A method for positioning electrodes during surface EMG recordings in lower limb muscles

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Abstract

Purpose: The aim of this work is to provide information about the degree of inter-subject uniformity of location of innervation zone (IZ) in 13 superficial muscles of the lower limb. The availability of such information will allow researchers to standardize and optimize their electrode positioning procedure and to obtain accurate and repeatable estimates of surface electromyography (sEMG) signal amplitude, spectral variables and muscle fiber conduction velocity.

Methods: Surface EMG signals from gluteus maximus, gluteus medius, tensor fasciae latae, biceps femoris, semitendinosus, vastus medialis obliquus, vastus lateralis, rectus femoris, tibialis anterior, peroneus longus, soleus, gastrocnemius medialis and lateralis muscles of ten healthy male subjects aged between 25 and 34 years (average \(\text{age} = 29.2\) years, S.D. = 2.5 years) were recorded to assess individual IZ location and signal quality.

Results: Tensor fasciae latae, biceps femoris, semitendinosus, vastus lateralis, gastrocnemius medialis and lateralis showed a high level of both signal quality and IZ location uniformity. In contrast, rectus femoris, gluteus medius and peroneus longus were found to show poor results for both indexes. Gluteus maximus, vastus medialis obliquus and tibialis anterior were found to show high signal quality but low IZ location uniformity. Finally, soleus muscle was found to show low signal quality but high IZ location uniformity.

Conclusions: This study identifies optimal electrode sites for muscles in the lower extremity by providing a standard landmarking technique for the localization of the IZ of each muscle so that surface EMG electrodes can be properly positioned between the IZ and a tendon.

Keywords: Electromyography; Electrode positioning; Lower limb muscles; Innervation zone; EMG variables; Standardization

1. Introduction

Surface electromyography (sEMG) has been used in both research and clinical applications for non-invasive neuromuscular assessment in several different fields such as sport science, neurophysiology and rehabilitation. Different variables, related to different aims, can be monitored: muscle activation intervals are useful to evaluate motor coordination and treatment efficacy (Benedetti, 2001; Mayer et al., 1997; Sutherland, 2001); myoelectrical manifestations of fatigue (De Luca, 1984, 1993b; Merletti et al., 1990) can be used to assess EMG signal modifications in pathologies such as back pain (De Luca, 1993a; Hodges and Richardson, 1997; Mannion et al., 1998; Roy et al., 1997), whiplash (Falla et al., 2002), neurological diseases (Zwarts et al., 2000) and in other neuromuscular alteration due to age (Merletti et al., 2002), exercise (Casale et al., 2003; Gerdlle et al., 1991; Hopf et al., 1974; Sadoyama et al., 1988) and disease (Berg et al., 1997; Edgerton and Roy, 1994).

In these situations, variable estimates, statistical results and conclusions are strongly dependent on different factors; proper and standardized electrode positioning plays, among others, a pivotal role. With the use of multichannel electrode arrays, a number of investigations have shown how EMG variable estimations vary along the muscle length (i.e. with respect to electrode positioning) (Masuda et al., 1985b; Merletti et al., 1999, 2001b; Roy et al., 1986) and disease (Rainoldi et al., 2002; Sadoyama et al., 1988). Research cited above has demonstrated that positioning sEMG electrodes over the region surrounding the neuromuscular junctions or over tendon terminations as well as movement of muscle underneath sEMG electrodes can substantially alter sEMG
variable estimates. These studies clearly show that accurate estimation of sEMG signal amplitude, spectral variables and muscle fiber conduction velocity are subject to electrode location and that failure to adhere to optimal electrode placement can provide misleading results.

Fig. 1 shows an example of EMG signal recorded with the linear electrode array technique. The picture highlights the recorded signal pattern as a consequence of the single differential acquisition mode. Due to the movement of the depolarized zones in opposite direction and to the subtraction between each couple of electrodes, the amplitude signal over the innervation zone (IZ, which is the location where nerve terminations and muscle fibers are connected) will be minimum (A) and the distal and proximal signals with respect to the IZ will appear with phase reversal (B1 and B2).

An example of EMG variable estimate variations along the muscle length is depicted in Fig. 2 for the vastus medialis muscle. Average rectified value (ARV) and mean frequency
(MNF) of the signal spectrum are estimated from each single differential signal of a linear electrode array, whereas correlation coefficient (CC) and muscle fiber conduction velocity (CV) are estimated from a pair of double differential (DD) signals as described in Merletti et al. (1990) and Rainoldi et al. (2000).

When the electrodes are placed over the IZ, an error in the variable estimates will occur because of the potentials travelling in opposite directions. Hence ARV and CC will be lower, while MNF and CV will be higher than in nearby locations (filled rectangles). The same effect is observed if the electrodes are placed over the tendon regions (empty rectangles), due to the action potential extinction. As a consequence the best locations for electrode positioning are the areas between IZ and tendon terminations where the EMG variable estimates are less affected by signal generation and termination effects and by small electrode displacements.

One centimeter electrode displacement in two subsequent measurements can generate variations of 200% in amplitude estimates (see Fig. 2, channel 6 versus channel 5) not related to physiological modifications.

The size of sEMG electrode positioning relative to IZ is rarely addressed in published research using sEMG. In a review of 144 papers on sEMG, Hermens et al. (2000) identified 352 descriptions of electrode location—most being generic terms such as “muscle belly”, “motor point” or “midpoint of the muscle”. To avoid biased results, contradictory findings and to increase the repeatability and comparison of measures among different laboratories it is necessary to standardize the electrode positioning procedure. Knowledge of IZ location is needed to position electrodes properly. The aim of this work is to provide information about the degree of IZ location uniformity in 13 superficial muscles of the lower limb in a sample of 10 healthy subjects.

2. Methods

Ten healthy male subjects with age between 25 and 34 years (average = 29.2 years, S.D. = 2.5 years) participated in this study after giving written informed consent. The subjects’ skin was prepared by gentle local abrasion using abrasive paste and cleaned with water prior to attachment of the surface electrodes, in accordance with the SENIAM recommendations for skin preparation (Hermens et al., 2000).

Myoelectric signals were detected from each muscle using a linear array of 8 or 16 electrodes (silver bars 10 mm apart, 5 mm long, 1 mm diameter) in single differential configuration (Merletti et al., 1999). The electrodes incorporated a front-end amplifier (unity gain voltage follower) with high input impedance (>100 MΩ) and a low output impedance (<100 Ω). Myoelectric signals were passed through a 10–450 Hz bandwidth filter (40-dB per decade roll-off on each side), amplified (gain = 2000), and sampled at 2048 Hz (ASE16-16 channel amplifier, LISIn Centro di Bioingegneria, Politecnico di Torino, Italy). Spectral analysis indicated that no significant power was present at frequencies above 400 Hz. The samples were digitized by a 12 bit A/D converter and stored on a personal computer. Double differential signals were computed off-line for conduction velocity (CV) estimation to check the proper electrode position with respect to the fiber direction.

Initial positioning and orientation of the electrodes was preceded by palpation of each muscle during manually resisted contractions, to outline its length and belly, according to information available from anatomical atlas (Kendall et al., 1993; Netter, 1989). Electrodes were located along the length of the muscle with the bars of the electrode array perpendicular to the direction of the muscle fibres. This muscle fiber orientation assessment procedure includes: (a) to place the electrodes following anatomical information obtained from atlas, (b) to check the uniformity of subcutaneous tissue thickness with ultrasound device to determine muscle fiber direction in the median plane and (c) to gently vary the array orientation until the signal appears of the same amplitude distally and proximally with respect to the IZ (for a detailed description of the procedure and of the theoretical explanation, please refer to the work of Merletti et al. (2001b)).

The following muscles were investigated: gluteus maximus, gluteus medius, tensor faciae latae, biceps femoris, semitendinosus, vastus medialis obliquus, vastus lateralis, rectus femoris, tibialis anterior, peroneus longus, soleus, gastrocnemius medialis and lateralis.

Since no isometric braces were available to hold the limbs for each muscle, the isometric contractions were obtained against manual resistance. The assessment of the proper subject positions to obtain the most selective contraction of the muscle of interest were obtained following the guidelines of Kendall et al. (1993).

For each of the 13 muscles studied, the following experimental protocol was adopted.

1. Evaluation of the EMG signals recorded during a mild and a maximal isometric contraction of five second duration in the selected direction.
2. Assessment of the IZ location corresponding to the single differential signal trace with minimum amplitude and/or phase reversal (Merletti et al., 1999). If the IZ is narrow and centered between two electrodes a signal trace with minimal amplitude will be evident (Fig. 1, A and Fig. 3a, A). If the IZ is directly underneath one electrode contact, phase reversal will be apparent in the two differential traces obtained from the two pairs sharing that electrode (Fig. 3b, E).
3. Localization of the electrode pair corresponding to the IZ on the subject’s skin.
4. Measurement of the position of each muscle’s IZ with respect to a reference line based on anatomical landmarks.
5. Assessment of EMG variable estimates (CV, MNF, ARV and CC), as evidence of the quality of the signals recorded (Merletti et al., 2001b).

Fig. 3. An example of sEMG signal traces recorded with a linear electrode array (inter-electrode distance equal to 10 mm, 0.2 mV/div Y axis, 12.5 ms/div X axis) from two muscles with different signal quality. (a) A sample of signal recorded from the biceps femoris muscle (excellent signal quality) is depicted. It is possible to recognize: the IZ (A) located under channel 8 corresponding to the signal trace with minimum amplitude between two channels (7 and 9) with phase reversal; the tendon termination (B) that can be recognized as the signal trace where the action potentials are extinguished (channels 3–2–1). The action potentials in channel 7, in fact, propagate toward the tendon and were detected by channel 6, 5, 4 and so on until they stop (and their amplitude decreases) under channel 1. Two different single motor unit potentials are highlighted and indicated with C and D. (b) A sample of signal recorded from the gluteus medius (fair signal quality) is depicted. As defined in the text, it is possible to still recognize the IZ (E) between channels 6 and 7, but the action potentials (highlighted in F) appears to reach tendon terminations with a non physiological CV (higher than 6 m/s).

Spectral and amplitude variables as well as CV were computed with numerical algorithms (Merletti et al., 1990) using signal epochs of 0.5 s thereby generating 10 estimates of each variable during each 5 s contraction. Conduction velocity was computed as \(\frac{e}{d}\) where \(e\) is the inter-electrode distance (10 mm) and \(d\) is the delay time between the two double differential signals. As previously published (Merletti et al., 1990), the delay \(d\) was obtained by identifying the time shift required to minimise the mean square error between the Fourier transforms of the two DD signals.

The correlation coefficient between two double differential signals used for CV estimation is adopted as indicator of signal similarity, suggesting monodirectional propagation of the MUAPs considered not trustable if the delay \(d\) is obtained from signals not similar enough (CC lower than 0.6).

The IZ position uniformity between different subjects was estimated for each muscle on the basis of the spread of the ten absolute locations. The semi-range (SR, mm) of these values, defined as \((\text{max. value} - \text{min. value})/2\), was selected as uniformity estimator. With this definition it is possible to eliminate the biasing effect that the arbitrary selected landmarks (i.e. different reference line lengths) introduce in other estimators (such as coefficient of variation) that require normalization with respect to the reference line length.

We defined excellent uniformity for \(\text{SR} \leq 10\) mm, good for \(10 < \text{SR} \leq 20\) mm, fair for \(20 < \text{SR} \leq 25\) mm and poor for \(\text{SR} > 25\) mm.

Fig. 4. Anatomical information about proper electrode positioning and examples of signals recorded are shown for the vastus lateralis and vastus medialis oblongus muscles. (A) The innervation zone was found at a distance of 94.0 ± 13.2 mm (mean ± S.D., \(N = 10\) subjects) along the line from the superior lateral side of the patella to the anterior superior iliac spine, starting from the patella. Excellent EMG signal quality. A linear array of 16 channels with 10 mm of inter-electrode distance was used. The top channel is proximal. Scale: 0.5 mV/div Y axis, 6.25 ms/div X axis. The IZ is located under channel 8. (B) The innervation zone was found at a distance of 51.7 ± 13.6 mm (mean ± S.D., \(N = 10\) subjects) from the superior medial side of the patella along a line inclined of 50° with respect to the anterior superior iliac spine. Excellent EMG signal quality. A linear array of 16 channels with 10 mm of inter-electrode distance was used. The top channel is proximal. 1 mV/div Y axis, 6.25 ms/div X axis. The IZ is located under the channel 7.
3. Results

Fig. 4 shows the results for vastus lateralis and medialis muscles, providing an example of the information obtained. For each muscle quality of signals was assessed and the position of the IZ was determined as an absolute distance (mm) with respect to anatomical landmarks (in the case of tensor faciae latae, vastus lateralis, vastus medialis obliquus) or as a percentage of a distance along a fixed line (in all other muscles). Signals recorded from each muscle were classified with respect to four different quality levels defined as follows.

• **Excellent**: The direction of the muscle fiber may be palpated and the array may be placed correctly and fastly; it is possible to identify the IZ, recognize the action potential propagation throughout the fiber length, estimate muscle CV within the physiological range (3–6 m/s) with high CC (>80%).

• **Good**: It is possible to identify the IZ, recognize the action potential propagation through out the fiber length, estimate muscle CV within the physiological range with high CC (>80%), however the correct positioning of the electrode array over the muscle requires a time consuming procedure (e.g. it is difficult to identify muscle fiber direction; it is difficult to isolate the muscle of interest when it is small and/or surrounded by others).

• **Fair**: It is possible to identify the IZ but not to recognize the action potential propagation throughout the fiber length, CV estimates are equal or greater to 6 m/s with high CC (>80%) and it is possible to place the electrode array over the muscle with an easy and fast procedure.

• **Poor**: It is possible to identify the IZ but not to recognize the action potential propagation throughout the fiber length, CV estimates are equal to or greater than 6 m/s with CC values lower that 60% and positioning of the electrode array over the muscle is difficult and requires a time consuming procedure.

In Table 1, reference lines, anatomical landmarks, and statistical results (mean ± S.D.) about IZ locations between subjects, are reported for the studied muscles.

In Table 2, absolute values of SR for each muscle are reported. IZ uniformity and signal quality are classified as above in the text. IZ location uniformity between subjects was found to be good in 6 muscles out of 13. Signal quality was found to be excellent or good in 9 muscles out of 13.

The values provided in Table 1 should be considered in relation to the muscle length and not only in relation to anatomical landmarks that may be far from the muscle. The last column of Table 2 provides a merging of the two classifications above and takes into consideration the muscle length.

Table 1: Reference lines, anatomical landmarks, and statistical results about IZ locations between subjects, are reported for the studied muscles in 10 subjects.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Anatomical landmarks and reference line</th>
<th>IZ position along the reference line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biceps femoris</td>
<td>The percentage distance from the ischial tuberosity to the lateral side of the popliteus cavity, starting from the ischial tuberosity</td>
<td>35.3 ± 6.8 (%)</td>
</tr>
<tr>
<td>Semitendinosus</td>
<td>The percentage distance from the ischial tuberosity to the to the medial side of the popliteus cavity, starting from the ischial tuberosity</td>
<td>36.3 ± 4.0 (%)</td>
</tr>
<tr>
<td>Vastus lateralis</td>
<td>The distance (mm) along a line from the superior lateral side of the patella to the anterior superior iliac spine, starting from the patella</td>
<td>94.0 ± 13.2 (mm)</td>
</tr>
<tr>
<td>Tensor faciae latae</td>
<td>The distance (mm) from the anterior superior iliac spine, along a line oriented of 30° with respect to the line joining the anterior superior iliac spine and the greater trochanter</td>
<td>75.6 ± 14.7 (mm)</td>
</tr>
<tr>
<td>Gastrocnemius medialis</td>
<td>The percentage distance from the medial side of the popliteus cavity to the medial side of the Achilles tendon insertion, starting from the Achilles tendon</td>
<td>50.5 ± 5.7 (%)</td>
</tr>
<tr>
<td>Gastrocnemius lateralis</td>
<td>The percentage distance from the lateral side of the popliteus cavity to the lateral side of the Achilles tendon insertion, starting from the Achilles tendon</td>
<td>61.2 ± 5.1 (%)</td>
</tr>
<tr>
<td>Gluteus maximus</td>
<td>The percentage distance from the second sacral vertebra to the greater trochanter, starting from the second sacral vertebra</td>
<td>33.8 ± 11.0 (%)</td>
</tr>
<tr>
<td>Vastus medialis obliquus</td>
<td>The distance (mm) from the superior medial side of the patella along a line medially oriented at an angle of 50° with respect to the anterior superior iliac spine</td>
<td>53.7 ± 13.0 (mm)</td>
</tr>
<tr>
<td>Tibialis anterior</td>
<td>The percentage distance from the tuberosity of tibia to the inter-malleoli line, starting from the tuberosity of tibia</td>
<td>15.5 ± 4.2 (%)</td>
</tr>
<tr>
<td>Soleus</td>
<td>The percentage distance from the tuberosity of tibia to the medial side of the Achilles tendon insertion, starting from the Achilles tendon</td>
<td>76.3 ± 3.7 (%)</td>
</tr>
<tr>
<td>Gluteus medius</td>
<td>The percentage distance from the iliac crest to the greater trochanter, starting from the greater trochanter</td>
<td>33.4 ± 12.8 (%)</td>
</tr>
<tr>
<td>Peroneus longus</td>
<td>The percentage distance from the head of fibula to the lateral malleolus, starting from the head of fibula</td>
<td>17 ± 4 (%)</td>
</tr>
</tbody>
</table>

Information about rectus femoris muscle are not in the list since it was shown not to reach the minimum criteria of acceptability described in the text.
Table 2

<table>
<thead>
<tr>
<th>Muscle</th>
<th>(Max − min)/2 (mm)</th>
<th>IZ uniformity</th>
<th>Signal quality</th>
<th>Global muscle classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biceps femoris</td>
<td>25</td>
<td>Fair</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Semimembranosus</td>
<td>15</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Vastus lateralis</td>
<td>20</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Tensor fasciae latae</td>
<td>20</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Gastrocnemius medialis</td>
<td>25</td>
<td>Fair</td>
<td>Good</td>
<td>Fair</td>
</tr>
<tr>
<td>Gastrocnemius lateralis</td>
<td>25</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Gluteus maximus</td>
<td>25</td>
<td>Fair</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Vastus medialis obliquus</td>
<td>20</td>
<td>Good</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Tibialis anterior</td>
<td>20</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Soleus</td>
<td>25</td>
<td>Fair</td>
<td>Fair</td>
<td>Poor</td>
</tr>
<tr>
<td>Gluteus medius</td>
<td>30</td>
<td>Fair</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Peroneus longus</td>
<td>20</td>
<td>Good</td>
<td>Poor</td>
<td>Fair</td>
</tr>
</tbody>
</table>

IZ uniformity and signal quality are classified as described in the text. The last column reports a final muscle classification qualitatively based on the IZ uniformity and signal quality ranks weighted by the muscle length (see the text for further explanations).

Gastrocnemius medialis and peroneus longus muscles were classified as fair, while soleus and gluteus medius muscles were classified as poor. Hence, on these four muscles, the IZ location is different in different subjects and it is necessary to determine it for each subject before placing the electrodes. Rectus femoris muscle was shown not to reach the minimum criteria of acceptability described in the text and it was not included in the both Tables 1 and 2.

Location of the IZ must be performed using an electrode array and a multichannel amplifier. Using an electrical stimulator to identify motor point as surrogates of the IZ is not an appropriate procedure.

4. Discussion

In this work the IZs of 13 muscles of the lower limb were studied, demonstrating that their location is not the same among healthy male subjects. The findings show that in 8 muscles out of 13 studied it is possible to provide suggestions based on bony landmarks for a standard EMG electrode placement between the IZ and distal/proximal muscle tendons (as described in Fig. 2). For the other five muscles, it is necessary to determine the IZ location for each subject before placing the electrodes. In particular the location of the IZ was not easily recognized for the rectus femoris muscle across all subjects; hence no statistics are available, confirming the difficulty to properly estimate EMG variables from such a muscle.

In case of dynamic contractions, the muscle shifts with respect to the skin and the recording electrodes. As a consequence the IZ can move by a 1–2 cm depending on muscle type and joint angle variation (Farina et al., 2001). This issue has been studied in several works (Masuda et al., 1985a,b; Zuniga et al., 1970) that have shown how such geometrical artifacts determine alterations of the EMG amplitude variables not related to real modification of the muscle activity. Also in the case of gait analysis, although joint angle variations are particularly small, such a bias further affects amplitude and timing estimations (Merletti et al., 2001a). It is possible to avoid this alteration in EMG signal interpretation by placing the electrode in the position less affected by these geometrical artifacts, as described by Rainoldi et al. (2000) and Farina et al. (2001).

The results have shown that while optimum electrode placement requires finding the IZ for each subject, for some muscles, electrodes can be placed, according to landmarks, between the IZ and the tendon termination without first finding IZ.

For these reasons the length of the muscle (i.e. the space available for proper electrode location) becomes a pivotal issue. We decided to classify the muscles merging the information about IZ uniformity and signal quality weighted by muscle length. As shown in Table 2, for instance, the fair IZ uniformity for the biceps femoris is less critical than the same classification of the gluteus medius since the former is longer and more space will be between the IZ and tendon terminations.

Findings from this investigation provide information allowing the final users (mainly those who use commercial adhesive electrode in bipolar configuration) to properly place the electrodes on the subject’s skin in order to avoid biased sEMG variable estimates and contradictory results.

Acknowledgements

Authors wish to thank Professor Roberto Merletti (Polytechnic of Turin, Italy), for the many useful discussions and his criticism in preparing the final version of this work, and Dr. Deborah Falla (University of Queensland, Brisbane, Australia) for the first revision of the manuscript. We wish to thank also Don Gnocchi Foundation—Onlus, Roma, Italy, for providing facilities and equipment. This study was supported by Tor Vergata University, Roma, Italy, by the Regional Health Administration Project “Ricerca Finalizzata”, Torino, Italy and by CRT Foundation and Compagnia di S. Paolo di Torino, Italy.
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