Correcting electrode displacement errors in motor unit tracking using high density surface electromyography (HDsEMG)

I Gligorijević[1,2], BTHM Sleutjes[3], M De Vos[1,2,4], JH Blok[3,5], I Montfoort[3] , B Mijović[1,2], M Signoretto[1,2] , S Van Huffel[1,2]

1 Department of Electrical Engineering-ESAT, SCD-SISTA, KU Leuven, Belgium;
2 IBBT Future Health Department, Leuven, Belgium;
3 Department of Clinical Neurophysiology, Erasmus MC, UMC Rotterdam, The Netherlands;
4 Neuroscience Lab, Dep. of psychology, Oldenburg University, Germany;
5 Department of Clinical Physics, Reinier de Graaf Hospital, Delft, The Netherlands

Abstract

This study discusses a technique to correct for effects of electrode grid displacement across serial surface EMG measurements with high-density electrode arrays (HDsEMG). A proof of concept study shows that automated correction is possible and that agreement is increased between the same motor unit action potentials observed across different measurements. It also shows great potential for assisting motor unit tracking studies, indicating that otherwise electrode displacements cannot always be precisely described.

Keywords *grid displacement, HDsEMG, motor unit tracking, rotation, surface electromyography*

1 Introduction

Motor units (MUs) are the smallest functional units of the peripheral motor nerve system. Neuromuscular diseases affect MUs, either directly or indirectly. The follow-up study of MUs during a disease process may, therefore, improve our understanding of neuromuscular diseases. Recently, MU tracking using high-density surface electromyography (HDsEMG) has been introduced as a neurophysiological technique that enables noninvasive follow-up of single MUs [1]. In this technique MU action potentials (MUAPs) are recorded with an array of densely spaced electrodes after electrical stimulation of the afferent nerve. In these HDsEMG recordings, each MUAP is presented as a spatio-temporal profile or fingerprint of the corresponding MU. Use of the characteristic information in the fingerprints facilitates detection of the MUAPs in consecutive recording sessions and, hence, allows for MU tracking.

MU tracking may provide insight into the relationship between MUAP properties and how these are affected during disease progression. However, before changes in a MUAP fingerprint between sessions can be ascribed to an underlying pathophysiological process, other factors that affect it have to be taken into account. It is known that MUAP properties depend on geometrical and anatomical factors such as muscle fiber length, signal stability (electrode-skin contact), electrode location, and electrode orientation [2]. In particular, even small shifts in electrode position can affect the MUAP parameters significantly.

In clinical practice, the recording grid can be rotated, translated and bended in a different way compared to how it was attached in the previous recording session. In [3], a method was proposed to correct for translational errors for the study of the external sphincter muscle. In this study we extend this correction procedure and show how the effects of rotation between sessions can be automatically compensated for. We illustrate the approach on a low-force voluntary contraction measurement of thenar muscles, following well-defined displacements.

2 Methods

2.1 Recordings

Test recordings of voluntary contractions were performed on three healthy subjects using a HDsEMG grid with 126 electrodes spaced equidistantly in 9 rows and 14 columns, as described in detail elsewhere [1]. The grid was placed over the thenar muscles. Initially, four configurations were introduced to illustrate the concept using recordings from a single subject, indicated in Fig. 1(a). Additionally, recording grid in configuration 1 was used as a reference configuration for 5 additional 2-minute recordings in each of 3 subjects: with the grid positioned in reference configuration, and positions rotated for -5, +5, -10 and +10 degrees around it, mimicking accidental grid displacement. Recordings were performed on a single day for each subject, with half-hour break intervals. Visual feedback in the form of bipolarly filtered signals was used to assist the subject in establishing and maintaining a stable, low-force contraction level, estimated at 1-5% Maximum Voluntary Contraction (MVC).

All signals were first decomposed automatically, separating each into contributions from individual MUs using the algorithm described in [4]. This yielded sets of MUAP fingerprints for each session.

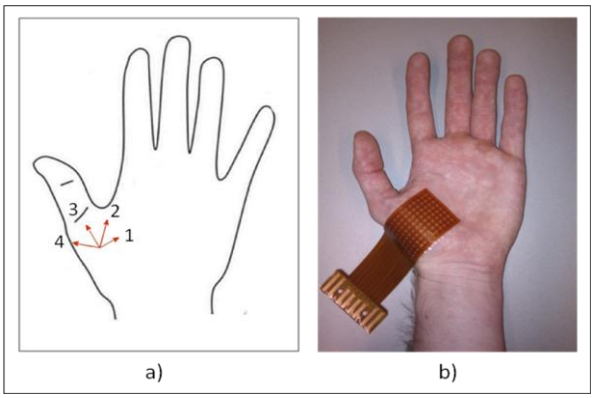


Figure 1: (a) Four test recording configurations; arrows indicate the direction from the side of PCB connector towards the horizontal end of the electrode grid; (b) recording grid in configuration 1.

Fingerprints that were observed at least 100 times during the two-minute recording were considered reliable, averaged and kept for further analysis.

2.2 Artificial recording grid displacement

To assess the effect of rotation of a grid around its center, we first assign coordinates (x,y) to the electrode locations in the original grid placement. After rotation over angle θ, new coordinates (x',y'), representing the position of these electrodes are then obtained by multiplication with a rotation matrix:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}, \qquad (1)$$

To assess the value of a fingerprint in every set of rotated coordinates (x',y'), we use the linear interpolation based on originally recorded values. This was done for each temporal sample to obtain a projection of a fingerprint on a rotated grid. The rotation procedure is depicted in Fig. 2 (a). The interpolation is reliable only in the intersection area (gray), while the rest of the values cannot be reliably assessed and were put to zero.

Apart from rotation, the in-plane translation of the recording grid is practically inevitable and thus has to be taken into account [3]. Comparing translated observations can be done only in the intersection area (gray in Fig. 2 (b)). Since we can compare only part of each fingerprint, it is necessary to choose a “subgrid” – 6x6 subset of electrodes around the place of the highest spike which is subsequently used for comparison. The subgrid "subfingerprint" is compared with each possible counterpart of the investigated fingerprint with which we attempt to match. The best possible position reveals the translation. This example is shown in Fig. 2 (b). In order to have a better than inter-electrode distance resolution we first need to upsample the signal. For this purpose, we apply bicubic interpolation [5] .

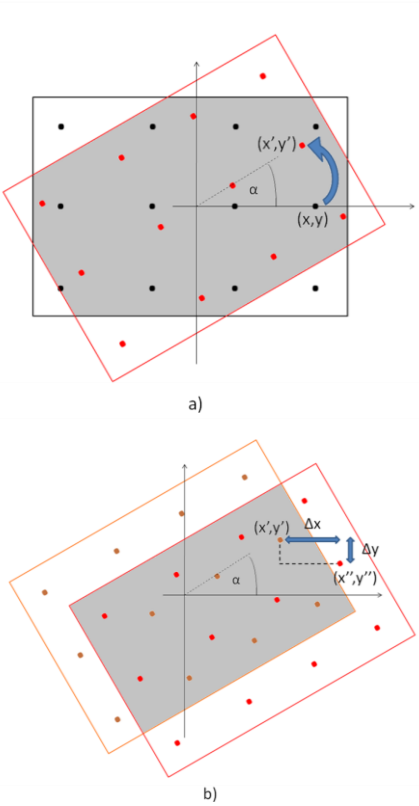


Figure 2: (a) Calculating the positions of electrodes of a rotated grid; (b) additional translation for finding the position of the best matching

Each fingerprint is upsampled and rotated for a chosen angle, followed by the estimation of optimal translation for the comparison with its "non-rotated" counterpart. We proceed with downsampling the signal to its original dimensions, and then compare rotated and "fixed" fingerprints using 2 parameters: correlation and normalized mean squared error (NRMSE) like in [4]. The peak of the ratio between these values (high correlation and small residue when we subtract fingerprints) indicates units that match. Each MUAP fingerprint obtained by a "displaced" grid is compared with its best match from the "fixed" grid measurement.

The complete procedure goes as follows: the rotation angle is varied and the optimal translation is calculated until the best overall result is achieved. Fine tuning is then applied around the indicated angle to pinpoint a correct value. The output provides the angle of rotation and the displacement in x and y directions.

3 Results

For the study with 4 configurations (Fig. 1 (a)) in total, 25 reliable MU fingerprints were extracted with the decomposition method. Out of these, 3 units could be tracked across measurements: 1 unit appeared in 3 configurations (1, 2, 4), and the remaining two were matched across configurations 1 and 2. An example for the automatic correction of the specified 45 degrees displacement is portrayed in Fig. 3, showing the correlation and the ratio between correlation and

NRMSE. The angle was estimated at 42 degrees, translation at -2 and 3 mm displacement in x and y directions respectively. Fig. 4. (a) and (b) indicate the originally recorded fingerprints from positions 2 and 1 respectively. Once the rotational and translational corrections have been applied, these 2 fingerprints proved to match almost perfectly (Fig. 4 (c)). The subgrid used for comparison is also indicated. Overlaid observation can finally be seen in Fig. 4 (d).

The second part of the study involved 3 subjects and aimed at MU tracking with simulated accidental displacements of the recording grid for configuration 1 (Fig. 1 (a)). On average, 5 fingerprints per subject could be tracked across one or more measurement configurations.

The number of units that were found and tracked per subject together with their average correlation before and after electrode placement corrections, are summarized in Table 1. It was found that the indicated grid displacements did not always match the ones extracted by our procedure. The largest observed difference was the one for measurement involving subject 1. While the indicated angle was 5 degrees, the calculated (and in fact, correct) one was -2 degrees with respect to the position 1 ("error" of 7 degrees). This may be the result of relative muscle-skin displacement (due to e.g. thumb movement) rather than angle measurement error. On average, estimated displacement was within ±3 degrees from the indicated value.

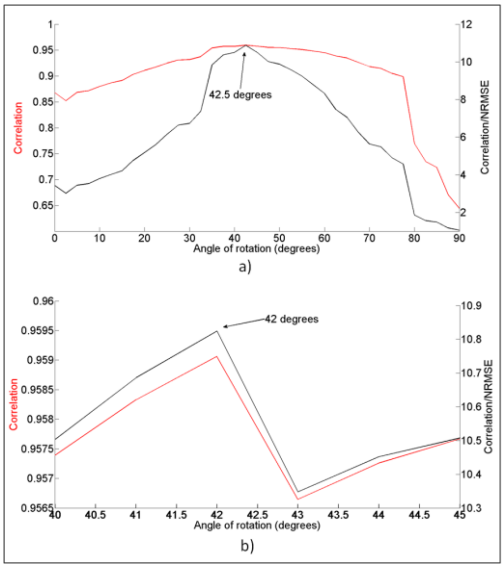


Figure 3: correlations (red) and the ratio correlation/NRMSE (black) between the original and fingerprint obtained by adjusting the displaced electrode grid (a) roughly identified angle of rotation (42.5 °) as a peak of the ratio correlation/NRMSE and (b) pinpointed precise value of 42 °

Angular precision could be tested on subject 2, where the same 2 fingerprints were found in two electrode displacement configurations. Searching for the joint peak of agreement revealed the angular ambiguity of 1.6 degrees.

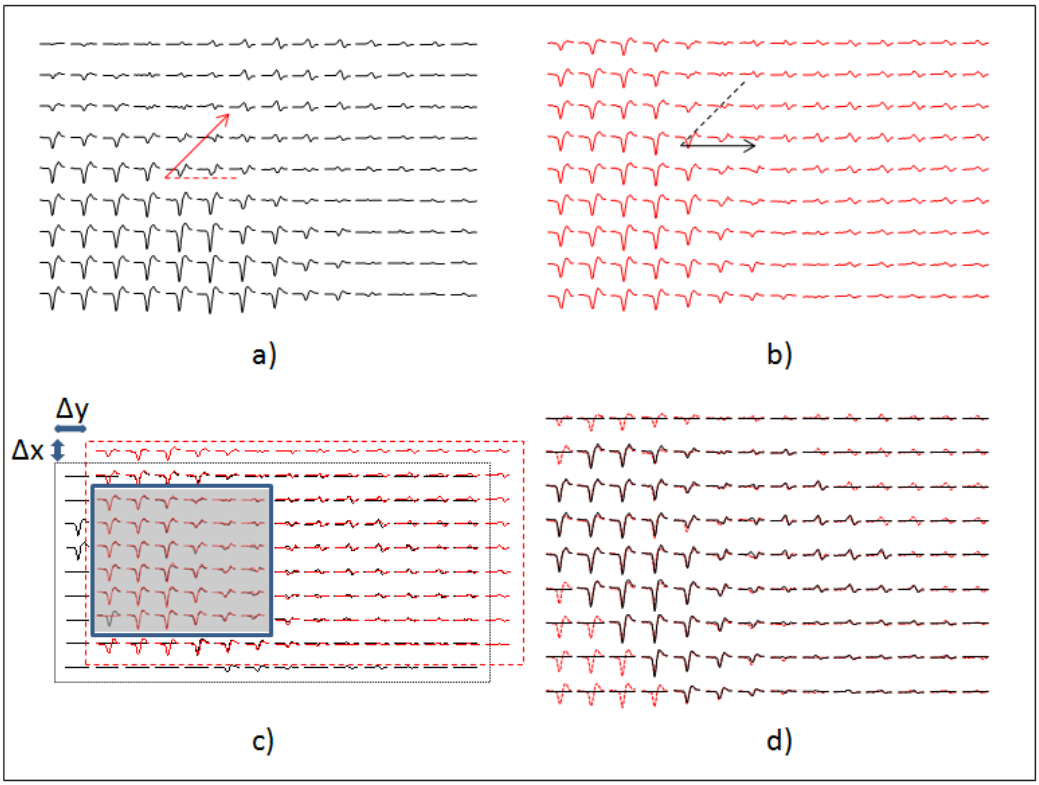


Figure 4: Matching the units from displaced grid recordings; (a) MUAP fingerprint obtained using grid rotated over 42 ° with respect to signature from (b); (c) matching corrected projection of (a) using the operators described in the text; subgrid used to pinpoint the translation displacement is depicted in gray; (d) overlaid signatures (b) - red and (c) - black

Subject	Fingerprints		Average correlation	
	Extracted	Trackable	Before correction	After correction
			%	
1	**51**	**8**	**86.3**	**92.4**
2	**39**	**6**	**84.0**	**93.4**
3	**30**	**3**	**82.2**	**90.0**

Table 1: Comparison of the fingerprints from measurements with displaced electrode grid, before and after applying the in-plane projection adjustment

4 Discussion

Even when electrode re-placement between sessions is done with great care, repositioning errors may remain. Mitigating the effect of such errors may be expected to improve the reliability of ascribing changes in the MUAP to true (patho) physiological changes. Extrapolating the results of our pilot study with known displacements indicates how this may be achieved when the replacement error is not known.

Thus far, MU tracking using HDsEMG has been performed without corrections for recording grid displacement [1] or accounting for translational displacements only [3]. This implied that correlations between identical but displaced MUAPs could be relatively low; indeed, the threshold for considering MUAPs to be similar was set to a cross-correlation value of 80% ([1],[3]). Being able to automatically adjust for re-placement errors might allow for a higher threshold, increasing the specificity. It may also simplify greatly the otherwise strict and time consuming procedure for placing the HDsEMG recording grid.

After adjusting the projection using rotation and translation operators, significant improvement in agreement was observable both visually and numerically via the correlation and NRMSE coefficients. Moreover, it was found that this method allows fine-tuning in the order of two degrees in angular direction in rotation and a quarter of the inter-electrode distance accuracy in translation. The correction procedure maximizes correlations between units in different sessions. Hard tresholding on these correlation parameters did not enable fully automatic matching in a sense that the visual confirmation on indicated "similar" units was still necessary. Further insight into methods for rotation and translation invariant pattern classification might provide more reliable measures for this purpose (e.g. [6]). To define the necessary agreement between fingerprints in order to consider them as originating from the same MU, the minimal disagreement between different MUAPs has to be described. Also, it is important to investigate and describe the changes that could be ascribed to the remaining modeling imperfections such as bending of the electrode grid, and changes in skin-electrode contact. This would enable to differentiate between the physiological changes of the muscle and the method limitations when comparing healthy units. This rule would help to maximize the applicability of MU tracking studies. The other remaining issues concern muscle specific properties.

5 Conclusions

We presented the method to track MUs across measurements more reliably when a recording grid is potentially not perfectly repositioned. The initial results show that the method reliably alligns MUs across sessions. This will allow to perform MU tracking with higher precision than currently possible.

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Address for correspondence:

Ivan Gligorijević
Faculty of Engineering, department of electrical engineering (ESAT), division SCD/SISTA, KU Leuven, Belgium
Kasteelpark Arenberg 10 postbus 2440, B-3001 Heverlee
ivan.gligorijevic@esat.kuleuven.be