Identification of muscle fasciculations from surface EMG: Comparison with ultrasound-based detection

Identification of muscle fasciculations from surface EMG: comparison with ultrasound-based detection*

Alberto Botter, Marco Carbonaro, Taian M. Vieira, Emma Hodson-Tole

***Abstract*—The clinical standard for the identification of muscle fasciculations is needle electromyography. However, both surface electromyograms (sEMG) and ultrasound imaging (US) have been recently proposed as alternative and more sensitive approaches. The aims of this study were to: (i) compare the sensitivity to muscle fasciculations of sEMG and US, (ii) assess the rate of agreement (RoA) between the two approaches, and (iii) investigate how much sensitivity and RoA are affected by the selectivity of sEMG detection. Surface EMGs were collected concurrently with US images using an array of 32 electrodes spanning the whole, posterior aspect of the leg. Muscle fasciculations were identified from US videos and from monopolar and single differential sEMGs computed between electrodes spaced by 1, 2, and 3 cm. Results from five healthy subjects showed that US detected as many fasciculations as single differential EMGs, but always less than monopolar sEMGs. However, monopolar sEMGs exhibited a very poor spatial selectivity, likely responsible for the small RoA with US measures. The RoA was maximal for single differential recordings with 3cm inter-electrode distance, however, it was always smaller than 75% (median=30%). Although preliminary, these results suggest that sEMG and US are sensitive to different events in the muscle volume and that their integration may increase the detection sensitivity to muscle fasciculations.**

I. Introduction

Muscle fasciculations, resulting from the spontaneous activation of motor neurons, are common in several motor neuron diseases, such as Amyotrophic Lateral Sclerosis (ALS) [1]. The clinical standard for the identification of muscle fasciculations is needle EMG. Although this technique is routinely used in clinical setting, its sensitivity to fasciculation potentials is relatively small. This characteristic has been associated with the small detection volume of needle electrodes, which limits the capability to detect sporadic and localized muscle activations, such as fasciculations [2].

In recent years, alternative approaches based on ultrasonography (US) and high-density sEMG have been shown to increase the sensitivity to muscle fasciculations. In both cases the improvement with respect to needle EMG was associated with the larger muscle portion these techniques are able to sample [3]–[6]. It is worthy to note, however, that the shapes of the detection volumes of US and sEMG are remarkably different. US images are equally sensitive to surface and deep sources generating muscle movements in a plane perpendicular to that of the transducer. Instead, sEMG detection is biased toward electrical events occurring in a superficial muscle volume, whose dimension depends on the skin surface covered by the electrodes as well as on their arrangement and detection configuration (i.e. spatial filtering) [7]. This suggests that sEMG and US may be sensitive to different events and that their combination could further improve the capability to identify and classify muscle fasciculations.

In this study we aimed at exploring this possibility. To this end, muscle fasciculations were detected simultaneously by sEMG and US to: (i) compare the sensitivity of the two approaches, (ii) investigate the number of common events identified by the two techniques, and (iii) quantify the effect of the sEMG detection configuration on the sensitivity of sEMG detection and on its agreement with US-based identifications.

II. Methods

A. Subjects

Five participants (age range: 27–40 years; height 168-187 cm; body mass: 65-80 kg), with no history of neurological or musculoskeletal impairment or disease were recruited. The study was performed following the principles outlined in the Helsinki Declaration of 1975, as revised in 2000. Informed consent was obtained from all participants after providing detailed explanation of the study procedures.

B. Protocol

1) Experimental procedure

Participants laid prone comfortably on a padded bed with the knee fully extended and the ankle in neutral position. The subject was asked to relax and to keep the same position during the entire experiment. Data collection was performed while the subject was resting. Thirty seconds of sEMG and US images were detected in four trials from four muscle regions distributed along the proximo-distal axis of the leg (Fig. 1).

2) sEMG recordings

Surface EMG signals were detected from the medial gastrocnemius and the distal part of soleus using a linear array of 32 electrodes (LISiN, Politecnico di Torino, Torino, Italy) with 10 mm inter-electrode distance (IED). The array of electrodes was aligned with the proximal-distal axis of the leg, 2cm medially with respect to the junction between the two gastrocnemius heads. Care was taken to ensure the position of

* Research supported by the bank foundation "Compagnia di San Paolo" (Convenzione_CSP_2016-2018).

A. B. and T. V are with the Laboratory for Engineering of the Neuromuscular System (LISiN), Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino and with the PoliToBIOMed Lab, Politecnico di Torino, Torino, Corso Duca degli Abruzzi 29, 10129 Italy (phone: +39 011-090-7762; e-mail: alberto.botter@polito.it).

M. C is with the Laboratory for Engineering of the Neuromuscular System (LISiN), Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino.

E. H. T. is with the School of Healthcare Science, Manchester Metropolitan University, UK (e-mail: e.tole@mmu.ac.uk).

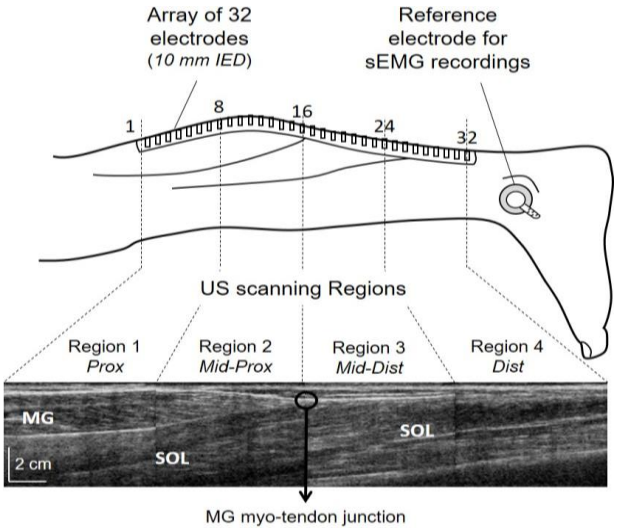

Figure 1. Schematic representation of the electrode positioning over the medial gastrocnemius (MG) and soleus (SOL). US images were detected from four adjacent muscle regions along the proximal-distal axis of the leg. A composite US image showing the architecture the studied muscles is reported in the lower part of the figure

the 16th electrode corresponded to the MG myo-tendon junction (Fig.1). The anatomical structures used as a reference for electrode positioning were identified with ultrasound scanning (7MHz linear probe, Echo Blaster 128, Telemed Ltd., Vilnius, Lithuania) performed after subject positioning. Signals were detected in monopolar derivation (referred to a remote reference on the medial malleolus), amplified, band-pass filtered (3 dB bandwidth, 10–500 Hz), sampled at 2048Hz and A/D converted with 12 bits resolution (multichannel surface EMG amplifier, EMG-USB2, OT Bioelettronica, Torino, Italy). An external trigger pulse signaling the start and the end of the US acquisition was acquired synchronously with sEMG signals.

3) Ultrasound recordings

Ultrasound B-mode images were acquired with an EchoBlaster 128 device (Telemed Ltd., Vilnius, Lithuania) equipped with a linear-array transducer (LV7.5/60/128Z-2) with variable frequency 5–8 MHz (set to 7MHz to analyze skeletal muscle). The ultrasound probe was aligned with the proximal-distal axis of the leg and positioned just medially to the electrode array, minimizing the distance between scanning region and electrode position; the transverse distance between the electrodes and the US probe was approximately 2 cm. The gain, the depth and focus position were defined initially to achieve good image quality. All system-setting parameters were kept constant throughout all trials for all subjects. The ultrasound images were recorded at ~80 frames/s and transferred to a workstation for analysis.

B. Data analysis

Monopolar sEMGs were imported in Matalb (R2016b, The MathWorks Inc., MA, USA) and band-pass filtered in the 20-400Hz frequency band (4th-order zero-phase Butterworth filter). The identification of fasciculation potentials (FPs) from sEMGs was performed for different electrode configurations; monopolar (MONO) and single-differential (SD) signals with different IEDs. Three sets of differential sEMG were obtained by differentiating monopolar EMGs detected by pairs of

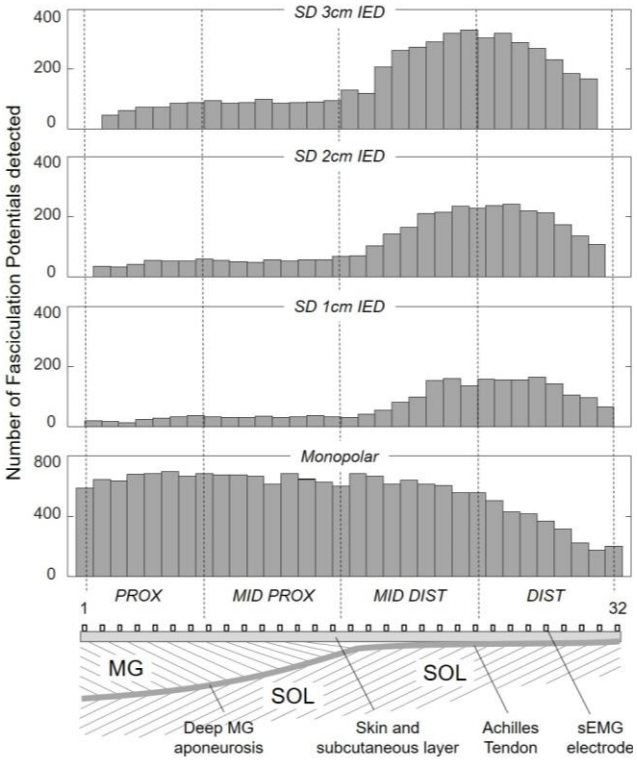

Figure 2. Number of fasciculation potentials detected by each channel of the three electrodes' configurations for all the subjects (cumulative detection time: 600s). The x axes of the hystograms are devided in four parts representing the four scanning regions of the US probe. The spatial relationship between scanning regions, sEMG electrodes and anatomical structires of undelying muscles is reported in the lower part of the figure.

electrodes distant 1cm (SD1), 2cm (SD2) and 3cm (SD3). For each set of signals, FP onsets were identified using an amplitude threshold defined over the background noise level. All sEMG signals were visually inspected by two expert operators to verify the correctness of the automatically-identified onsets and to exclude spurious FPs due to noise or artifact-related threshold crossing. The channels where the FP was represented were used to define the FP spatial support and to associate each FP to one or more muscle regions (*Prox, Mid-Prox, Mid- Dist, Dist*).

US videos were analyzed using ImageJ (NIH, Bethesda, MD, USA). Fasciculation twitches (FTs) were visually identified and characterized in terms of: twitch onset, duration, location and area of the displaced muscle tissue, with frame time adjusted to account for the variable inter-frame interval present in the system used [8]. The visual analysis of US videos was independently performed and cross-verified by two expert operators.

The fasciculation onsets and locations were used to identify whether pairs of events detected in sEMG and US could be attributed to the same muscle fasciculation; i.e. if FT_i and FP_j were the mechanical and electrical representation of the same physiological event. To this end, we defined the following criteria: (i) the spatial support of FP_j must be included in the region scanned by the US probe and (ii) the time lag between FP_j and the beginning of FT_i must be compatible with the electromechanical delay. If both criteria were met, the pair FT_i and FP_j were considered as *matched*. In addition to the number

of matches, the rate of agreement (RoA) between US and sEMG measures was calculated as:

$$RoA = \frac{nM}{nFP_o + nFT_o - nM} \quad (1)$$

where *nM* denotes the number of fasciculations identified by both techniques (*matches*), *nFPo* the number of fasciculations identified only by sEMG, and *nFTo* the number of fasciculations identified only by US.

III. RESULTS

1) Number of fasciculations identified by sEMG and US

The number of FPs identified by sEMG depended on the selectivity of the electrode configuration as well as on the muscle region considered. This behavior is well described by the cumulative distribution of FPs identified by each sEMG channel (Fig. 2). While monopolar configuration showed a relatively uniform distribution across most electrodes, with a progressive reduction for the most distal region, the distribution associated with the three single differential configurations was highly region-dependent and skewed toward the two most distal regions.

Fig. 3 reports the number of fasciculations per minute (*fpm*) detected in each muscle region by US and by the four sEMG derivations (SD1, SD2, SD3 and MONO). Although a large inter-subject variability was found in both sEMG- and US-based identifications, a common behavior can be observed. For all participants and muscle regions, monopolar sEMGs allowed to identify more fasciculations than US and single differential sEMG. As the selectivity of sEMG detection increased (i.e. with the reduction of IED from 3 cm to 1 cm), the number of fasciculations identified in sEMG and US became comparable. Similarly to sEMG, also US showed a spatial variation in the number of events detected. For all the subjects the number of FTs was maximal for either the *distal* or *mid-distal* region of the leg.

2) Matches between the identified fasciculation potentials (FPs) and fasciculation twitches (FTs)

Although the number of fasciculations detected by sEMG and US was similar for some experimental conditions, only a fraction of the identified events was classified as common (also referred to as *matches*) and therefore attributable to the activation of the same motor unit. Fig. 4a shows the number of matches normalized with respect to the total number of FTs (i.e. the percentage of FTs that was also identified in sEMG). Similarly to the absolute number of FPs (Fig. 3), the number of matches was the highest for monopolar sEMG detection and decreased progressively for SD3, SD2 and SD1; i.e. with the increase of sEMG detection selectivity.

The Rate of Agreement (RoA) between the EMG-based and the US-based fasciculation identification was always lower than 75%, with a median value across sEMG detection configurations of 25%. Although the limited number of subjects did not allow a statistical evaluation of the results, the highest RoA between electrode configurations could be obtained for the 3cm IED single differential detection (SD3).

IV. DISCUSSION

Surface EMG and US are two complementary techniques not only in terms of measured quantity but also in terms of spatial selectivity. US is equally sensitive to superficial and deep muscle movements, while the volume conductor of sEMG depends on the electrode configuration. When sEMGs are recorded in monopolar configuration, both superficial and deep sources may be detected, suggesting the possibility of achieving high rates of agreement (RoA) with US recordings. However, monopolar sEMG is also sensitive to far-field

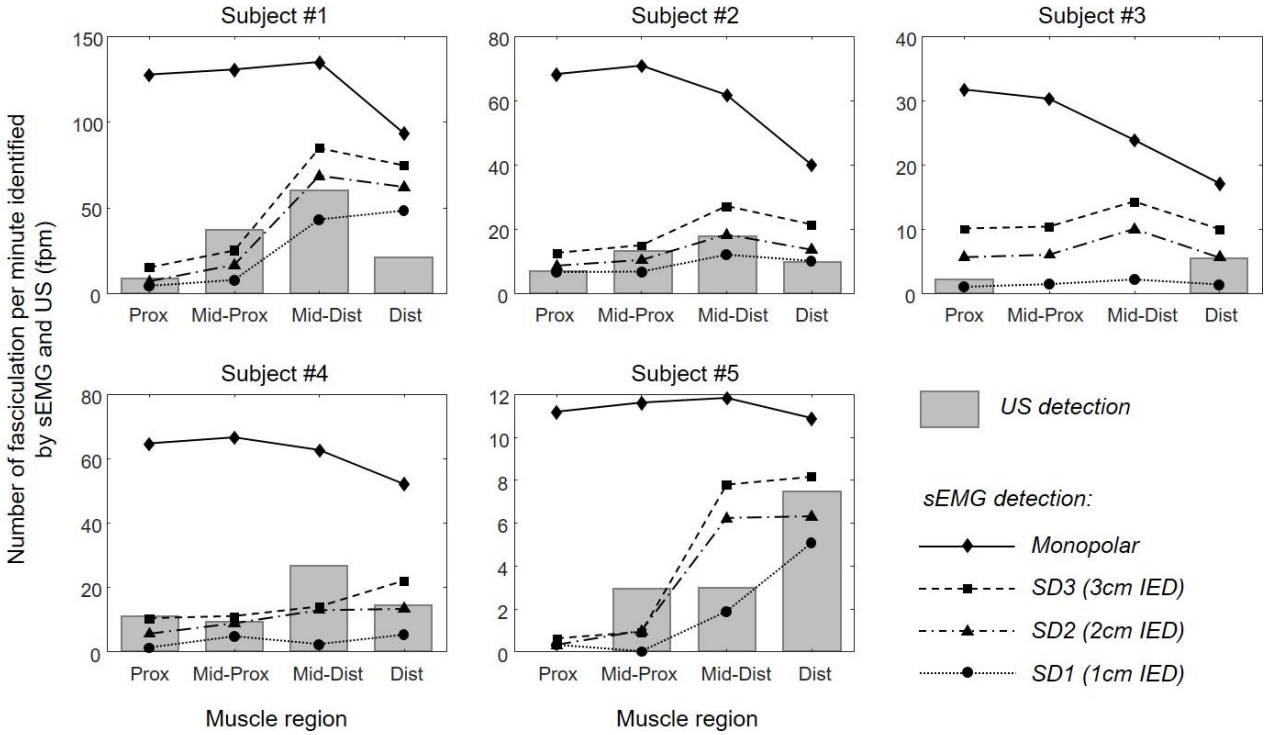

Figure 3. Number of fasciculation potentials (FP) detected by the four sEMG electrode's configurations and number of fasciculation twitches (FT) captured by US imaging. Results are reported for the four muscle regions considered: Prox, Mid-Prox, Mid-Dist, Dist, as defined in Figure 1.

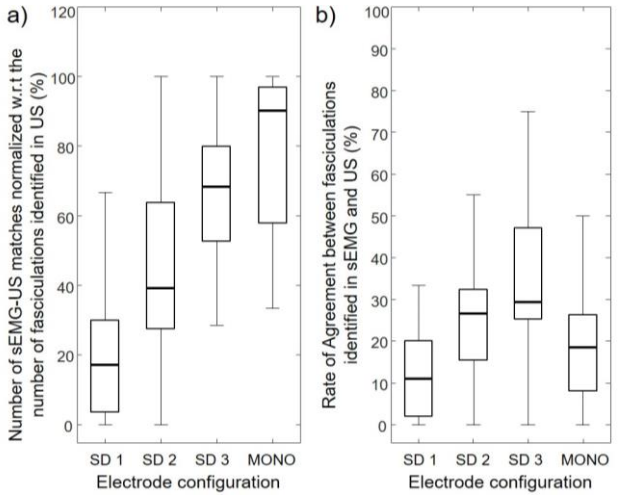

Figure 4. (a) Number of sEMG-US matches normalized to the number of FTs identified by US. (b) Rate of Agreement between fasciculation identified by sEMG and US. Each wisker plot represents the distribution of N=20 datapoints (5 subjects x 4 muscle regions).

sources [9], not necessarily included in the field of view of US. This low specificity may explain the large number of monopolarly identified FPs (Fig. 2), the discrepancy between the number of fasciculation events detected in monopolar sEMG and US (Fig. 3) and the fact that, despite the number of matches was maximal in this configuration, the RoA with US was not the highest among the four electrode configurations considered (Fig. 4).

Differently from monopolar configuration, a similar number of fasciculations was identified in single-differential sEMGs and US. Single-differential configuration reduces the volume conductor of sEMG recording [7], resulting in fewer fasciculations being detected. This behavior was already described by Jahanmiri-Nezhad and colleagues who showed that the 74% of the fasciculations detected in monopolar configuration could not be captured in single differential recordings [10]. On one hand, differential sampling reduces the pick-up volume of electrodes and therefore the number of FPs potentially identified; the shorter the distance between electrodes the smaller the pick-up volume is [11]. This likely explains the progressively smaller number of FPs identified for the shorter IEDs (Fig. 2). On the other hand, selective sampling ensures minimal, if any, influence of spurious potentials, resulting from other distant muscles or artifacts [12]. On this regard, it is noteworthy that the spatial distribution of detected FPs (Fig. 2) is consistent with that of FTs (always larger for *mid* and *mid-dist* locations, Fig. 3) for single differential, though not for monopolar recordings, which are less selective. The key question here is which detection system is best when it comes to the identification of FPs from surface EMGs. Addressing this question is currently not possible as it would first demand ascertaining the clinical relevance of false positives and false negatives occurrences. While this issue urges further testing, our preliminary results suggest though that differential signals sampled by 3 cm spaced electrodes provide a conservative compromise for the identification of FPs. This configuration is also the one with the largest RoA with US measures, which is likely due to the compromise between the sensitivity to FPs and the spatial selectivity. The relatively low values of RoA suggest, however, there is a relevant number of fasciculation that are captured only by sEMG or by US. This may be due to (i) deep sources, detected by US but not sampled by differential sEMG, (ii) events occurring outside the US field of view, but within the sEMG volume conductor or (iii) multiple events closely spaced in time, which are detected as a single twitch in US, but can be distinguished in sEMG recordings.

V. Conclusions

In this study we compared the number of muscle fasciculations identified by sEMG and US in the calf muscles. Although preliminary, our results indicate that sEMG has the potentiality to identify a larger number of fasciculations than US, but with a poor spatial selectivity. By increasing sEMG selectivity the number of identified fasciculations becomes comparable to that of US imaging. In any case the RoA between the two approaches is relatively low, suggesting the two techniques are sensitive to events taking place in different muscle regions and with different timings. The integration of sEMG and US recordings seems therefore a promising approach to increase the detection sensitivity to fasciculations.

References

[1] M. De Carvalho, R. Dengler, A. Eisen, J. D. England, R. Kaji, J. Kimura, K. Mills, H. Mitsumoto, H. Nodera, J. Shefner, and M. Swash, “Electrodiagnostic criteria for diagnosis of ALS” vol. 119, pp. 497–503, 2008.

[2] M. Regensburger, F. Tenner, C. Möbius, and A. Schramm, “Clinical Neurophysiology Detection radius of EMG for fasciculations : Empiric study combining ultrasonography and electromyography,” *Clin. Neurophysiol.*, 2017.

[3] S. Misawa, Y. Noto, K. Shibuya, S. Isose, Y. Sekiguchi, S. Nasu, and S. Kuwabara, “Ultrasonographic detection of fasciculations markedly increases diagnostic sensitivity of ALS,” *Neurology*, vol. 77, no. 16, p. 1532 LP-1537, Oct. 2011.

[4] A. Grimm, T. Prell, B. F. Décard, U. Schumacher, O. W. Witte, H. Axer, and J. Grosskreutz, “Clinical Neurophysiology Muscle ultrasonography as an additional diagnostic tool for the diagnosis of amyotrophic lateral sclerosis,” *Clin. Neurophysiol.*, vol. 126, no. 4, pp. 820–827, 2015.

[5] P. Zhou, X. Li, F. Jahanmiri-nezhad, W. Z. Rymer, and P. E. Barkhaus, “Duration of observation required in detecting fasciculation potentials in amyotrophic lateral sclerosis using high-density surface EMG,” *J. Neuroeng. Rehabil.*, vol. 9, no. 1, p. 1, 2012.

[6] G. Drost, B. U. Kleine, D. F. Stegeman, B. G. M. van Engelen, and M. J. Zwarts, “Fasciculation Potentials in High-Density Surface EMG,” *J. Clin. Neurophysiol.*, vol. 24, no. 3, 2007.

[7] C. Disselhorst-Klug, J. Silny, and G. Rau, “Improvement of spatial resolution in surface-EMG: a theoretical and experimental comparison of different spatial filters.,” *IEEE Trans. Biomed. Eng.*, vol. 44, no. 7, pp. 567–74, 1997.

[8] D. Miguez, I. Loram, and P. J. Harding, “A technical note on variable inter-frame interval as a cause of non-physiological experimental artefacts in ultrasound Subject Category : Subject Areas :,” 2017.

[9] D. F. Stegeman, D. Dumitru, J. C. King, and K. Roeleveld, “Near- and far-fields: source characteristics and the conducting medium in neurophysiology.,” *J. Clin. Neurophysiol.*, vol. 14, no. September 1997, pp. 429–442, 1997.

[10] F. Jahanmiri-Nezhad, P. E. Barkhaus, W. Z. Rymer, and P. Zhou, “Sensitivity of fasciculation potential detection is dramatically reduced by spatial filtering of surface electromyography,” *Clin. Neurophysiol.*, vol. 125, no. 7, pp. 1498–1500, 2014.

[11] P. A. Lynn, N. D. Bettles, A. D. Hughes, and S. W. Johnson, “Influences of electrode geometry on bipolar recordings of the surface electromyogram.,” *Med Biol. Eng. Comput.*, vol. 16, no. 6, pp. 651–660, 1978.

[12] T. M. Vieira, A. Botter, S. Muceli, and D. Farina, “Specificity of surface EMG recordings for gastrocnemius during upright standing,” *Sci. Rep.*, vol. 7, no. 1, pp. 1–11, 2017.