34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Evaluation of novel algorithm embedded in a wearable sEMG device for seizure detection

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Abstract— **We implemented a modified version of a previously published algorithm for detection of generalized tonic-clonic seizures into a prototype wireless surface electromyography (sEMG) recording device. The method was modified to require minimum computational load, and two parameters were trained on prior sEMG data recorded with the device. Along with the normal sEMG recording, the device is able to set an alarm whenever the implemented algorithm detects a seizure. These alarms are annotated in the data file along with the signal. The device was tested at the Epilepsy Monitoring Unit (EMU) at the Danish Epilepsy Center. Five patients were included in the study and two of them had generalized tonic-clonic seizures. All patients were monitored for 2-5 days. A double-blind study was made on the five patients. The overall result showed that the device detected four of seven seizures and had a false detection rate of 0.003/h or one in twelve days.**

Index Terms— **Epilepsy, seizure detection, tonic-clonic, GTC, surface Electromyography, sEMG, wireless device.**

I. INTRODUCTION

About 1% of the world's population suffers from epilepsy, which is defined as a brain disorder with repetitive seizures due to an abnormal excessive or synchronous neural activity in the brain [1]. If patients are medicated appropriately most become seizure free, but about one third are characterized as medically refractory patients [2], [3]. Most of these patients experience seizures with predominantly motor symptoms such as generalized tonic-clonic (GTC) seizures [4]. Epilepsy causes major societal burden [5]. GTC seizures carry major risk complications as fractures, falls, cardiac complications, cognitive dysfunctions and ultimately sudden unexpected death in epilepsy (SUDEP) [6], [7], [8]. GTC seizures may occur in situations where the patients are unobserved and consequently helpless, e.g. while alone or during sleep. Beside these complications GTC seizures cause major concern to the patients and their relatives.

One way to help the patients is through a simple alarm system, capable of detecting the GTC seizures. Such an alarm system would then alert relatives and caretakers, whenever a seizure sets in. In a previous study we found that there are significant differences between tonic seizures and the tonic phase of tonic-clonic seizures, when comparing them to simulated tonic activity [9]. Based on this knowledge we proposed an algorithm for the purpose of detecting GTC seizures [10], which seems reliable on conventional sEMG data. This algorithm has been modified and implemented in a small sEMG wireless device developed by DELTA, Denmark, on behalf of IctalCare A/S, Denmark.

Several groups (including ourselves) have attempted to develop an effective alarm system based on accelerometer data [11], [12], [13], [14], [15], but with a performance which could be improved. Our previous results [11] on conventional sEMG data (measured with standard sEMG electrodes) were promising and we expect to achieve even better results with the wireless sEMG data, due to the avoidance of artifacts from wire-pulls. We present the results of an implementation of a novel algorithm into a wireless detection device. It is able to detect most GTC seizures, with a relatively short latency and without too many false alarms. Our approach is generic and based on a single wireless device placed on the tibial muscle. The device with the algorithm implemented has for this study been tested on five patients.

II. METHODOLOGY

A. Patients

Five consecutive patients were included from the Danish Epilepsy Center in Dianalund, Denmark, for diagnostic reasons. All patients included have a history of GTC seizures. The patients's age, gender, amount of GTC seizures during the recording, duration of the seizures and the recordings are all listed in Table I.

TABLE I
THE PATIENTS'S GENDER, AGE, THE AMOUNT OF SEIZURES, THE LENGTH OF THE ADMISSION AND THE LENGTH OF THE GTC SEIZURES.

Patient	Gender	Age	# GTC	Seizure duration [s]	File length [h]
D207	F	15	0		-
D208	M	34	3	88, 77, 52	68.4
D209	M	48	0		50.1
D210	M	38	0		53.3
D211	M	44	4	100, 105, 98, 102	126

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B. Recordings

The normal admission recordings included electroencephalography (EEG), video, electrocardiography (ECG) and sEMG electrodes placed on several, clinically relevant muscles. Along with this our wireless device for measurements of sEMG was placed on a tibial muscle (left/right) as shown in Fig. 1. The choice of side for the placement of the device (left/right) was decided by the physician based on records on where each patient normally have their seizures expressed the most. The device only sets hidden alarms, which means that the staff at the hospital are unaware of the times of the alarms. The admission lasted 2-5 days depending on the patient, thus providing us with a huge amount of data for each patient. The sEMG was sampled with a frequency of 1024Hz. Two of the patients had GTC seizures, while the others had other kinds of seizures or none at all. The times for the beginning and ending of the seizures were annotated by a physician based on the gold standard (video and EEG signals). For the first patient we had some recording problems, which means that unfortunately no data have been recorded from the wireless device placed on the tibial muscle, see table I.

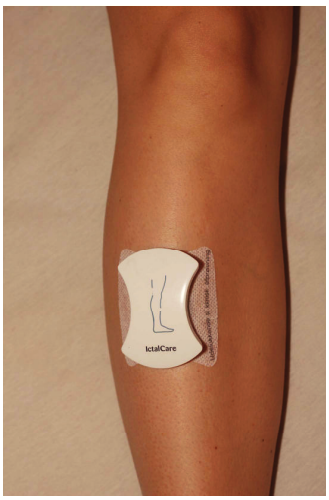

Fig. 1. The wireless sEMG device placed on the tibial muscle.

C. Algorithm implementation

The original algorithm [10] is based on a high pass filtering and a count of zero-crossings above and below a hysteresis of $\pm 50\mu$V. This count of zero-crossings is calculated for a window of 1 second and every window overlaps the previous and the next by 75%. For the algorithm to detect a seizure the count of zero-crossings should be above a threshold (first parameter) for a certain number of windows (second parameter). The two parameters (*threshold* and *number of windows*) were trained for the data on which it was intended to be used. Even though the algorithm was developed with consideration to a later implementation in a small detection device, small changes had to be made to realize the implementation. The first thing changed was the filter, since the device could not encompass a filter of the size we used in the off-line algorithm. A new filter was designed, so as it resembles the old one as closely as possible, and at the same time with an order as low as 11 (the maximum number of coefficients allowed for the filter to follow the limitations regarding the capacity of the current version of the wireless device). The off-line filter had an order of 21, which means we have lowered both the summations and multiplications with 10 in the algorithm. The filter in the off-line algorithm was a finite impulse response (FIR) hamming window filter, with the filter characteristics shown in blue in Fig. 2. The new filter was chosen as an FIR equiripple filter with order 11. This filter is shown in red in Fig. 2.

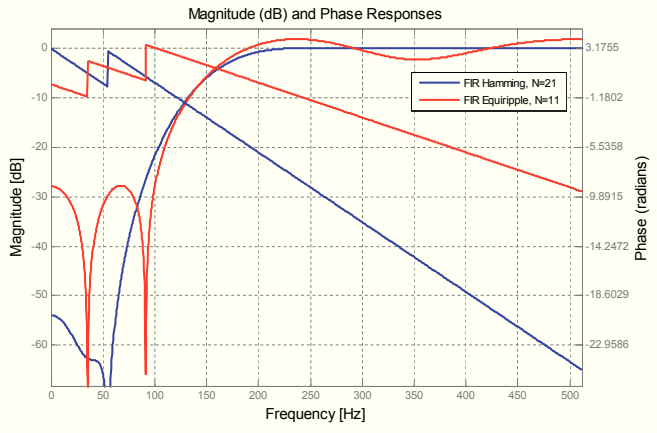

Fig. 2. The filter characteristics for the off-line filter (blue) and the new on-line filter (red) implemented in a wireless detection device.

The frequencies of interest are all above 150 Hz, where the phase is seen to be linear for both filters. For the on-line filter the equiripples make small differences in the suppression of the signal above a frequency of 150 Hz. For the frequencies below 150 Hz, a larger difference is seen, but for both filters, this part of the signal is lowered tremendously. This means, that it will be inconsiderable, when continuing with the count of zero-crossings above and below the hysteresis of $\pm 50\mu$V. Since the algorithm is to be used on sEMG from our wireless sEMG device, the parameters (*threshold* and *number of windows*) must be fitted to this exact type of data. At the time of implementation we only had data from two patients with GTC seizures. Normally we would record from both the biceps and the tibial muscle, but in the case of these two patients, unfortunately we had some technical problems with the device on the biceps, which meant that we only had sEMG data from the tibial muscle during the seizures. The parameters were trained as described in [10], from which we found the optimal parameters to be *number of windows* = 15 and *threshold* = 300. Thus the number of windows is similar to the one obtained in our off-line study [10] for the conventional sEMG data, whereas the threshold in case of the wireless device data is a bit higher than for the conventional sEMG data.

D. Data evaluation

The data were collected from the recording site and visualized through the free-ware program EDFbrowser [16]. The data files contain one vector featuring the sEMG signal and one holding a notation vector, which contains the alarm times. An example of a GTC seizure and the matching hidden alarms are shown in Fig. 3. Several alarms are shown, but in a final product only the first one will set off an actual alarm. The time for each alarm is annotated and sent to a third party, before the true seizure times are received from the recording site. This is to verify that it is a double-blind study. The results for each patient are shown in Table II.

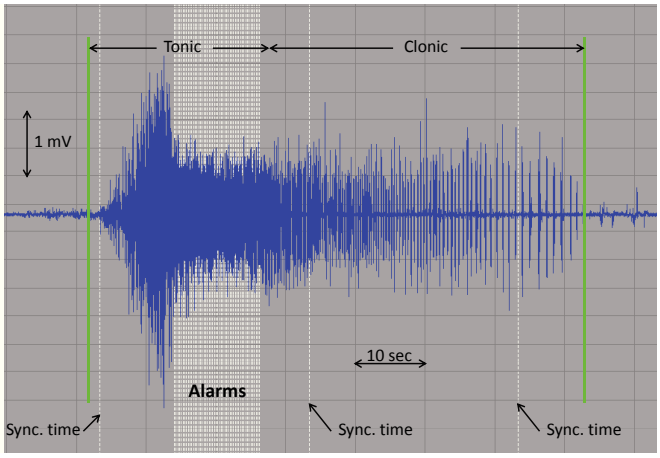

Fig. 3. The sEMG during the second GTC seizure from patient D208. The period is divided into a tonic and a clonic phase. It is seen that all the consecutive alarms are set within the tonic phase. The two green vertical lines mark the beginning and end of the seizure. The three single white vertical lines are as stated synchronization time stamps, which are set by the wireless device to keep track of the time.

For patient D207 no data are recorded on the tibial muscle. Patient D209 and D210 had no seizures, but neither did we detect any false alarms. Patient D208 had three GTC seizures during the admission, while patient D211 had four. For patient D208 we were able to detect all three seizures, and at the same time we did not register any false alarms. For patient D211 we succeeded in detecting one of the four seizures, while the other three were missed. Furthermore, we registered one false alarm for this patient.

TABLE II
THE RESULTS FOR EACH OF THE PATIENTS.

Patient	Sensitivity [%]	Latency [s]	FDR [/h]
D207	-	-	-
D208	100	31; 18; 5	0.000
D209	-	-	0.000
D210	-	-	0.000
D211	25	46	0.008
Mean	57	25	0.003

III. DISCUSSION

The device proved to function intentionally for patient D208-D210 with a 100% sensitivity and no false alarms. Unfortunately, it did not show as well a result for patient D211.

In patient D211, where the algorithm failed to detect three of the seizures, the seizures are quite different from the typical GTC seizures. These seizures consist of more interchanging tonic and clonic phases than the usual two. Furthermore each phase is shorter than during a classical GTC seizure. GTC seizures are usually fairly homogeneous, outliers like patient D211 have however previously been noticed by physicians. In Fig. 4 the count of zero-crossings during seizures are plotted for patient D200 (used for training of the parameters), D208 and D211. The features (zero-crossing) for the seizures are very much alike within each patient. It is furthermore seen that the feature for the seizures for patient D208 is very similar to the ones for patient D200, whereas the ones for D211 is seen to be very different. The algorithm detects the peak, which is seen to be both shorter and lower for the seizures for patient D211. Thus the tonic phases for patient D211 may not be long and strong enough for the algorithm to capture them. The many alternating phases of tonic and clonic activity may explain the longer latency, since there is a clonic phase before the tonic phase, where the seizures are detected. In general the latency could be improved, which is the plan for our future device. The used parameters are trained on a very narrow basis, and a modification of the algorithm towards a shorter detection time would be welcome. If the threshold was lowered to 250 (about the value for the conventional sEMG data) six of the seven seizures were captured, but the amount of false positives would also increase to seven.

Comparing the mean results in Table II (sensitivity = 57%, latency = 25s, FDR = 0.003/h) to our results on conventional sEMG data on the tibial muscle (sensitivity = 77%, latency = 14.1s, FDR = 0.2/h) presented in [10], the overall impression is an improvement, especially when taking into account that patient D211 in this study is an outlier. The sensitivity was better for the algorithm on the conventional sEMG data, but the false detection rate was significantly improved in our on-line algorithm.

If we compare our results to Kramer *et al.* [15] they have a higher sensitivity (91%). Our FDR is however slightly lower than theirs (0.004/h). Also Lockman *et al.* [14] have an interesting study with a sensitivity of 88% and 204 false positives. Unfortunately they do not list the number of hours of data which they have analyzed, but they do state, that they have a very high FDR. Our results do show a too low sensitivity compared to these studies, but if we exclude the outlier patient (D211), we would have shown a 100% sensitivity, which we expect to do for future patients with typical GTC seizures as well. Our false detection rate is the lowest of all the studies, which make our system the most reliable regarding false alarms. Since the other two methods are based on a detection in the clonic phase, compared to ours in the tonic phase, we expect to have a lower latency period.

In our previous study on the conventional sEMG data, the results showed to be significantly better for the data

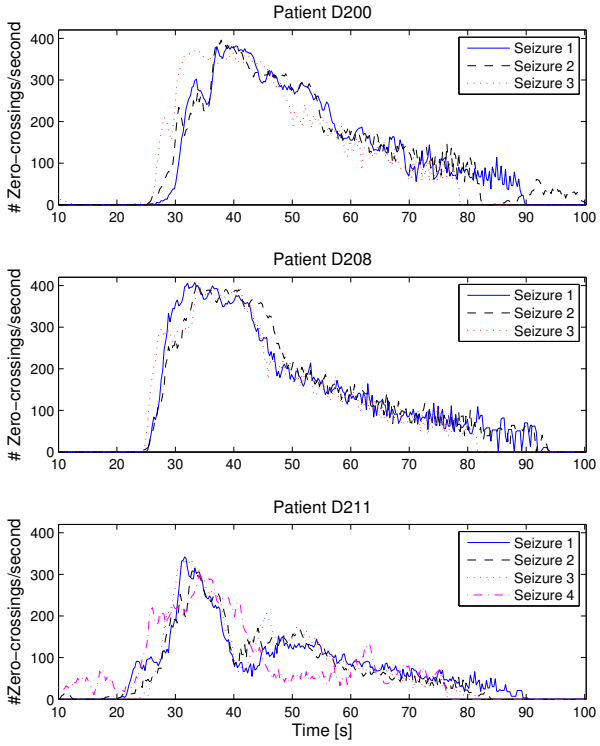

Fig. 4. The zero-crossing counts for each seizure for patient D200, D208 and D211, respectively.

recorded on deltoid, compared to those recorded from the tibial muscle. In an unpublished study we obtained the same promising results for data recorded from biceps. We therefore expect to get a better result when testing the algorithm on data from our wireless device recorded from the biceps, however firstly we need to train parameters for this, since there are differences between the two muscles with respect to using the algorithm.

The missing data for the first patient imply that we have some recording problems, which need to be clarified. It should be noticed that the used wireless device is only a prototype and the next version is in preparation. Thus the complications are expected to be corrected.

IV. Conclusion

Our wireless device with an implemented generic algorithm is the first device developed towards detection of GTC seizures based on a single sEMG channel. The algorithm detects whenever a GTC seizure starts. The results showed that the device performed as intended for three of the five patients. For one patient it failed to record any data and for another it only managed to register one of four GTC seizures. However, the FDR has proven to be extremely low, despite our huge amount of data for each patient. Furthermore we have an explanation towards the three missing detections, so we find that the results are very promising. We expect to achieve an even better result, when we test our device on sEMG data from the biceps.

V. Acknowledgements

This work was supported by the Peter & Jytte Wolf Foundation for Epilepsy, the Danish Epilepsy Centre, the Danish Agency of Science Technology and Innovation, the Technical University of Denmark, and the Danish National Advanced Technology foundation.

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