



An automatic pre-processing method to detect and reject signal artifacts from full-shift field-work sEMG recordings of bilateral trapezius activity

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ABSTRACT

Bipolar surface EMG (sEMG) signals of the trapezius muscles bilaterally were recorded continuously with a frequency of 800 Hz during full-shift field-work by a four-channel portable data logger. After recordings of 60 forest machine operators in Finland, Norway and Sweden, we discovered erroneous data. In short of any available procedure to handle these data, a method was developed to automatically discard erroneous data in the raw data reading files (Discarding Erroneous EPOchs (DESEPO) method. The DESEPO method automatically identifies, discards and adjusts the use of signal disturbances in order to achieve the best possible data use. An epoch is a 0.1 s period of raw sEMG signals and makes the basis for the RMS calculations. If erroneous signals constitute more than 30% of the epoch signals, this classifies for discharge of the present epoch. Non-valid epochs have been discarded, as well as all the subsequent epochs.

The valid data for further analyses using the automatic detection resulted in an increase of acceptable data from an average of 2.15–6.5 h per day. The combination of long-term full-shift recordings and automatic data reduction procedures made it possible to use large amount of data otherwise discarded for further analyses.

1. Introduction

At least through the two last decades neck disorders are globally increased to be a relative huge problem compared to other health disorders (Vos et al., 2017). The risk factors for neck pain are often described as work-related, e.g. work for extended periods with stooped neck, use of low force for long periods and little variation (da Costa and Vieira, 2010; Hanvold et al., 2013; Luttmann et al., 2010; Veiersted et al., 2013; Østensvik et al., 2009b). One well documented risk factor is sustained low-level trapezius activity with little variation related to trapezius myalgia and other neck disorders (Hansson et al., 1997; Hanvold et al., 2013; Hägg, 1991; Luttmann et al., 2010; Sinderby et al., 1995; Sjøgaard et al., 2000; Veiersted and Westgaard, 1993; Visser and van Dieën, 2006; Østensvik et al., 2009b). The prevalence of self-reported neck pain among forest harvest operators can vary in order from 30% (Østensvik et al., 2008a, 2008b, 2009a, 2009b), even up to 70% (Lynch et al., 2014).

Quantitative assessment of Sustained Low-level Muscle Activity (SULMA) at the work place has been in focus since the 1970s (Hansson et al., 1997; Madeleine, 2010). However, assessing long term measurements requires considerable resources and involves the use of direct measurements like surface electromyography (sEMG) that represent

rather challenging aspects during whole-day field works (Hansson et al., 1997, 2003; Walters et al., 2013).

sEMG, even if it gives rise to noisy electrical signals, is a suitable method because of its non-invasive nature (Conforto et al., 1999). Even when the measuring system is set optimally, contamination in recordings can still be forthcoming from sources of interference (Chan and MacIsaac, 2018). Further, since the sEMG signals are dependent on the anatomical and physiological properties of the skin and subcutaneous tissue, the signals may acquire noise while traveling through the tissue (Reaz et al., 2006). Additionally, the electromyographic signal that originates in the muscle is inevitably contaminated by various noise signals of artifacts that originate either at the skin-electrode interface, in the electronics that amplifies the signals or in external sources (De Luca et al., 2010). However, most of the artifact contribution is allocated in correspondence to muscular contraction that cause the electrodes to move (Conforto et al., 1999). In spite of modern technology, baseline- and movement artifact noise may influence the low-frequency part of the sEMG frequency spectrum and lead to an erroneous interpretation of the signal (Conforto et al., 1999; Frigo et al., 2000).

Research and extensive efforts have been made in this area, developing better algorithms, upgrading existing methodologies, improving detection techniques to reduce noise and to acquire sEMG signals

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(Baratta et al., 1998; Chan and MacIsaac, 2018; Clancy et al., 2002; Sinderby et al., 1995). Although nonlinear error modeling approach of sEMG signal processing have been launched (Law et al., 2011), it is difficult to obtain reliable sEMG recordings especially from field data and even more difficult to discern their quality (Chan and MacIsaac, 2018).

The issue of erroneous data is an ongoing challenge; our field-study was no exception. The challenge is to apply EMG equipment to tolerate long term dynamic movements during full-shift sEMG recordings in the open field work. The aim of this paper is to present a procedure of how efficiently, identify and discard non-reliable or erroneous signals in order to get as much reliable data as possible for further muscle activity pattern analysis.

2. Material and methods

2.1. Subjects

A total of 60 healthy, male, forest machine operators driving harvesters (FMOH) from Finland, Norway and Sweden, participated in three separate field-works over a period of three months in the autumn 2013, Table 1. The Norwegian Institute of Bioeconomy Research (NIBIO) was in charge of the project and the Institute of Natural Resources Research in Finland (LUKE) and Skogforsk in Sweden participated.

The main selection criteria required that the FMOH could be reached with a camper at their individual forest workplace within 2–3 h' drive from a chosen geographic center. The calibration test was performed and the sEMG equipment applied on and off in the camper. The Regional Ethical Committee for Medical Research approved the study protocol and a written informed consent was obtained from all the volunteers in advance.

2.2. Working conditions

The areas for the investigation in the three countries were relatively similar concerning terrain conditions and the harvested tree species. The forest vehicles were standardized to include the most applied brands; John Deere (n = 26), Komatsu (n = 16) and Ponsse (n = 18). Seated in the cabin, all the FMOHs perform a continuous bilateral manual handling of control levers with high precision to carry through the harvest work-cycle during a full-shift. First the FMOH approaches the lowest part of the tree with the vehicle and grasp around it with the aggregate. Second, he cuts the tree and balances the stem into a horizontal position while simultaneously disbranch and make crosscuts on the logs. Repeatedly the transfer of the vehicle from one tree to the next includes back and forth movements resulting in twisted body positions of the head, neck and shoulder. Additionally, the FMOH attends the PC-screen for production results and occasionally performing engine adjustment or repair. The work-cycle is described in (Østensvik et al., 2008b, 2008a). We did not interfere with the setup in the cabin while the physical basis could be acknowledged to be the best personalized ones. The FMOH accommodated the chair to make the best fit to his

Table 1

Anthropometrics in the Nordic occupational groups.

	Finnish (n = 20)		Norwegian (n = 20)		Swedish (n = 20)	
	Mean	SD	Mean	SD	Mean	SD
Age (years)	33.9 ^b	11.2	42.0 ^{ab}	11.9	43.8 ^a	10.2
Weight (kg)	89.2 ^a	17.5	87.3 ^a	9.4	90.5 ^a	10.9
Height (cm)	179.4 ^a	5.9	180.4 ^a	7.2	182.1 ^a	7.5
BMI	27.6 ^a	4.7	26.9 ^a	2.6	27.4 ^a	3.7

Means followed by different letters ^a and ^b within the same row are significantly different at $p < 0.05$ (Tukey's Studentized range test).

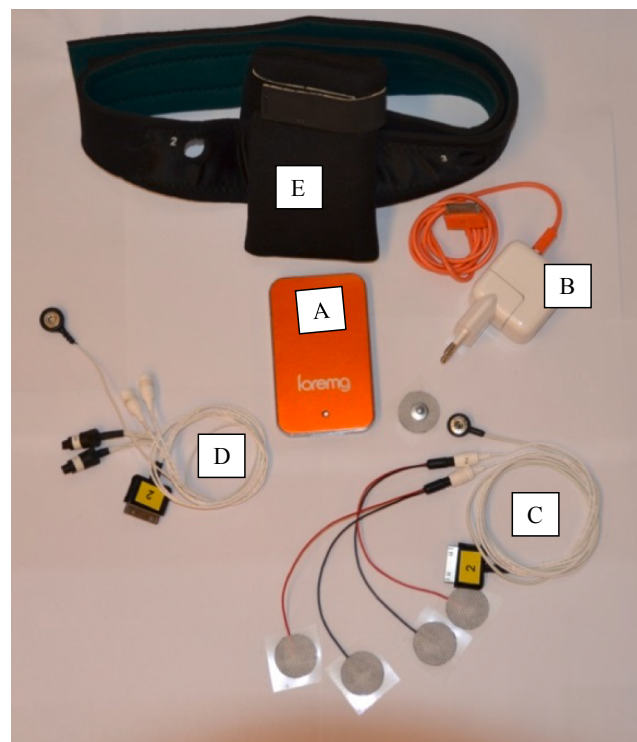


Fig. 1. (A) A four channel sEMG data logger, 'Foremg' (OT Bioelettronica, Italy). (B) USB 2.0 cable to transfer data and charge the Foremg offline. (C) Electrodes and cables for sEMG recordings in channel 1 and 2. (D) Electrodes and cables for MVC recordings in channel 3 and 4. (E) Adjustable belt applied on the chest with a protected etui for the Foremg.

body, including the distance to the control levers. Likewise, the tempo of the machine ruling could be preset to adaptable levels.

2.3. Surface electromyography

2.3.1. Equipment and techniques

A portable, customized four channels, small and light cellphone shaped sEMG data recorder with internal lithium-ion-cell battery, 'Foremg' (OT Bioelettronica (OTB) Italy) was used, Fig. 1 A. Bipolar sEMG raw data signals were recorded continuously during a full work-shift in left- and right trapezius in channel 1 and 2, respectively and amplified and filtered in the band-width 10–400 Hz. All the signals have been A/D converted simultaneously with an 8 bits resolution and stored internally in the Foremg device in an internal micro SD card and then transferred to a PC through an USB 2.0 cable (OTB). All sEMG signals were sampled at a frequency of 800 Hz. The sEMG were amplified and filtered in a differential preamplifier close to the electrodes. In a standardized procedure to reduce impedance to acceptable levels ($< 10 \text{ k} \Omega$) the skin area of current interest was shaved, lightly sandpapered and finally cleaned with 75% mixture of ether (1/4) and alcohol (3/4). Two pairs of Ag/AgCl sEMG disposable adhesive circular surface electrodes (ref.no.:CDE02401500BX) 24 mm in diameter and 15 cm cable were applied together with the reference electrode (ref.no.:CDES000024) delivered from sub-supplier, Spes Medica and described in OTB catalogue (Bioelettronica, 2013). The bipolar electrode technic was utilized for the acquisition of the sEMG signal (Fuglevand et al., 1992). The four electrodes were after palpation, sited in two pairs at each trapezius muscle with a 20 mm inter electrode distance, parallel to the underlying muscle fibers over the muscle belly and 2 cm lateral of half way between the origins of the 7th cervical vertebra and the insertion of the acromion of the scapula. The Surface EMG for Non-invasive Assessment of Muscles (SENIAM) protocol was used to place the electrodes (Hermens et al., 2000). To avoid friction towards the electrodes and

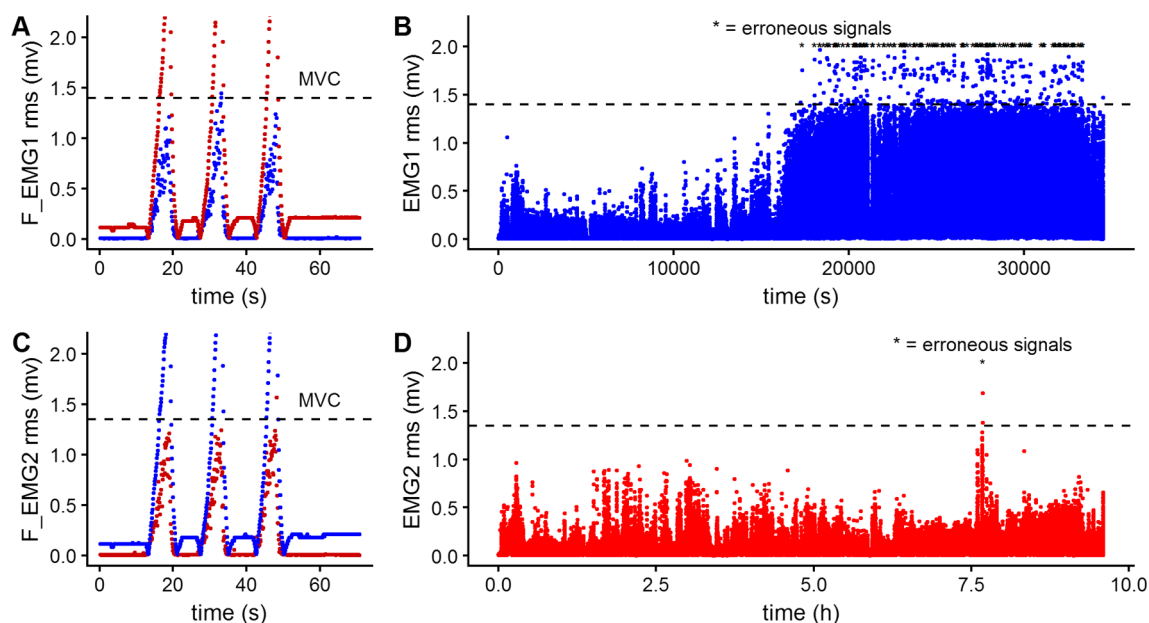


Fig. 2. Four graphic plots demonstrate how the automatic Discarding Erroneous EPOchs (DESEPO) method was used to identify and discard erroneous too high sEMG signals (B & D) and too low MVC values (A&C) after full-shift field-work to the final output of valid data for further analyses. These plots are from the authentic recordings of one of the affected forest machine operators. Different colors are used to distinguish between left and right trapezius, accordingly the upper two plots in blue color (A&B) is left trapezius while the lower two plots in red color (C&D) is right trapezius. Plot (A) shows the RMS values (blue lines) from the MVC calibration and the developed power through the tensile force (red points). The average of the three highest RMS values is indicated by a horizontal line and is defined as the valid MVC. In plot (C) likewise plot (A), but with opposite colors. In plot (B) the recordings of the RMS values (0.1 s) from left trapezius and in plot (D) right trapezius. On top of the two latter plots the text ‘* erroneous signals’ is shown. The erroneous signals are defined as the signals above the new defined MVC level. Below is a tiny dotted line, each dot ‘*’ indicates an erroneous EMG-value at the position (time) it is plotted. In plot (B) after 16000 s (4.4 h) from start, a sudden unexpected signal recording is discovered. In this case there are less erroneous signals in plot D than B. (See text Section 2.3.4 for more information). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cables, they were stabilized with adhesive tape, Leukosilk (Beiersdorf AG, Germany, Ref.no.1024) (Roy et al., 2007). The FMOH were told not to touch or scratch the shoulder and asked to wear a T-shirt during the measurements.

2.3.2. Data acquisition and processing

Three maximal voluntary contractions (MVCs) were performed with straight vertical arms. The length of the straps, located between the handles and the force transducer, was adjusted so that the force transducer was activated when the shoulders were lifted a few mm (Troiano et al., 2008). Equipped with the electrodes bilateral on trapezius and seated in an adjustable position unable to touch the floor with the feet, the FMOH was asked to contract the muscles gradually for approximately 10 s and performed a simultaneous recording of the EMG signal and force continuously from min- to maximum registered in the Foremg. Both left and right trapezius muscles were measured simultaneously in the force channels 3 and 4, respectively (Fig. 1D). The acquisition system has been customized to accept connection of load cells on these two channels that were disconnected after the calibration procedure. Immediately after the last of the three MVC efforts was recorded directly into the logger, the force set of electrodes were disconnected from the logger and the EMG electrodes were connected to the logger with channel 1 and 2 (Fig. 1C), respectively. The reference electrode was placed in the same established spot as during the force procedure by means of push button procedure (Fig. 1D). Subsequently, the force signals, transduced from load cells, were amplified and low pass filtered at 20 Hz. To check that no acute harm could have occurred during the three MVC efforts, the subject reported if he felt any pain compared to before the efforts. Off-line, a second 30–399 Hz band-pass filter on sEMG signals was performed to reduce artifact, and the estimation of the sEMG RMS in 100 ms (ms) distinct epochs was done, i.e. 80 samples in each epoch.

2.3.3. Signal quality

We observed after a long period with normal recording of sEMG signals that for some FMOHs the maximum values turned out to be higher than during the MVC calibration trials (Fig. 2, plots B and D). The raw EMG signal showed a behavior similar to the case when the electrode are nearly disconnected, with signals reaching the amplifier saturation level. Based on the observations off-line of all individual recordings of the sEMG signals, values of more than 2 mV was set as the threshold for erroneous data (Fig. 2, plots B and D). This corresponded with the level where signals showed more or less stable high values for extended time compared to far less and more variable signal values during earlier registration. The erroneous signals could occur sparsely, scattered, grouped, or almost continuously. This highlight that also during periods of normal contact, it can happen to have a few erroneous signals, probably due to artifact movement, but in contrast to the loss of the electrode-skin contact, the artifact can be ‘accepted’ under certain circumstances and not discarded. If we included erroneous signals in our data analysis, the RMS values, which are the basis for other calculations, e.g. SULMA (Østensvik et al., 2009a) would be biased.

2.3.4. Valid epochs to analyze

Fig. 2 visualizes the way we implemented the automatic Discarding Erroneous EPOchs (DESEPO) method to the final output of valid data for further analyses. The four graphic plots in the figure is an authentic recording from one affected operator used as an example to demonstrate both the erroneous EMG signals and the corrected MVC level, see chapter 2.3.5 for details. The erroneous signals are defined as the signals above the new defined MVC level.

To be comparable with earlier results of SULMA recordings where the RMS was based on 0.1 s, the 100 ms epoch was chosen. The epoch of 100 ms was defined as a period of sEMG raw signals without any erroneous signals, where the RMS-value for the time-slot is calculated straightforward. In order to get use of epochs with only a restricted

Table 2

Work-related temporal characteristics in general and during the test day among the Nordic occupational groups.

	Finnish (n = 20)		Norwegian (n = 20)		Swedish (n = 20)	
	Mean	SD	Mean	SD	Mean	SD
Years of practice	8.3 ^b	6.7	15.5 ^a	8.3	18.5 ^a	9.2
Usual working hours/ day	9.1 ^{ab}	0.9	9.3 ^a	1.1	8.4 ^b	0.8
Recorded test hours	7.6 ^{ab}	0.9	8.2 ^a	1.2	7.2 ^b	1.2
Valid recorded hours	6.5 ^a	1.8	6.2 ^a	2.3	6.7 ^a	1.6

Means followed by different letters ^a and ^b within the same row are significantly different at $p < 0.05$ (Tukey's Studentized range test).

number of erroneous signals, the following treatment was done: The first step was to identify all erroneous sEMG signals within all epochs. Secondly, if less than 30% of the signals in an epoch were erroneous, the epoch was considered valid and the RMS-value for the epoch was calculated based on the epoch's non-erroneous sEMG signals. Third, if more than 30% of the signals in an epoch were erroneous, the epoch was considered invalid, and that epoch and all subsequent epochs were discarded in further analysis Fig. 2, plots B and D. Our rationale for the threshold of 30% is based on the raw data signals that enable us to be certain of whether or not the signal is erroneous. We chose a threshold of 30% as a reliable figure realizing that the error of calculating epochs based on 70% or more of all epoch signals would not deviate much from a calculation based on all signals.

The RMS values were expressed as percentage of MVC and the epochs with RMS values minor or equal to the noise level, defined as 0.5% of MVC, have been considered with no muscle activity. The RMS values from all valid epochs form the basis for all further analysis.

2.3.5. Treating low MVC values

The straight forward determination of the MVC values are the mean of the three largest sEMG_{rms} values determined in the calibration procedure. However, during the analysis of the MVCs trials, we observed some anomalous amplitude in the sEMG signals visualized offline. They proved to be really low values and the estimation of the 0.5% MVC produced a threshold lower than the electrode-skin contact noise, generally around 3–4 μ V. The use of these MVC values would generate erroneous sEMG statistical values for the working period. To be able to utilize the sEMG data from the full shift recordings, a MVC value was in those cases set as the mean of the three highest sEMG signals during the first two hour of the full shift recording Fig. 2, plots A and C. Both the recordings of the left- and right trapezius were adjusted accordingly.

2.3.6. Statistics

All the sEMG signals from each study subject were read into to a GNU Octave environment (Eaton, 2016) and treated in loop control statements. For more detailed information, the DESEPO script and the Appendix can be obtained through first author. The script is the program handling the raw sEMG signals, the discarding of erroneous samples and the final RMS calculations. The result of the script is the data structure for each operator and the basic structure to calculate the SULMA variables. The Appendix is the GNU Octave treatment and the second step in the valid data analyzes pre-processing. The plots are made by using R (Core Team, 2018). For statistical analyses of group differences between countries, Tukey's studentized test were performed for variables normally distributed. For non-normal distributed variables Wilcoxon signed-rank test was used for paired sample comparisons. For correlation analyses Spearman's rho were performed in Statistical Analysis System 9.3 (SAS, 2010). Statistical significance level was set to $p = 0.05$.

3. Results

The major result of the work was the development of the DESEPO method that primarily cleaned the RMS values and made us keep as

Table 3

Number and percentage of all FMOHs with discarded registrations, the duration of discarded registrations and percentage of total working hours in left and right trapezius.

Trapezius muscles n = 60	FMOH with discarded registration		Duration of discarded registrations	
	n	%	hours	% of total
Left	17	28.3	59	12.8
Right	25	41.7	73	15.8

much as possible of the full-shift sEMG recording of field data of sustained low-level trapezius activity and the EMG gaps. Additionally the method also contributed to establish the MVC values by obviously calibration fault. Table 2 reveals that the recorded average sEMG time without any correction was 7.7 h; while the average recorded working hours used for further treatment was reduced to 6.6 h. Without using the DESEPO method the recorded working hours would have been only 2.15 h when samples with no erroneous signals should have been used.

Table 3 shows the distribution of the difference of total work hours in percentage, between the total recorded 461 and the 329 h left after discarding. There were no differences concerning total discarded data among FMOHs driving the three different standardized machine brands (Wilcoxon signed-rank test). The valid sEMG reading for each operator was analyzed towards individual data in order to find possible explanations for the erroneous sEMG readings. No significant trends (correlations) between the reduction in readings and individual parameters like age, weight, height and BMI, among the FMOH were found.

4. Discussion and conclusions

4.1. DESEPO method

The primarily intention with this study was to measure the exposure to sustained low-level trapezius muscle activity during bilateral manual handling of control levers with high precision, in a seated position, during a full-shift forest harvesting field work. However, off-line we were faced with incidences of periodically low-quality sEMG signals in the recordings and some too low MVC values. Consequently, an automatic method to identify and discard erroneous data was needed, but to our knowledge, no such automatic tool was at hand to 'clean' field data for further analyses. One assumption for the paper is that the time consuming and hard achieved field data could in a good manner describe the actual work pattern during a whole working day. However, facing a large number of possible obstacles it is of great importance to utilize as much data as possible from whole day studies. This will be enhanced through the automatic pre-processing 'Discarding Erroneous EPOchs' (DESEPO) method.

We have not tried the set-up calculation method on other muscle groups, but we assume that it could be useful also in investigating other muscle groups, since we talk about a data treatment method. One limitation is that the method needs the storage of "raw" surface EMG signals (sample frequency 800–200 Hz) and not only the calculated

RMS data that earlier has been a common base for further analyses. However, this is just a choice of program and data storing capacity.

The DESEPO method minimized these challenges and the results revealed that the amount of data, useful for further analyses, increased from 2.15 h to 6.6 h on an average of 60 persons due to the procedure, Table 1. Further, the reduction of valid data from the total working hour in right trapezius (15.8%) was slightly more than in left trapezius (12.8%), but more or less comparable, Table 3. Likewise, the total discarded data leveled out quite even among the standardized three brands of forest vehicles.

Facing erroneous signals off-line, the foremost question came to causative factors affecting the sEMG signal. Artifact rejection methods have mostly been tailored within individual research groups and therefore not been published (Chan and MacIsaac, 2018). Their project ‘CleanEMG’ is established while sEMG measurements have been hindered by difficulties in estimating and interpreting parameters measured at the skin surface. According to Chan, the onset of small, wireless and even wearable sEMG technology efficiently can store large data sets, therefore it is becoming increasingly important because collection of redundant data is commonplace (Chan and MacIsaac, 2018).

In the case of sEMG recording, the electrode–skin interface has a reactive impedance (Clancy et al., 2002). Although we reduced to a minimum the electrode–skin impedance, by careful skin preparation, including cleansing with alcohol prior to electrode placement, some noise will always accompany the desired signal (Clancy et al., 2002). ‘True’ sEMG signals may be either minimally or non-linearly affected by baseline noise, particularly at low contraction intensities, when signal to noise ratios (SNRs) may be lowest (Law et al., 2011). However, today's advanced technology have minimized the effects of extrinsic noise sources, such as power line and cable motion artifact, while thermal and electrochemical noise on the other hand remain unaffected (De Luca et al., 2010). Of interest, electrochemical noise is produced from fluctuations in electrical potential at the skin-electrode interface (Clancy et al., 2002) and the electromagnetic interference at frequencies other than the power line frequency, may often be present in the field (Law et al., 2011). Further, the intrinsic noise are due to physiological, anatomical and biochemical factors that vary between individuals (Reaz et al., 2006). Since active fibers and the amount of tissue between surface of the muscle and the electrode might contribute to lack of contact (De Luca, 1979; Reaz et al., 2006; Stegeman et al., 2000), we reflected on a possible effect of the Body Mass Index (BMI) close to overweight and present in all the three groups, Table 1. We believe that a general high BMI combined with long term recordings caused induced sweating and a degradation of the skin-electrode contact that produced erroneous signals.

Another methodological aspect that could be discussed is our choice of threshold for accepting an epoch reading. We argued in this protocol that more than 70% of the epoch signals should be valid readings in order to be utilized further. When it comes to the rejection of all subsequent epochs after the first rejected one, it could be argued that subsequent epochs after a period with erroneous ones, could have been accepted for further analyses. However, then we would have faced a challenge of defining an acceptable maximum length of erroneous epoch readings. The question of how reliable the later epoch values are would also have been raised. Visual analyses of all data showed just a few examples of lasting signal recovery (shown Fig. 2D) after the first erroneous epochs. These aspects lead us to the simple transparent rejection rule that was chosen.

In comparison with an earlier automatic extensive study of muscle fatigue that statistically calculated the degree of disturbances by a discriminant analysis (Kadefors et al., 1968), we assured by the flash memory card in our data logger, enabling whole-day ambulatory field recordings of raw data without any need for reduction or compression of the data, made a step forward in terms of validity and quality (Chan and MacIsaac, 2018). Power spectrum analysis of sEMG data is time consuming, what makes automatic assessment a presumption for

validity and reliability (Sinderby et al., 1995). Accordingly, independent of erroneous data or not, it is quite important to carry out an investigation to classify the actual problems of sEMG signal analysis and justify the quality of the data, the DESEPO method may represent such a range of use.

4.2. MVC values

The MVC procedure of maximum force together with the contraction of the intended muscle is a joined activity and practice reveals that there are considerable problems in actually performing this joint measuring of MVC correctly (Disselhorst-Klug et al., 2009). If we had such a contingency with this more laborious equipment during the calibration procedure, we could have visualized and thereby guided the participant how to join the electrophysiological activation of the muscle together with the mechanical force production. Therefore, to explain the incidences of periodically low MVC values, we assumed, in accordance with what seems to be the most reported fault during the MVC efforts, that opposite to the instructions given of how to perform the MVC effort, some operators activated adjacent muscles rather than trapezius (Staudenmann et al., 2010). Most importantly, since the three sEMG_{max} values were selected from the recorded readings within validated epochs, they represent valid replacements. We believe that our procedure was the only solution while the mean of the three maximum values in the valid data during the EMG recording is representative for the person who failed in the MVC procedure and therefore would not limit our study.

4.3. Conclusion

The way the DESEPO method was protocolled, allows full-work shift of quantified bilateral sustained low-level trapezius activity. By means of a trade-off of simple recording equipment and a robust analysis system, made the effects of erroneous data to a minimum. This automatic artifact rejection tool permits the field-work design that embraces the light and short-cycle work-tasks in rough environments. If we are to make progress in revealing association between temporal exposure and work-related trapezius myalgia, this methodological approach may be meaningful and could contribute to the accountability for future field-work studies. However, the approach should be further discussed.

Conflict of interest

None declared.

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