrode distance*

The effect of the inter-electrode distance (IED) on SEMG signal characteristics is regarded as one of the most relevant property of the SEMG sensor. Fig. 3 shows an overview of the different IED occurrences found in the scanned publications, both for line/array and for bipolar electrode configurations.

A high variability and a wide range of values for IEDs were found. One could expect that larger distances would be used for larger muscles. This seems not to be true; for most of the larger muscles the whole range of electrode distances was found (i.e. biceps brachii 10–40 mm, biceps femoris 20–50 mm, deltoideus 20–40 mm, gastrocnemius 10–50 mm, rectus femoris 10–50 mm). Authors seem to have a preference for IED values which are a multiple of 10 mm. The largely preferred distance was 20 mm.

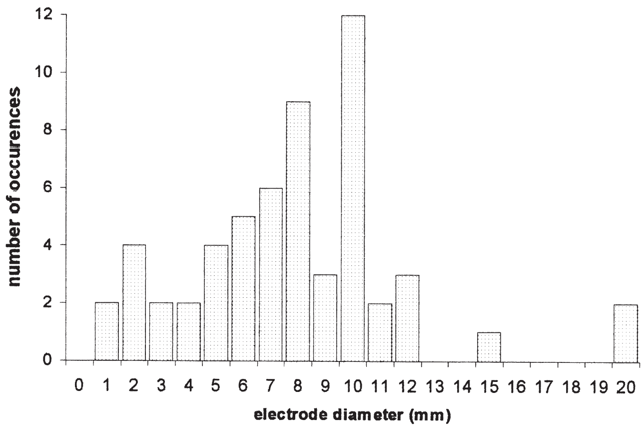

Fig. 2. Occurrence of the diameter of circular SEMG electrode sizes found in the literature.

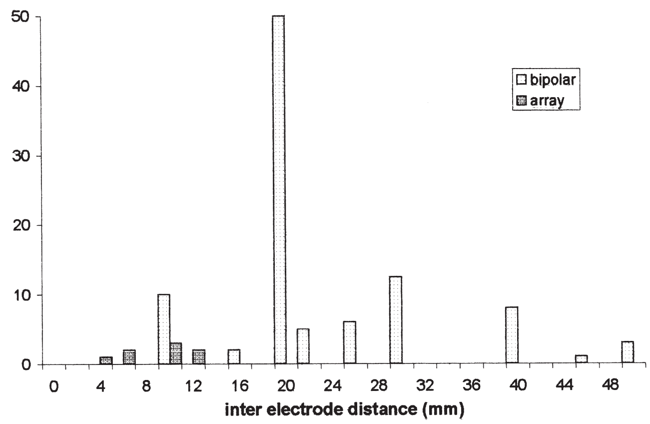

Fig. 3. Occurrence of inter-electrode distances (in mm) of bipolar and array SEMG electrodes found in the literature.

3.1.7. Skin preparation

In 89 (62%) of the publications the skin preparation technique used was not mentioned. After feedback from authors this amount was reduced to 68 (47%). In the remaining 76 (53%) publications, standard skin preparation techniques [2] were mentioned such as shaving, rubbing/abrasion and cleaning of the skin, or a combination of these techniques. Rubbing/abrasion of the skin was done with sandpaper, glasspaper, alcohol/ether until redness. Cleaning was done using alcohol, ethanol, ether, acetone, a mixture of these products or a cleaning gel. A total of 18 publications (13%) indicated that the skin impedance was checked before SEMG recordings were taken. Fig. 4 shows an overview of the maximum impedance, which was accepted in those publications. Apart from one exception (100 kΩ) all authors accepted a maximum skin impedance below 10 kΩ.

In 115 publications (80%) it was not clearly indicated whether gel was used or not. In 19 (13%) cases the author indicated that gel was used while the skin preparation techniques used were further detailed. In the remaining 10 (7%) publications it was clearly indicated that no gel was used at all.

3.1.8. Sensor location and orientation on the muscle

The publications were also scanned on the location and orientation of the bipolar sensor on the investigated muscle(s). In this context *Location* is defined as the position of the sensor on the muscle. It has been assumed that the location description described the location of the geometrical center of the sensor, unless specified otherwise. *Orientation* is defined as the direction of the bipolar sensor with respect to the direction of the muscle fibers.

In the 144 papers scanned, in total 352 descriptions of the sensor location were counted. These descriptions applied to 53 different muscles. In four of the 352 (1%) descriptions neither the muscle(s) of which the SEMG has been recorded nor the sensor location was mentioned. In 58 (16%) descriptions the sensor location on the muscle was not mentioned. The remaining 294 descriptions mentioned both the name of the muscle and described the sensor location or referred to the literature. The main literature references which were found are [1,2,24,27,28]. These publications contain detailed sensor location descriptions for a large number of muscles. Some of the scanned publications also contained detailed sensor location descriptions for a large quantity of muscles [12,26].

Tables 2 and 3 show some examples of sensor location descriptions for biceps brachii and gastrocnemius muscles. In SENIAM 5 additional tables can be found for the soleus and trapezius muscles as well as the references to the papers in these tables.

Table 2 shows that, in total, 21 sensor placement descriptions for the biceps brachii muscle were found. In three publications the sensor location was not mentioned at all.

Globally, three placement strategies can be discerned:

1. on the center or on the most prominent bulge of the muscle belly (10 out of 21);

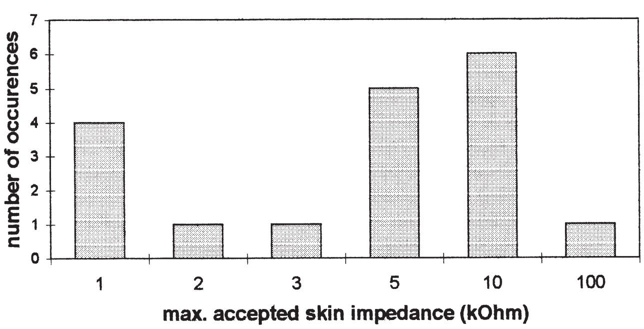

Fig. 4. Occurrence of the maximum accepted skin impedance of SEMG electrodes (in kΩ) after skin preparation, found in the literature.

Table 2
Overview of electrode location descriptions on the biceps brachii muscle

Electrode location	Author
Middle of muscle belly	Woensel W. van
To the muscle belly	Martin A.
Over the belly	Martin A.
Midpoint to contracted muscle belly	Clarijs JP.
?	Kluth K.
One of the two recording electrodes placed above the motor point	Maton B.
Most bulky part of the long head	Christensen H.
Over the muscle in line with the main fiber direction of the short head of the muscle, distal to the motor point. Location accepted if maximum cross-correlation coefficient between bipolar recorded EMG signals (see below) >0.7	Stegeman D.
Parallel to fiber orientation, halfway between innervation zone and distal tendon	Van der Hoeven H.
?	Fellows SJ.
Between endplate region and tendon insertion	Rau G.
On short head parallel to the muscle fibers	Vogiatzis I.
Belly-tendon montage	Logullo F.
Belly of the muscle	Esposito F.
Parallel to fiber orientation, halfway between innervation zone and distal tendon	Van der Hoeven H.
In the midst of the muscle belly	Happee R.
Over the belly	Orizio C.
Halfway between the motor endplate zone and the distal tendon aligned in the direction of the muscle fibers	Hermens HJ.
On the muscle after having determined the motor endplates with an electrostimulation apparatus	Kahn JF.
Over the medial belly of each head (long head and short head) parallel to muscle fibers	Perot C.
?	Hummelsheim H.

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