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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.

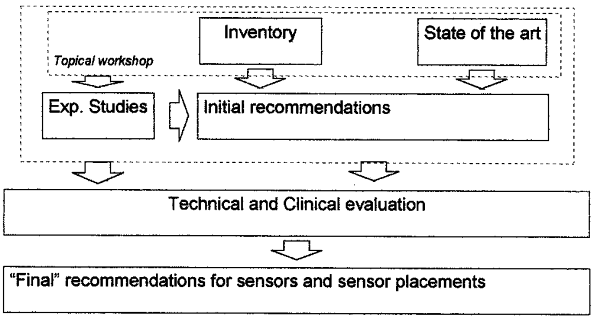


Fig. 1. Sequence and interrelations between the SENIAM sensor tasks.

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.

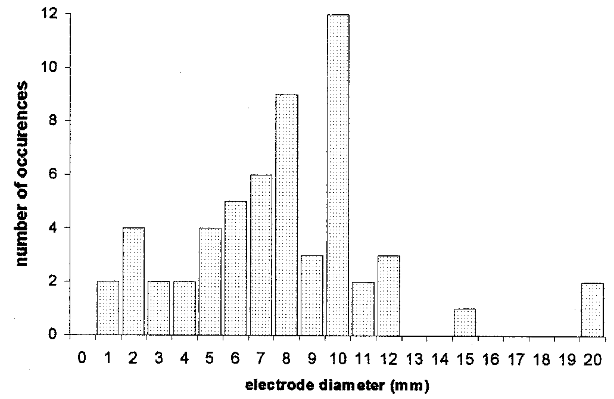


Fig. 2. Occurrence of the diameter of circular SEMG electrode sizes found in the literature.

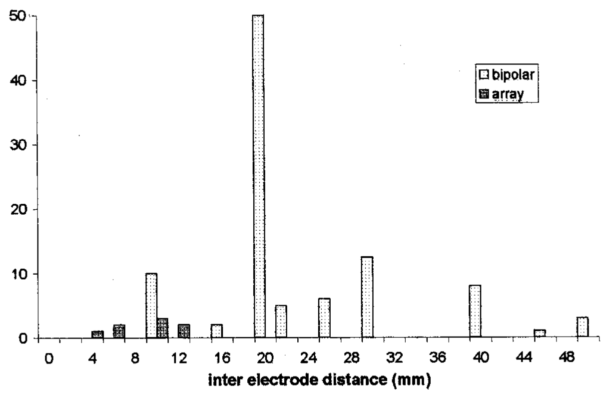


Fig. 3. Occurrence of inter-electrode distances (in mm) of bipolar and array SEMG electrodes found in the literature.

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].

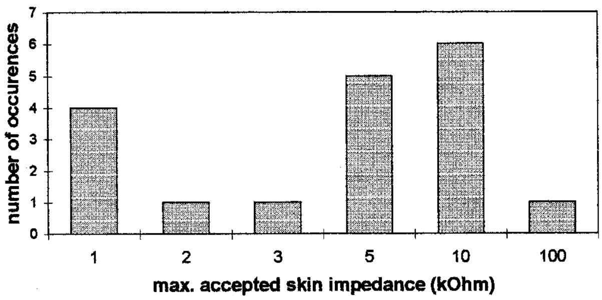


Fig. 4. Occurrence of the maximum accepted skin impedance of SEMG electrodes (in kΩ) after skin preparation, found in the literature.

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);

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.

Table 3
Overview of electrode location descriptions on the gastrocnemius muscle

Electrode location	Author
Over the motor point of the medial muscle (location using electrical stimulation); if muscle has multiple motor points, the motor point with the lowest threshold was chosen	Hainaut K.
In the belly of the medial muscle group	Svantesson U.
Longitudinally on the muscle belly of the lateral head	Avela J.
On midpart of lateral muscle bellies, approximately parallel to muscle fibers	Voigt M.
Upper third of the leg, over the medial muscle belly	Abbruzzese M.
Over the most prominent bulges of the medial muscle	Peeters M.
Upper third of the leg, over the lateral muscle belly	Abbruzzese M.
Over the belly of the muscle	Rissanen S.
On top of the muscle	Trenkwalder C.
?	Trenkwalder C.
Center of the belly of the muscle	Portero P.
Longitudinally on the lateral muscle belly	Nicol C.
Longitudinally over the muscle belly	Kyrolainen H.
Separated measurement—a pair of electrodes on the midst of each muscle belly, across the fiber direction; combined measurement—each electrode of the pair was on a muscle belly	Hof A.
On the lateral muscle belly in the direction of the muscle fibers	Ament W.
Proximal electrode placed above bulkiest part or middle of the medial muscle belly	de Looze MP.
Over the motor point of the lateral muscle (location using electrical stimulation); if muscle has multiple motor points the motor point with the lowest threshold was chosen	Hainaut K.
On the belly of the lateral muscle group	Svantesson U.
Longitudinally over the muscle belly; longitudinal distance between electrode pairs at least 10 cm	Kyrolainen H.
On medial gastrocnemius	Gantchev N.
On the muscle belly of gastrocnemius medial in the direction of the muscle fibers	Ament W.
Over the area of greatest muscle bulk on the medial calf	Sinkjaer T.

2. somewhere between the innervation zone and the distal tendon (6 out of 21);
3. on the motor point (1 out of 21).

In the remaining four publications the sensor location was not mentioned or was unclear.

Altogether this shows that half of the authors use a belly-montage. Certain authors differentiated between the long head and the short head. The orientation of the electrodes with respect to the direction of muscle fibers was seldom mentioned.

Table 3 shows that in the gastrocnemius muscle, the sensor placement is in general much clearer. In total, 22 descriptions were found of which only one author did not mention the electrode location at all. Most authors clearly indicated whether the EMG of the lateral or medial gastrocnemius was measured and placed the electrodes on the muscle belly. Most authors described the sensor location used in a rather global manner: on the belly of the muscle, on the most prominent bulge/calf of the muscle, on the top of the muscle. The orientation of electrodes on the muscles was seldom mentioned.

With the soleus muscle, 22 sensor placement descriptions were found. In principle, the description for this muscle is more critical compared to other muscles since the largest part of the muscle is covered by the gastrocnemius muscle, so only a small part can directly be accessed from the surface. The literature scan showed that there was a large variety of locations used and it was difficult to categorize the electrode location descriptions. From a large number of descriptions it was unclear how to reproduce the exact electrode location (i.e. it is difficult to determine the exact location of the muscle belly if most of the belly is covered by the gastrocnemius muscle).

In contrast to this muscle, the sensor placement descriptions for the trapezius muscle were much clearer. With the trapezius muscle 35 sensor placement descriptions were found. In only one case was the electrode location not mentioned at all. In most of the descriptions it was clearly indicated whether electrodes were placed on the trapezius ascendens, transversalis or descendens muscle. The trapezius descendens muscle seems to be the most commonly investigated part of the trapezius muscle. In comparison to other muscles, the placement was referring much more often to bony landmarks, facilitating a good reproduction. For the pars descendens a preference for a position midway between C7 and the acromion can be recognized.

Hence, in general the description of the placement of the SEMG sensor is not good enough to enable a good replication of the experiment, although there are considerable differences between the different muscles. One could get the impression that in the more 'difficult' muscles the description of the placement is worse. Another general comment is that the orientation of sensor was seldom mentioned.

3.1.9. Fixation on the skin

The way the sensor is connected to the body is referred to as 'fixation'. This facilitates a good and stable electrode–skin contact, a limited risk of movement of the sensor over the skin as well as a minimum risk of pulling of cables.

In general, authors hardly ever reported the fixation methods used. Reported fixation methods mentioned include the use of (double-sided) adhesive tape or collar, stickers, elastic bands, and keeping the sensor on the desired location by hand.

3.1.10. Location of reference electrode

In general, the location of the reference electrode was not well reported. In only 54 of the 144 (38%) publications was the location of the reference electrode mentioned. This means that for 237 of the 352 (67%) electrode location descriptions the location of the reference electrode is not known.

In principle, the reference electrode is placed over inactive tissue (tendons or bony parts), often at a distance from the active muscles. In some cases the reference electrode was placed as close as possible on a bony part, the tendon or next to the SEMG electrodes.

'Popular' locations to place the reference electrode were the wrist, waist, tibia, sternum and the processus spinosus (proc. spin.) of C7 vertebra. The wrist was often used while measuring the EMG of leg, arm, back, shoulder/neck as well as facial muscles. The waist was used when many shoulder/neck and back muscles were measured simultaneously. The tibia was used in combination with both lower and upper leg muscles and the sternum in combination with back muscles and the processus spinosus (proc. spin.) of C7 vertebra in combination with shoulder/neck muscles.

4. The effect of sensor properties and sensor placement procedures on SEMG characteristics

During the topical workshop extensive discussions took place on all relevant aspects of sensors and sensor placement procedures with respect to their effects on SEMG signal characteristics. The main conclusions will be described in this section and the resulting recommendations will be described in the last section. A restriction is that this concerns only the bipolar electrode configuration. During the workshop it was concluded that electrode arrays have great potential [7,8], especially in neurology, but it is too early to develop guidelines for them.

4.1. Sensor properties

4.1.1. Electrode shape and size

Although the inventory showed that circular electrodes are by far the most used, the state of the art showed that when considering differences only in shape (i.e. comparing a circular electrode with diameter R with a square electrode size $R{\times}R$), not much difference can be expected. As long as the total surface area for both electrodes is similar the skin impedance and noise will also be similar.

In conclusion there are no clear and objective criteria for recommendations for the electrode shape. It is important that the shape and size of the electrodes are clearly reported.

With respect to the size of SEMG electrodes, it is obvious that on increasing the size, perpendicular to the muscle fibers, the impedance will decrease and it is expected that the view of the electrodes increases, but no quantitative data on the extent of this latter effect could be found. With respect to an increase of the size in the direction of the muscle fibers, it can be shown that this has an integrative effect on the SEMG signal, decreasing the high-frequency content. The effect of an increase of this size on the amplitude of the SEMG signal is not clear.

4.1.2. Electrode material

Electrodes must provide good electrode–skin contact, low electrode–skin impedance, low noise and 'stable' behavior (that is with respect to impedance and chemical reactions at the skin interface). The inventory has shown that Ag/AgCl electrodes are most commonly used. In the many years that these have been applied, it has become clear that they provide a stable transition with relatively low noise and are commercially available.

4.1.3. Inter-electrode distance

The signal detected by an electrode pair is the difference between two monopolar signals and is strongly affected by their delay. Blok and Stegeman [5] carried out an interesting simulation study in which they varied the IED and looked at the effect on the action potential of a motor unit at some distance. They quantified this by using the area under the rectified action potential A. The results clearly predict that different phases can be discerned. Upon an increase of the IED, A will increase from zero to a maximum and then decrease to a plateau at which the action potentials are completely separated. This maximum will occur for an IED at which the negative peak of one monopolar signal coincides with the positive peak in the other monopolar. The simulations indicate that this peak will occur when the IED is about 20 mm (coinciding with about half the duration of the action potentials).

With respect to obtaining a large SEMG signal and consequently a low signal-to-noise ratio, it seems optimal to choose the IED such that it is near this peak. An important condition, however, is that the electrodes will not be above innervation or tendon zones as this will lower A to another plateau value, about half that of the former value [5]. The IED should always be chosen such that the two electrodes do not approach these areas.

The effect of the distance between motor unit and recording electrodes has often been described in terms of the following function:

$$V=\frac{V_0}{(r/r_0)^D} \tag{1}$$

where D and V_0 are constants and r_0 some reference distance from the electrical center of the motor unit, where $V=V_0$. This electrical center locates one equivalent generator of the MUAPS. This equation was found by Buchthal et al. [6] and Gydikov et al. [11], by fitting experimental data obtained with surface electrodes. The exponent D is a function of the IED. In the literature it has often been suggested that a decrease of the IED would limit the view of the surface electrodes and consequently would help to limit crosstalk. This would imply higher values of D upon decreasing IED. In the literature no evidence can be found for this. Hermens [13] collected action potentials using a spike triggered averaging method at two different IEDs of 20 and 40 mm. He calculated values for D but did not find any significant differences. More recently, Roeleveld et al. [25] performed a detailed experimental study investigating the contribution of motor unit potentials to the surface EMG, in bipolar recordings while varying IED from 6 to 84 mm. They used a similar description to Eq. (1) and found for the MUAP area A, a relation between IED and the exponent D, being maximal at around IED=20. The relative contribution of superficial and deep motor units to the recorded SEMG signal was found to be comparable as long as IED<40 mm [25]. Only with a considerable inter-electrode distance (IED>40 mm) are deeper motor-units represented relatively better in the SEMG signal then superficial ones.

This finding also suggests that decreasing IED, at least up to 6 mm, is not a proper technique to limit the view of the electrodes and consequently to decrease crosstalk.

4.1.4. Sensor construction

The sensor construction concerns the (mechanical) way electrodes and cables are integrated. It is expected that the construction (and its mass) does not directly effect the SEMG characteristics. However, one has to take into account that when the construction is such that electrodes and cables can move, there is the potential risk for artifacts due to pulling of cables or inertia of the construction.

Another relevant aspect is that, when the construction is such that the inter-electrode distance can vary during muscle contraction, this will effect the SEMG signal characteristics. An example in which this requires specific attention concerns the use of SEMG in low back muscles during dynamic contractions in the full range of motion and, to a lesser degree, the thigh muscles.

4.2. Sensor placement procedures

4.2.1. Skin preparation

Traditionally, a skin impedance as low as possible was necessary since the recording equipment had only a limited input impedance. Nowadays, the input impedance of SEMG amplifiers is such that the electrode–skin impedance becomes less critical.

Proper skin preparation is necessary to reduce the electrode–skin impedance and to obtain a better fixation of the electrodes. The direct effects of this are: a better SEMG recording, fewer and smaller artifacts (electrical interference), less risk of imbalance between electrode impedances resulting in a smaller common mode disturbance signal and less noise. Good skin preparation consists of: shaving, sandpapering and cleaning of the skin. Electrode gel and paste are also used to reduce the electrode–skin impedance. In practice, the use of separate gel is very cumbersome. Therefore, most researchers use pre-gelled electrodes. When using electrodes on which gel needs to be added, special care should be taken that the gel is not smeared as this will seriously affect the EMG signal by causing a short circuit between the two electrodes. Massage of the skin with conductive gel and removal of the gel may be accepted.

4.2.2. Location and orientation on muscle

Traditionally, surface EMG sensors were placed on top of the muscle belly or over the motor endplate zone since it was the easiest location to record 'large' SEMG signals. Present knowledge, however, clearly indicates that the SEMG pattern near or over the motor endplate zone is not very 'typical' for the muscle: it is not very stable or reproducible since relatively small displacements of the sensor will shift it to a place next to or over the innervation zone. Blok and Stegeman [5] and Merletti (this issue) showed that small shifts of one electrode over the motor endplate zone cause large effects on the amplitude of the SEMG signal. Also, Mathiassen and Hägg [22] showed in their review that the amplitude varies while displacing electrodes in longitudinal direction over the muscle. As a consequence, when studying EMG/force relationships these amplitude variations may lead to wrong estimates. EMG studies on the trapezius, vastus medialis and lateralis muscles show dip-zones and plateau-regions (Rainoldi, this issue). These dip-zones can probably be related to the presence of innervation zones.

Thus, when the approximate location of the innervation zone is known, the SEMG sensor should be placed in a region 'far away' from the innervation zone and the end zone of the muscle, preferably somewhere in the middle of this region. In most cases the distal part of the muscle will best satisfy this requirement, as placement of the sensor in the proximal area may easily cause a shift of one electrode below the endplate zone when the muscle contracts.

With respect to the transversal direction, the vicinity of other active muscles increases the risk of crosstalk. The characteristics of this effect will depend strongly on the characteristics of these nearby active muscles, meaning that proper guidelines can only be given when there is sufficient knowledge on these aspects.

With respect to the orientation of the sensor with respect to the muscle fibers, there is a general consensus that the orientation should always be parallel to the muscle fibers.

4.2.3. Fixation

Poor fixation will (in general) only have an indirect effect on the recorded SEMG in the sense that it can cause all kinds of disturbances: noise, common mode voltages, movement artifacts [3], etc. The real effect of poor fixation on the MUAP and SEMG characteristics has never (quantitatively) been studied but in general it is accepted that proper connections are needed to guarantee proper electrode–skin contact without limiting the range of motion of limbs, body-parts, etc. In general, this can best be realized using an elastic band or tape.

4.2.4. Location of reference electrode

It is generally accepted that reference electrodes need to be placed on electrically inactive tissue, using electrodes which are considerably larger than SEMG electrodes. The location has to be chosen in such a way that the risk for a large common mode disturbance signal will be minimized. The literature scan showed that a number of locations are preferred: the wrist, ankle, tibia, sternum, and the proc. spin. of C7. The particular choice of a location depended largely on the muscle(s) under investigation.

The location of the reference electrode only has an indirect effect on the MUAP and SEMG characteristics in the sense that large common mode disturbance signals (e.g. 50 Hz, line voltage, ECG) will have an influence on the recorded SEMG.

4.3. Other relevant aspects

4.3.1. Subdivision of muscles

There is an increasing amount of evidence that many muscles seem to have functional subdivisions. In their review, Mathiassen and Hägg [22] indicated consequences of functional subdivisions in individual muscles for SEMG recordings. Functional subdivisions can occur at certain levels in a muscle. In most cases subdivision means that the muscle consists of clearly separable heads (i.e. m. biceps brachii). In some cases subdivisions have been indicated at the level of neighboring topographical regions in a muscle (i.e. m. trapezius). In a few cases the subdivision may be found in terms of structurally intermingling motor units with distinguishable biomechanical functions. The concept of functional subdivision implies that the perception of 'a muscle' as one delimited entity gradually dissolves. Different 'muscles' in a synergy might in some cases be more functionally related than distinct subdivisions of the same muscle. This view leads to the idea that surface EMG recordings with biomechanical or ergonomic objectives should aim more at reflecting different motor functions than at representing different muscles according to anatomical textbooks.

4.3.2. Crosstalk

Crosstalk is particularly important in some SEMG applications, such as movement analysis in children with cerebral palsy [4]. In this application muscle activation patterns are studied using SEMG to obtain a good view on the muscle coordination. Based upon the results of such assessment, clinical decisions are made on treatment, often involving orthopaedic surgery. An additional complicating factor is that the risk of having crosstalk from adjacent muscles is rather high due to the small circumference of the limbs of these children.

At the moment, there is no general consensus about the importance, i.e. quantity, of crosstalk; the available literature is contradictory. For example, Merletti [23] presented some results from experiments performed on back muscles. The muscles on one side of the spine were activated selectively in isometrics conditions, using electrical stimulation. Single and double differential-evoked signals were detected on the stimulated muscle and on the contralateral ones. It was observed that the signals detected on the non-stimulated muscle were considerably higher than expected and predicted by theory. This finding can partially be explained by simulations performed, using a model that accounts for the potentials generated by the extinction of the travelling sources at the musculo-tendon junction. It suggests that most of the crosstalk signal is due to these potentials.

5. SENIAM recommendations for sensors and sensor placement procedures

As a result of the inventory and the state of the art SENIAM has developed an initial proposal for recommendations for sensors and sensor placement procedures. This proposal was distributed among all SENIAM partners and SENIAM club members and has been technically and clinically evaluated. Based on the outcome of the evaluation, the recommendations have been completed and published in a booklet [21] and on the SENIAM CD-ROM [10]. The SENIAM recommendations contain recommendations for the SEMG sensors and for a general sensor placement procedure, which has been worked out in detail for 27 muscles.

5.1. SEMG sensors

'Sensor' is defined as the ensemble of electrodes, electrode construction and (if applicable) the integrated preamplifier. For bipolar sensors, recommendations have been developed with respect to: electrode shape and size, inter-electrode distance, electrode material and sensor construction.

5.1.1. Electrode shape and size

'Electrode shape' is defined as the shape of the conductive area of SEMG electrodes. The state of the art indicated no clear and objective criteria for recommendations for electrode shape. SEMG users should indicate clearly the type, manufacture and shape of the electrodes used.

'Electrode size' is defined as the size of the conductive area of a SEMG electrode. It is recommended that the size of the electrodes in the direction of the muscle fibers should not exceed 10 mm.

5.1.2. Inter-electrode distance

'Inter-electrode distance' is defined as the center-to-center distance between the conductive areas of two bipolar electrodes.

It is recommended to apply the bipolar SEMG electrodes at the recommended sensor location with an inter-electrode distance of 20 mm. When bipolar electrodes are being applied on relatively small muscles, the inter-electrode distance should not exceed one-quarter of the muscle fiber length. In this way unstable recordings due to tendon and motor endplate effects can be avoided.

5.1.3. Electrode material

The electrode material which forms the contact layer with the skin needs to realize good electrode–skin contact, low electrode–skin impedance and 'stable' behavior in time (that is with respect to impedance and chemical reactions at the skin interface). It is recommended to use pre-gelled Ag/AgCl electrodes.

5.1.4. Sensor construction

'Sensor construction' is defined as the (mechanical) construction which is used to integrate the electrodes, the cables and (if applicable) the pre-amplifier.

It is recommended to use a construction with fixed inter-electrode distance, built from lightweight material. Cables need to be fixed using (double-sided) tape or elastic bands in such a manner that pulling artifacts can be avoided.

5.2. The sensor placement procedure

A sensor placement procedure for SEMG consists of a number of sequential steps:

1. Selection of the SEMG sensor;
2. Preparation of the skin;
3. Positioning the patient in a starting posture;
4. Determination of the sensor location;
5. Placement and fixation of the sensor;
6. Testing of the connection.

For each of these steps recommendations have been developed. Some recommendations are general recommendations (steps 1 and 2), in the sense that they are always valid, independent of the muscle on which the sensors are placed. Other recommendations (steps 3–6) are based on general starting points, which have been specified in detail for the individual muscles. In this section the general recommendations and the general starting points will be discussed.

5.2.1. Step 1: selection of the SEMG sensor

When choosing a bipolar SEMG sensor, the shape, size, inter-electrode distance, material and construction have to be selected. It is recommended to select sensors according to the recommendations mentioned in the previous section.

5.2.2. Step 2: preparation of the skin

After selection of the sensor, the skin of the patient needs to be prepared to get good electrode–skin contact. Good electrode–skin contact is important for obtaining better SEMG recordings (in terms of amplitude characteristics), fewer and smaller artifacts (electrical interference), less risk of imbalance between electrodes (smaller common mode disturbance signal) and less noise (better S/N ratio).

It is recommended to shave the area if the skin surface at the sensor location is covered with hair and to clean the skin with alcohol and allow the alcohol to vaporize so that the skin will be dry before the sensor is positioned.

5.2.3. Step 3: positioning the patient in a starting posture

After skin preparation, the subject has to be placed in the starting posture which allows the determination of the proper location of the sensor on the muscle. In this starting posture it is possible to determine clearly (via palpation) the muscle and the anatomical landmarks which help to determine the proper sensor location.

The recommendations contain for each individual muscle a description of the starting posture. In general, the description of the starting posture contains a description of the posture of the patient (sitting, lying, prone, etc.) as well as the position and orientation of the body segment at which the sensor will be placed.

5.2.4. Step 4: determination of the sensor location

When the subject has been positioned in the recommended starting posture, the location of the SEMG sensor can be determined and marked. Here, 'sensor location' is defined as the position of the center of two bipolar electrodes on the muscle. Sensors should be placed at a location at which a high-quality and stable SEMG can be obtained. Factors that strongly influence the stability of an SEMG recording are: the presence of motor points and/or muscle tendons and the presence of other active muscles near the SEMG sensor (crosstalk).

In total, 27 recommendations for sensor locations on individual muscles have been developed. The location of the bipolar sensor is always described as a point on a line between two anatomical landmarks. In order to place the sensor properly, first the position of the anatomical landmarks has to be located. Next a line needs to be drawn between the two landmarks. The location of the sensor is then somewhere at a relative position on this line.

The specific recommendations for each muscle have been based on two general starting points:

- with respect to the longitudinal location of the sensor on the muscle it is recommended to place the sensor halfway between the (most) distal motor endplate zone and the distal tendon;
- with respect to the transversal location of the sensor on the muscle it is recommended to place the sensor at the surface away from the 'edge' with other subdivisions or muscles so that the geometrical distance of the muscle to these subdivisions and other muscles is maximized.

5.2.5. Step 5: placement and fixation of the sensor

When the sensor location has been determined and marked, the sensor needs to be placed and fixed at the marked location. This involves a choice of the orientation, the fixation method and the location of the reference electrode.

'Orientation' is defined as the position of the line between the two electrodes with respect to the direction of the muscle fibers.

It is recommended that the bipolar SEMG electrodes are placed at the recommended sensor location with the orientation parallel to the muscle fibers. This is worked out in detail for each individual muscle.

With respect to the fixation of the sensor, it is recommended to use elastic bands or (double-sided) tape/rings and cables in such a way that the electrodes are properly fixed to the skin, movement is not hindered and cables are not pulling the electrodes (construction).

The reference electrode needs to be placed at a location in which the risk for a large common mode disturbance signal is minimal, so preferably on electrically inactive tissue. Depending on the muscle and application, it is recommended to use the wrist, the proc. spin. of C7 or the ankle as the standard location of the reference electrode. The recommendations contain a specific recommendation for each of the 27 muscles.

5.2.6. Step 6: testing of the connection

After placement of the sensor and the reference electrode, a test can be performed to determine whether the electrodes have been placed properly on the muscle and connected to the equipment so that a reliable SEMG signal can be recorded. This has been specified for each individual muscle. The clinical tests are generally accepted muscle tests which guarantee (under normal circumstances) activity of the tested muscle. The clinical test starts from the starting posture and specifies a certain motion and/or pressure against motion. The tests are not 'selective' contractions in which only the desired muscle is active and all other muscles are inactive.

So, for each muscle the recommendations include a description of the muscle anatomy (subdivision, origin, insertion, function), the SEMG sensor, the sensor location and orientation, the starting posture and clinical test [9,21]. Fig. 5 shows an example of the recommendations for the peroneus brevis muscle.

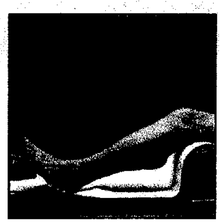
6. Discussion

The main conclusion of the literature scan is that, in general, authors report very poorly on the way the SEMG is being recorded. This relates both to the description of the sensor properties and to the description of the location of the sensors. With respect to the sensor properties, it can be concluded that in at least half of the publications they were not mentioned properly. With respect to the sensor placement procedure, in most cases the muscle and the sensor location were mentioned but in the majority only in very general terms. This makes determination of the exact location and reproduction of the experiment very difficult.

Another conclusion is that the variability of sensor properties is quite large. If we should address the most commonly used sensor configuration, this is a circular Ag/AgCl sensor with a diameter of 10 mm, used in a bipolar configuration with an inter-electrode distance of 20 mm. The skin is shaved, rubbed and cleaned before sensor placement. Gel or another type of contact paste is not used. The sensors are fixed using adhesive tape or elastic bands.

An impressive variability in sensor locations was also found. Unfortunately, from most of these locations some signal may be detected; as a consequence the author receives the impression that the location is good. As mentioned in other papers in this issue, this is usually not the case. In particular, any location near the innervation zone implies large variations of signal intensities when the muscle moves slightly under the skin (this issue); these variations may be interpreted incorrectly as changes in muscle activation.

Altogether, these results confirmed the need for a standardization effort for sensor properties and sensor placement procedures in order to facilitate reproduction of the experiments, which is a basic issue in science. But the results also show that recommendations are necessary on how to report in publications on the methodology used for SEMG investigations. At the moment, only the Jour-



SENIAM

Muscle

Name: Peroneus brevis
Subdivision:

Muscle Anatomy

Origin: Distal 2/3 of lateral surface of fibula and adjacent intermuscular septa.
Insertion: Tuberosity at base of fifth metatarsal bone, lateral side.
Function: Eversion of the foot and assist in plantar flexion of ankle joint.

Click image for larger view

Recommended Sensor Placement Procedure

Starting posture: Sitting with extremity medially rotated.
Electrode size: Maximum size in the direction of muscle fibres: 10 mm.
Inter electrode distance: 20 mm.

Electrode placement

-Location: Electrodes need to be placed anterior to the tendon of the m. peroneus longus at 25% of the line from the tip of the lateral malleolus to the fibula-head.
-Orientation: In the direction of the line from the tip of the lateral malleolus to the fibula-head.
-Fixation on the skin: (Double sided) tape / rings or elastic band.
-Reference electrode: On / around the ankle or the proc. spin. of C7.

Clinical test: Support the leg above the ankle joint. Everse the foot with plantar flexion of the ankle joint while applying pressure against the lateral border and sole of the foot, in the direction of inversion of the foot and dorsiflexion of the ankle joint.

Remarks: It is difficult to access the peroneus brevis muscle from the surface since it is mainly covered by other muscles. Avoid crosstalk / overlap from the extensor digitorum lateralis muscle.

Fig. 5. Example of a sensor placement procedure, as developed within the SENIAM project (peroneus brevis muscle).

nal of Electromyography and Kinesiology provides such guidelines.

Within the SENIAM project a first attempt has been made to develop recommendations on sensor properties and sensor placement procedures, based on a consensus procedure. This has been done in a number of sequential steps, with the continuous involvement of the members of the SENIAM club (over 100 members). Looking back, it is obvious that it has been a very time-consuming process with results that may seem trivial to the SEMG experts. Nevertheless, one should keep in mind that such recommendations are not meant primarily for the research groups that are involved in the basic issues of SEMG modelling, signal processing or physiological investigations.

The recommendations are meant especially for the large group of users of SEMG that are focusing their efforts on 'clinical' questions. This concerns, for example, the rapidly growing areas such as ergonomy, sports, rehabilitation and neurology. In general, they have no profound knowledge of the consequences of the choice of a particular methodology. They want to use it for their purpose and we should be aware that the number of applications in which SEMG is being used in fact determines its relevance.

So far, the recommendations concern only bipolar sensors. Electrode arrays have not been considered, as they still seem largely in the development phase. Yet they offer great promise, both for the identification of innervation zones and in the field of neurology, in which diagnosis by characterization of the recorded action potentials is of great importance [7,8].

We should be aware that standardization efforts are principally lagging behind and will never be completed. The funding by the European Community of the SENIAM project has enabled a first step forward on this avenue. It is foreseen that these recommendations should be updated on a regular basis, based on new emerging knowledge. Such an effort cannot be made by one person or by one research group only. It requires the combined efforts of experts in the field, preferably organized by an international society, such as ISEK or the SENIAM club. We sincerely hope that such coordinated activity will be continued in the near future.

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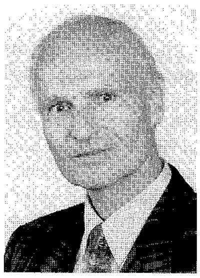

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