Standards for surface electromyography: the European project "Surface EMG for non-invasive assessment of muscles (SENIAM)"

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The SENIAM (surface EMG for non-invasive assessment of muscles) project was organised as a European concerted action, financed in the context of the Biomed 2 program of the European Community (1996 – 1999). The objectives of the project were to integrate basic and applied research on surface EMG (sEMG) at a European level, to establish European co-operation and to solve key items that presently prevent a useful exchange of data and clinical experience. The key topics of this joint effort were: (1) sEMG sensors and sensor placementprocedures, (2) sEMG signal processing and (3) sEMG modelling.

These three topics were handled according to a specific scheme in which first an inventory was made by literature searches or exchanges, from which the state of the art was defined. When necessary, additional evaluation tasks were defined. Sets of recommendations and/or test facilities were the final result for each of these topics.

The paradoxical problem with sEMG is that it is one of the easiest electrophysiological signals to measure, but also one of the hardest to interpret quantitatively. With an oscilloscope and two metal objects connected to the oscilloscope's input one will often display sEMG without notice. "To its detriment, electromyography is too easy to use and consequently too easy to abuse" (DeLuca, 1997).

The SENIAM project brought together the expertise of 16 European groups working on developments and applications of sEMG. The initiative came from and the project co-ordination was done by Roessingh Research and Development (Hermie Hermens and Bart Freriks, Enschede, NL). The project management group further consisted of Roberto Merletti (Torino, IT), Cathy Disselhorst-Klug and Günther Rau (Aachen, D), Goran Hägg (Solna, S) and Dick Stegeman (Nijmegen, NL).

The project has resulted in: (1) recommendations for electrode design and placement procedures, (2) recommendations for recording and processing of sEMG signals, (3) a set of 4 computer models for better insight in sEMG generation, (4) a set of reference signals, (5) eight books with various contributions of the participants of the project, (6) the SENIAM CD-ROM, and (7) the SENIAM club, a European network on sEMG with over 100 members.

The last book (SENIAM 8, ISBN 90-754562-15-2) and the CD-ROM (ISBN 90-754552-14-4) contain the European SENIAM recommendations for sEMG especially in kinesiological applications and are easily available.

In the following sections, important recommendations with respect to (only) bipolar sensor design , placement and signal conditioning principles are given. The recommendations are partly based on sEMG model simulation results. The modelling task is not treated separately in this contribution. Details can be found in the SENIAM deliverables listed at the end of this contribution.

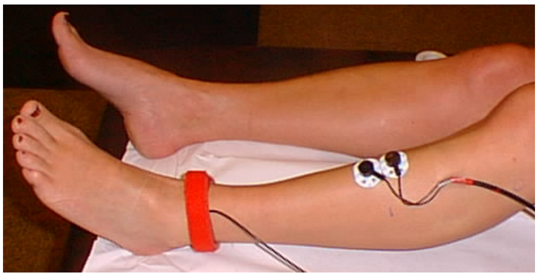
Spatial sensor characteristics and sensor placement procedures

The term sensor, instead of electrode, is used to stress the fact that each sEMG measurement needs an ensemble of (at least 2) single electrodes, often housed together, whereby the preamplifier might be integrated in the housing. In most practical situations, a bipolar electrode montage is used which means that a single sEMG signal is recorded as the electric potential difference between two electrodes over the muscle which are relatively closely spaced in comparison to the muscle's dimensions. A bipolar sEMG recording is influenced by the electrode shapes, sizes, positions, orientations and the inter electrode distance (IED).

Electrode shape: To begin with a "weak" recommendation: with respect to electrode shape no clear and well defendable standard was recommended by SENIAM, apart from what is said below on electrode size in different directions with respect to the muscle fibres. No major influence on the sEMG signal is expected from taking different shapes (e.g. square vs. circular). Users should however clearly indicate the shape of the electrodes used.

Electrode size: In current sEMG practice, electrode size varies between 1 mm^2 until a few cm^2. Different from the electrode shape, the electrode size clearly influences sEMG signals. It should be realised that the potential recorded by a finite size electrode can be conceived of as the average over the electrode surface of the potential actually present under that electrode surface. Upon an increase of the size perpendicular to the muscle fibres (e.g. in case of a rectangular bar electrode transversally over the muscle), the view of the electrodes increases. No absolute quantitative data on this effect per muscle have been studied. Upon an increase of the size in the direction of the muscle fibres, it can be shown theoretically and experimentally that this mainly has a low pass filtering effect on the sEMG signal. It is recommended that the size of the electrodes in the direction of the muscle fibres should not exceed 10 mm. The European inventory showed that circular electrodes with a diameter of 10 mm are preferred.

Figure 1: Example of SENIAM recommendation.
Placement of bipolar electrodes and reference electrode for the tibial anterior muscle
(from: SENIAM 8)



Sensor position: In SENIAM 8 and 9, recommendations for the location of sensors for a number of often studied muscles are given (e.g. Figure 1). They are derived from the following principle: with respect to the longitudinal (in fibre direction) location of the sensor on the muscle, it is recommended to place the sensor halfway 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 locate the sensor at the surface away from the 'edge' with other subdivisions or other muscles so that the geometrical distance to other muscles is maximised.

Sensor orientation and IED: It is advisedto place the bipolar sEMG electrodes around the optimal sensor location directed parallel to the muscle fibres. The recommendations for sensor locations for individual muscles in SENIAM 8 also give an advise for the orientation of the bipolar sEMG electrodes for each individual muscle. It is preferred to apply bipolar sEMG sensors with an IED of 20 mm, because a maximal sEMG amplitude is expected with this IED. This recommendation is, among others, based on model simulation studies. If bipolar electrodes are applied on relatively small muscles, IED should not exceed 1/4 of the muscle fibre length. In this way unstable recordings, due to tendon and motor endplate effects can be avoided.

Concluding remark: The above recommendations for electrode size, sensor orientation and IED are derived from considerations on sEMG signal amplitude and the representativeness of the signal for a muscle as a whole. In case of other aims, like an increased selectivity of the sensor for superficial motor units, other IED (e.g. 3-5 mm) and electrode size values may be optimal.

Electrode material and sensor construction

The electrode material, which forms the contact layer with the skin, needs to realise a good electrode skin contact, a low electrode-skin impedance and a ‘stationary’ behaviour in time (that is with respect to impedance and chemical reactions at the skin interface). In case of sEMG , the electrode material is less critical than in case of brain electric signals (EEG) where lower signal frequencies (around or below 1 Hz, see next section) must be detected. An inventory has shown that different types of material are used, mostly Ag/AgCl, AgCl, Ag, Au, of which the Ag/AgCl electrodes are most common. They provide a stable transition with low noise and are easily available commercially. Electrodes are mostly combined with electrode gel. Both pre-gelled and non-gelled electrodes are commercially available. Electrode gel and paste are used to reduce the electrode-skin impedance. A low impedance gives stable recordings and low electrode noise levels. Since use of non-gelled electrodes is cumbersome and time consuming, pre-gelled electrodes are recommended, although the performance of pre-gelled and non-gelled electrodes is similar. It is not expected that the sensor construction (and its mass) do directly effect sEMG characteristics. There are nevertheless two important indirect effects which can disturb or interfere with the recorded sEMG pattern. First, if the construction of the sensor is such that IED can vary during muscle contraction, this will artificially modulate the amplitude, shape and width of the action potentials and will consequently affect both sEMG amplitude and frequency characteristics. Second, if the construction of the sensor is such that electrodes and cables can move due to pulling of cables or inertia of the construction, there is the potential risk for movement artefacts, because of destabilisation of the electric layer and changes of impedances and magnetically induced currents in the cables. It is therefore recommended that a sensor construction with fixed inter electrode distance is used, made of light weight material. Cables need to be fixed using (double sided) tape or elastic band in such a manner that pulling artefacts can be avoided. If in fast dynamic contractions the sensor causes too much (movement) artefacts (due to the inertia of the construction), it is recommended to fix the inter electrode distance using (double sided) tape or rings.

SEMG signal conditioning and processing

In Figure 2 the basic principles of sEMG signal conditioning and digital computer acquisition are depicted. At the ‘low frequency’ side of the signal spectrum the choice for a high pass filter is mostly determined by the need to remove slow variations in the signal caused by the movement artefacts mentioned. It is obvious that the situation in case of a dynamic movement studies is much more vulnerable to these disturbances. In most cases a high pass filter between 10 and 20 Hz will preserve the important frequencies in the sEMG. However, in the 5-20 Hz frequency range, the sEMG spectrum contains information concerning the firing rates of the active motor units, but in many cases (e.g. in movement analysis) this information may not be of great interest. Note that sudden signal changes due to movements may not be completely attenuated by a 10 – 20 Hz filter.

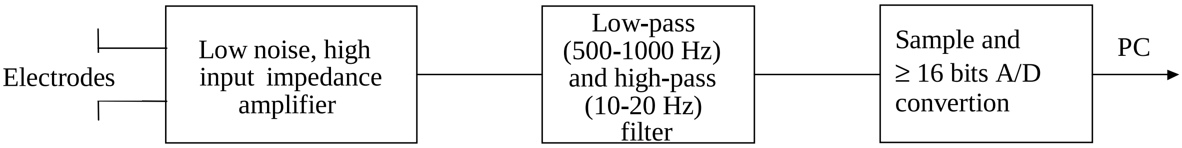


Figure 2: schematic outline of an sEMG recording system

With the exception of a few cases, about 95% of sEMG power is accounted for by harmonics up to 400 Hz and most of the remaining percents by electrode and equipment noise. A low pass filter has to be applied to the signal to further attenuate these unwanted components. The cut-off frequency is usually chosen near to 500 Hz and the sampling frequency must then be 1000 samples/second or higher (sampling theorem: sampling must be >2 times the highest frequency in the signal). The digitisation requirement for the sEMG signal is dependent on the smallest and the highest amplitudes expected. The delectability of low amplitude details of the sEMG signal is limited by the noise level of the amplifier system. Modern amplifiers have a noise level of a few μVs. Therefore, a digitisation of about 0.5 μV/bit is sufficiently accurate. A 16 bit A/D convertor has $2^{16}-1 = 65535$ levels, meaning that without gain adaptations the range of measurements with such a convertor is ± 16 mV, which is enough for almost any sEMG application.

SEMG signal analysis

In the context of this contribution it is not possible to go into details with respect to signal processing after the sEMG has been captured in digital form. The possibilities are virtually unlimited. Most often used are amplitude estimation (RMS, mean after rectification), spectral analysis (after Fourier transformation) and the measurement of muscle fibre velocities. An important distinction again has to be made between dynamic and non-dynamic muscle contractions. Different classes of signal processing tools have to be selected because many well known tools are based on the assumption of stationarity, which means that the signal characteristics are assumed constant over time. For dynamic conditions such requirement is per definition not met. Especially in case of the much applied spectral analysis of the sEMG signal, the stationarity condition has to be evaluated.

Conclusion

The above gives a summary of the SENIAM concerted action within the limited space of this contribution. The reader should feel free to contact the authors for further information or to acquire a selection of the SENIAM deliverables (www.rrd.nl; h.hermens@rrd.nl). We are convinced that the goal of reaching full maturity of sEMG as a scientifically founded set of experimental methods in the study of human movement came closer by the SENIAM initiative.

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