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Long-term home monitoring of hypermotor seizures by patient-worn accelerometers

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ABSTRACT

Long-term home monitoring of epileptic seizures is not feasible with the gold standard of video/electro-encephalography (EEG) monitoring. The authors developed a system and algorithm for nocturnal hypermotor seizure detection in pediatric patients based on an accelerometer (ACM) attached to extremities. Seizure detection is done using normal movement data, meaning that the system can be installed in a new patient's room immediately as prior knowledge on the patient's seizures is not needed for the patient-specific model. In this study, the authors compared video/EEG-based seizure detection with ACM data in seven patients and found a sensitivity of 95.71% and a positive predictive value of 57.84%.
The authors focused on hypermotor seizures given the availability of this seizure type in the data, the typical occurrence of these seizures during sleep, i.e., when the measurements were done, and the importance of detection of hypermotor seizures given their often refractory nature and the possible serious consequences. To our knowledge, it is the first detection system focusing on this type of seizure in pediatric patients.
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1. Introduction

Epilepsy is a serious neurological condition affecting almost one percent of the world population of which 30% suffers from refractory or intractable (uncontrollable) seizures [1,2]. In order to both assist such patients and reassure parents or caregivers, a seizure detection system is needed that can be used in a home situation. This will entail the use of long-term monitoring and creating a system that is both easy to install and as unobtrusive as possible. It would permit actions such as putting the patient in a correct position (e.g., prone to supine to prevent suffocation), stimulating the patient by e.g., rolling him or her over (passive muscle movement), cardiopulmonary resuscitation and defibrillation, medication administration, clearing of the airway, and seeking help if needed. Furthermore, it would allow the parent or caregiver to reassure the patient and to clean the bed in case of vomiting or incontinence.

The gold standard of video/electro-encephalogram (EEG) monitoring does not fulfill the above mentioned criteria. It is a short-term measurement. It is uncomfortable (electrodes attached to scalp) and professional installation and supervision are required. In addition, a system that allows automated seizure detection with sufficient sensitivity (seizure detection) and positive predictive value (PPV, false positive rejection) based on this intracerebral signal has yet to be developed.

Given that extracerebral body signals are also altered by seizures, they provide the opportunity for the development of detection systems that fulfill the home monitoring requirements and can be available sooner. The authors have experienced that the availability of commercial extracerebral seizure detection devices in Belgium is limited. Those that are available are aimed at detecting tonic-clonic seizures or 'violent movement' only. Aside from this limitation, the authors partake in the general criticism [3] that under mattress- or bed-attached systems (the most widespread) evoke many false positive alerts.

The authors consist of a multidisciplinary team composed of engineers and caregivers from different settings in Flanders, Belgium: a university, university hospitals, a university college and a rehabilitation center. The team focuses on accelerometer (ACM) [4–6] and video [7–10] recordings since they are commonly used (in other fields) for movement detection and since many epileptic seizures have a motor component, often early in the course of the event [11]. Three-axial ACM measures the acceleration in three orthogonal directions fixed to the sensor.

The authors focused on hypermotor seizures (in pediatric patients) as described below given the availability of data, their occurrence during sleep, their often refractory nature and the possible serious

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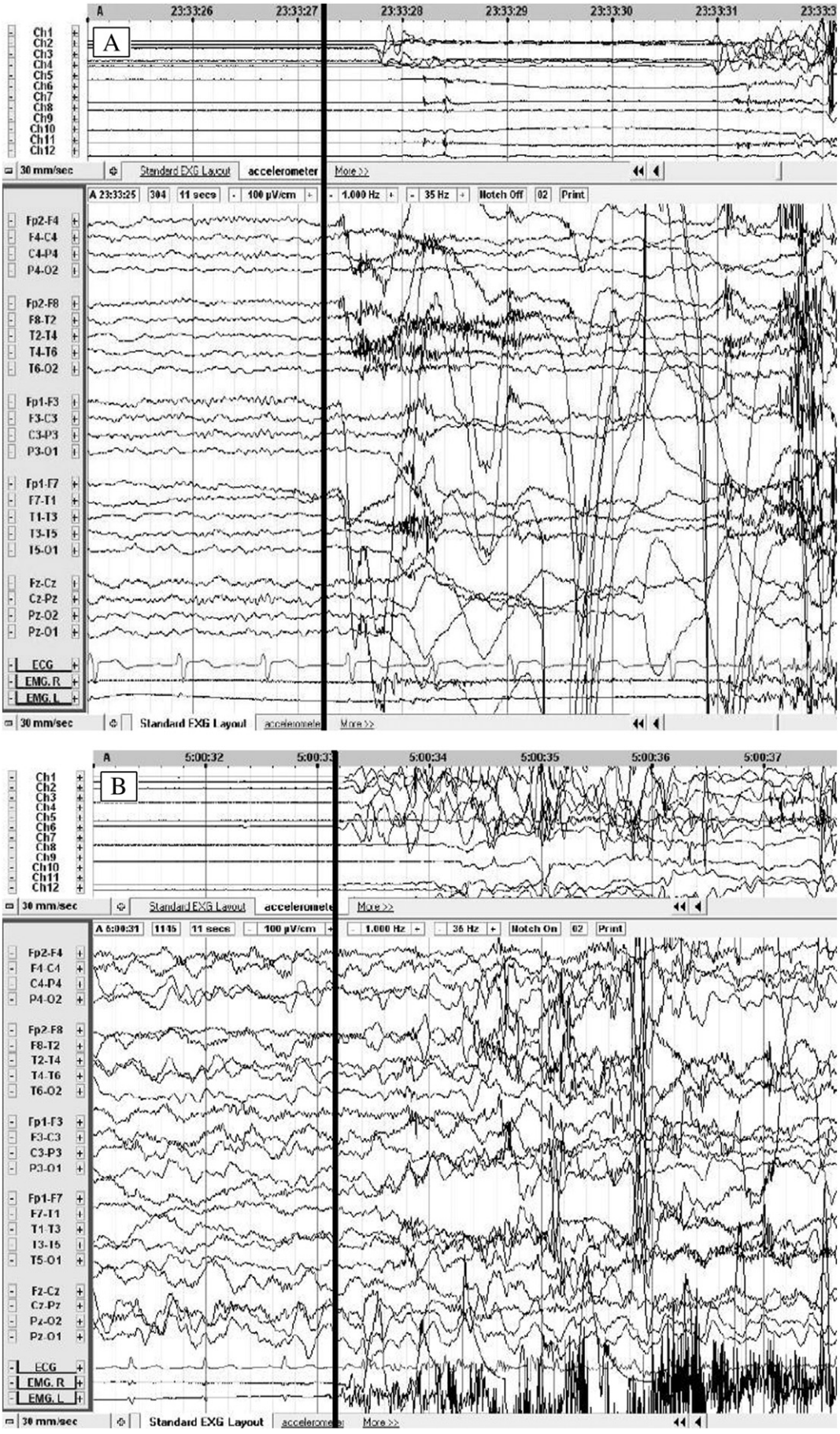
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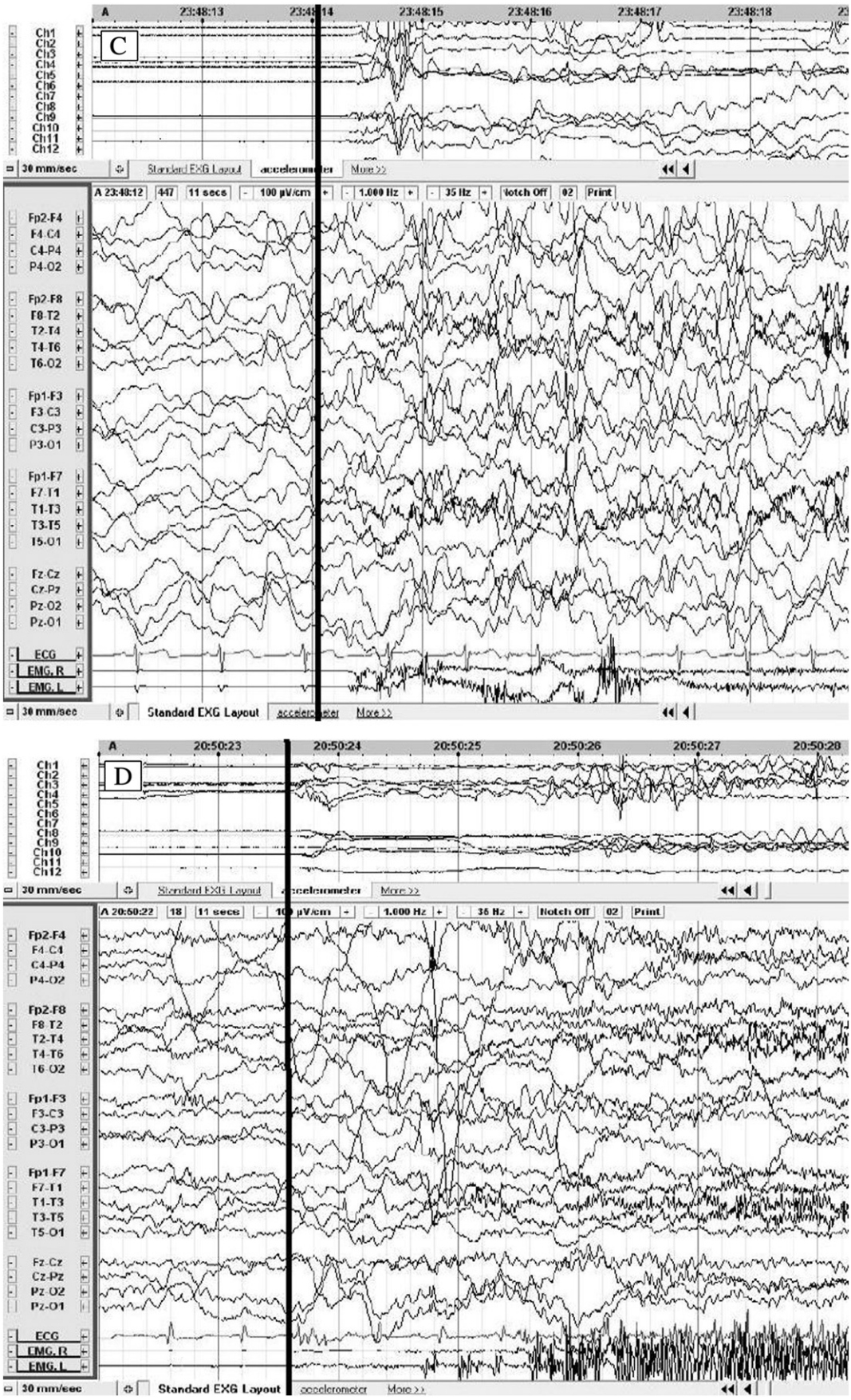

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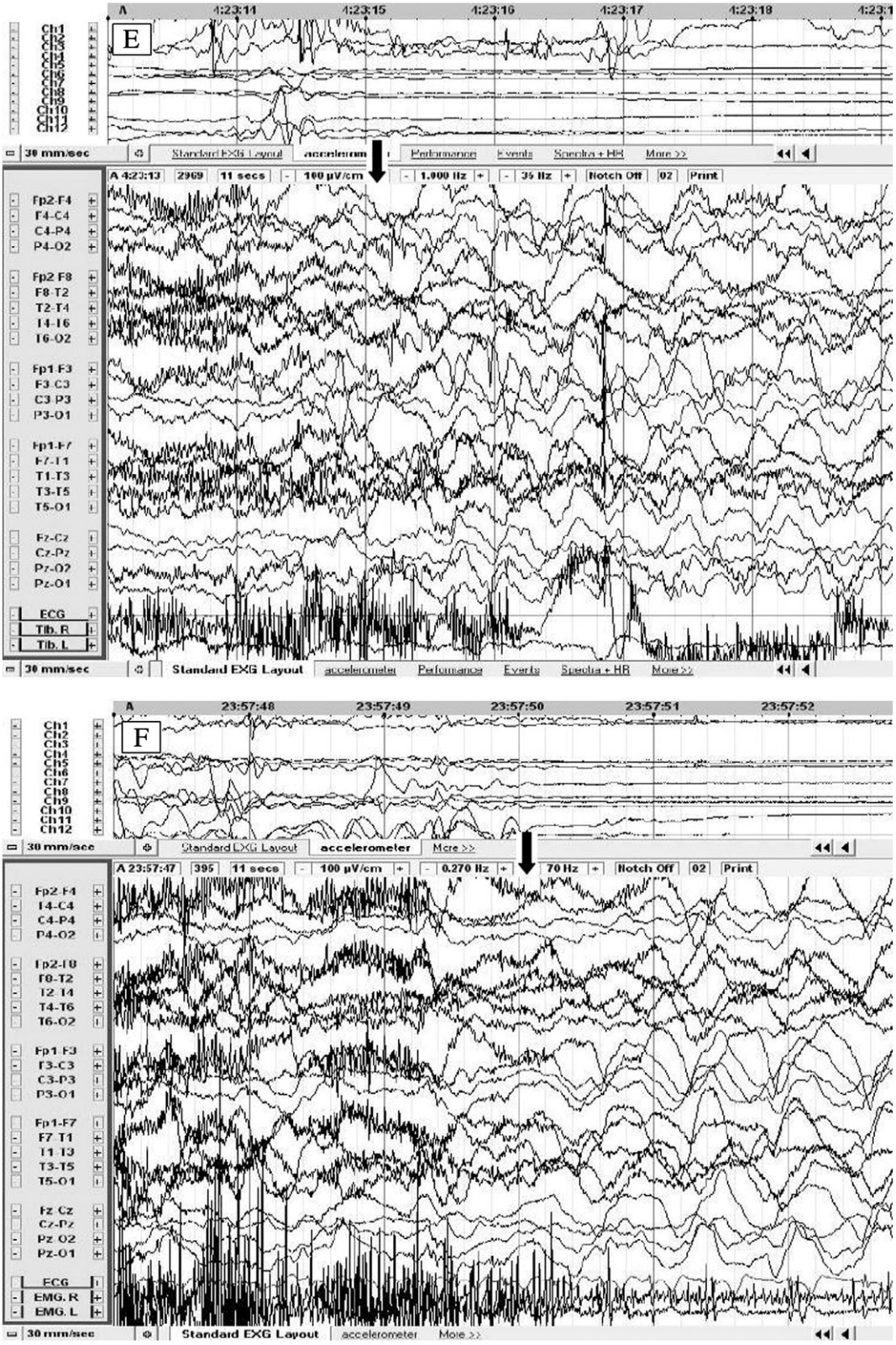

Fig. 1. Examples of (lacking) ictal EEG patterns in hypermotor seizures of the seven patients using scalp electrodes. The twelve upper channels are accelerometer signals of wrists and ankles, and the two lower channels are electromyography signals of upper arms. Seizure starts at the vertical line. Most of the time, no ictal EEG patterns are observed (A and B). Often, the patterns are very similar to arousals (theta and muscle activities, C and D). Sometimes, only post-ictal frontal slowing is seen (start at arrows in E and F). Rarely, the hypermotor seizure is preceded by a myoclonic jerk (G). The seizures were labeled based on video, EEG and medical history of the patient.

consequences such as dizziness, headache and confusion, or injuries because of the uncontrolled movements, or even death. Furthermore, hypermotor seizures are manifestations of nocturnal frontal lobe seizures, known to have subtle or absent (the latter in about 50%) ictal patterns on scalp EEG [12]. See Fig. 1 for different ictal patterns occurring in the seven patients that were monitored.

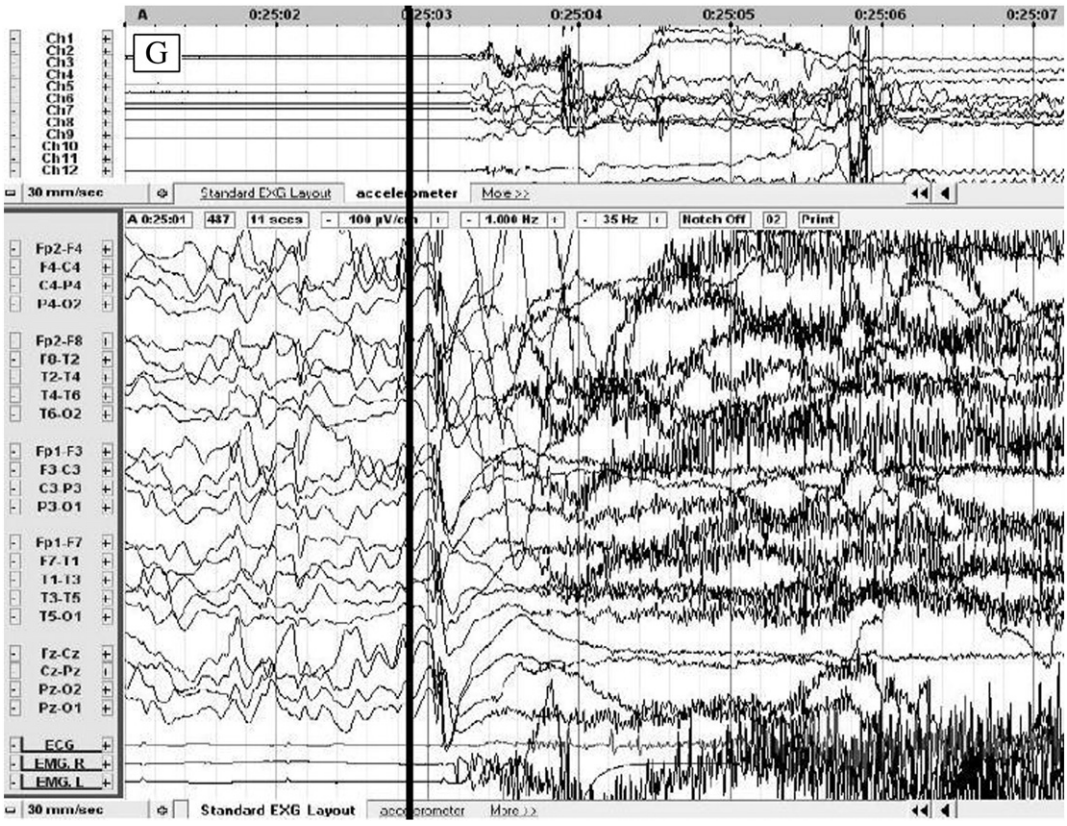

Fig. 1 (*continued*).

Hypermotor or hyperkinetic seizures are convulsive seizures with a frontal lobe onset and consist of natural movements in abnormal circumstances or with an abnormal violence or repetition, mainly including bilateral (but often not coordinated) proximal limbs or axial muscles (opposed to distal limbs and oral muscles in temporal automotor seizures), e.g., pedaling, flailing, pelvic thrusting, thrashing (swim kicking), and boxing [13–15]. The onset is often from non-REM sleep, mainly during stages 1 and 2 (at a significantly higher

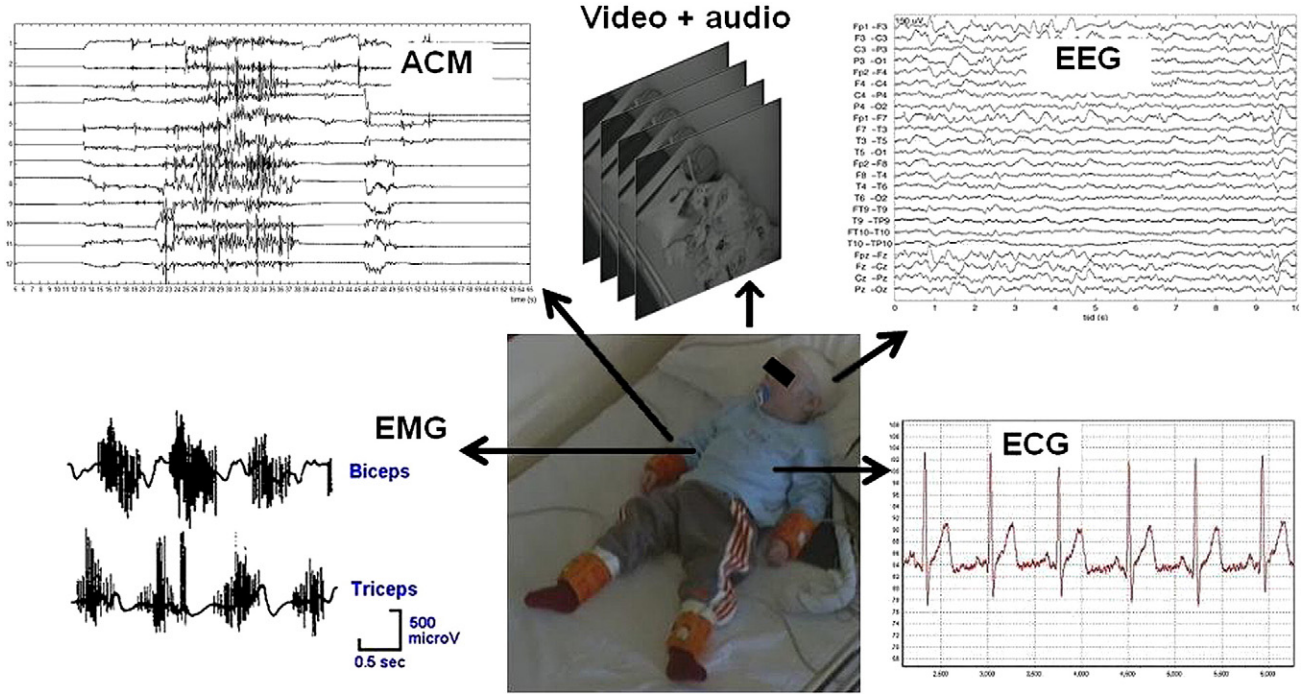

Fig. 2. Set-up of the patient while monitoring EEG (electro-encephalography), ECG (electrocardiography), EMG (electromyography, of upper arms), video, audio and ACM (accelerometry, of wrists and ankles) signals.

Table 1
Results per patient (pt). Sensitivity (sens), positive predictive value (PPV), specificity (spec) and negative predictive value (NPV) are shown together with their respective standard deviations (std). The last columns give the number of nocturnal datasets (Ds), hypermotor seizures (H) and normal movements (N) available per patient. Totals are shown in bold.

System performance											
Pt	Sens (%)	Std (%)	PPV (%)	Std (%)	Spec (%)	Std (%)	NPV (%)	Std (%)	Ds	H	N
1	100.00	0.00	48.00	11.88	92.73	3.26	100.00	0.00	1	2	117
2	100.00	0.00	59.71	26.80	93.64	5.97	100.00	0.00	2	9	287
3	100.00	0.00	64.67	21.50	95.76	3.26	100.00	0.00	2	2	439
4	100.00	0.00	60.67	21.71	95.15	2.93	100.00	0.00	1	2	239
5	70.00	25.82	55.33	27.90	94.85	4.30	98.15	1.60	5	26	784
6	100.00	0.00	57.17	20.88	93.94	5.15	100.00	0.00	2	7	381
7	100.00	0.00	59.33	19.49	94.85	3.51	100.00	0.00	2	3	468
Total	**95.71**	3.69	**57.84**	21.45	**94.42**	4.05	**99.74**	0.23	15	51	2715

frequency than and opposed to onset from later stages for arousal disorders) and stereotyped in one patient (opposed to being quite variable in arousal disorders) throughout the night, and can last from a couple of seconds to some minutes. Post-ictal confusion is often absent [16,17] which means that the patients often recall a 'strange feeling' and need comforting.

Monitoring was conducted during patient's sleep as hypermotor and other (mainly frontal lobe) [18] seizures occur mainly at night. It is also advantageous as there is less noise from voluntary movement and because seizures occur more or less in a controlled reproducible manner. Development of a nocturnal detection system is also important because of reduced or no supervision at night.

The goal of this study was to examine the added value of ACM for hypermotor seizure detection in seven pediatric patients.

2. Methods

2.1. Database

The authors have, thus far, monitored 65 pediatric patients, obtaining a total of 1020 motor seizures of different types for a period of 192 nights (typically from 20:00 in the evening until 8:00 in the morning) by EEG (electro-encephalography), ECG (electrocardiography), EMG (electromyography, of upper arms), video, audio and ACM (accelerometry, of wrists and ankles) (Fig. 2). Approval by the Medical Ethical Commission of the Antwerp University Hospital, Belgium and signed informed consent forms from all parents were obtained prior to inclusion in the study, which was performed in accordance with the 1964 Declaration of Helsinki.

The authors studied 7 patients between 5 and 15 years old at the time of measurement (between September 2007 and December 2010) and 51 hypermotor seizures (Table 1).

2.2. Acquisition system

To acquire the ACM data, the engineers developed a hardware system with four three-dimensional ACM in comfortable bands (Fig. 2), and ACM signals (Fig. 3) were recorded synchronously with the standard video/EEG recording.

2.3. Detection algorithm

After having undertaken different approaches [4–6], the current detection algorithm consists of three steps [Cuppens, K., Karsmakers, P., Van de Vel, A., Bonroy, B., Milosevic, M., Ceulemans, B., Lagae, L., Van Huffel, S., Vanrumste, B., 2012. Accelerometer based home monitoring for detection of hypermotor seizures with estimation of probability density function. submitted].

In the first step, movement epochs (epileptic or not) are detected within the ACM data. Movement events less than 30 s apart are clustered. This step reduces the data to 1.5% to 3.0% of the raw data.

In the second step, features (as described in the literature) are extracted from the movement epochs, and those with the highest discriminative power are determined. The authors preferred features that are channel independent, which resulted in obtaining the following: 1. maximum signal amplitude over both arms (so over 6 channels); 2. mean standard deviation of signal amplitude over all channels; 3. length of epoch (time); 4. mean 'root mean square' of signal amplitude over all channels; 5. minimal power in frequency band 1–3 Hz over all channels.

In the third and final step, a model is built based on normal (not labeled as epileptic based on video/EEG) movement by estimation of its probability density function (pdf) (Fig. 4) of which two parameters need to be determined: a. bandwidth which has an influence on the smoothness of the estimated distribution; and b. threshold at which normal and epileptic (seizure) movements are separated. They are determined in the *training phase*, and the patient-specific

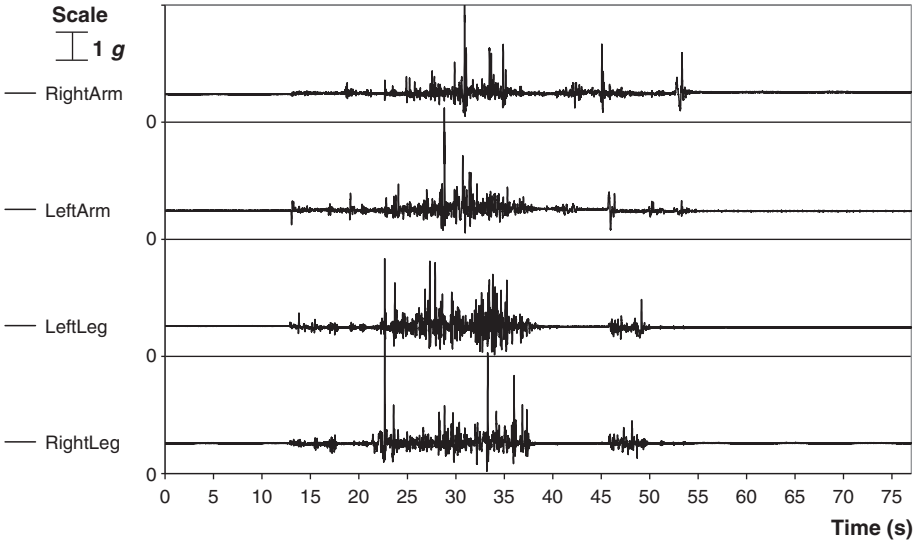

Fig. 3. Resultant of accelerometer signals per sensor.

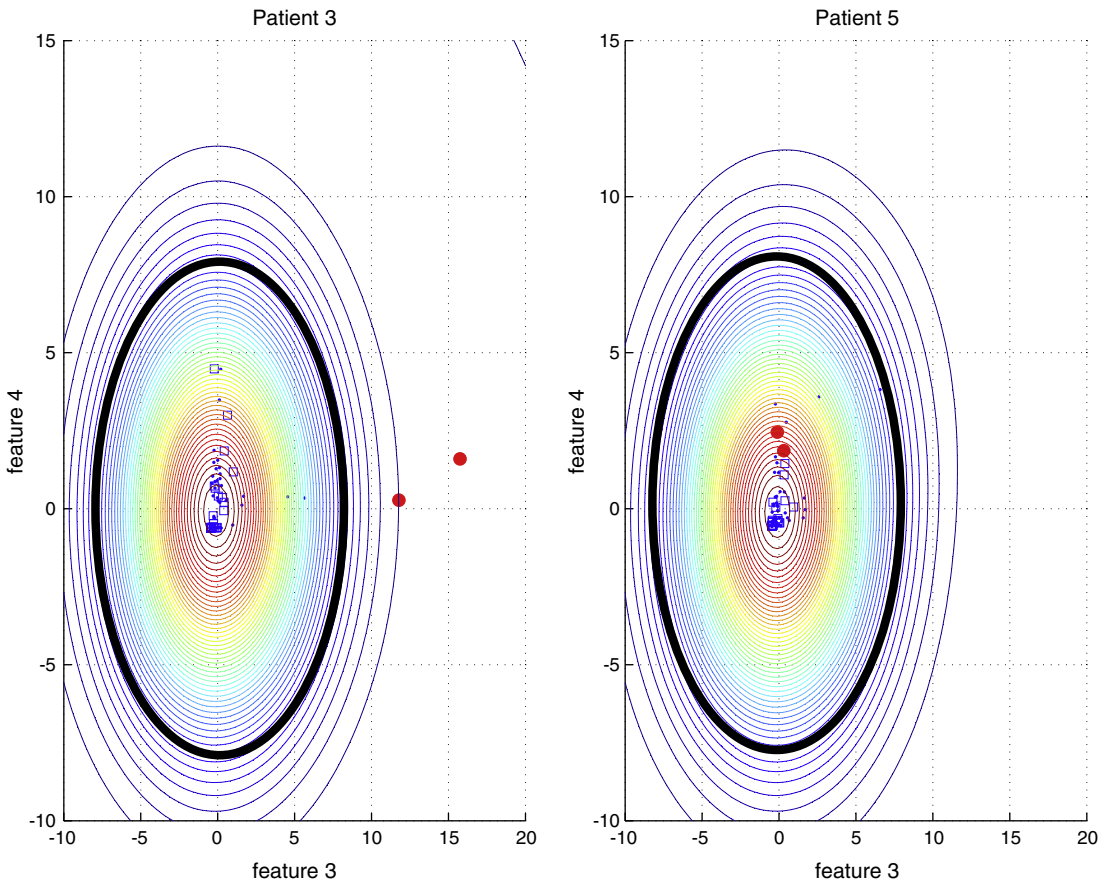

Fig. 4. Probability density functions of patients 3 and 5 for features 3 and 4. The (red) dots are the seizures in the test phase, the thin (blue) lines represent the probability density function of the normal activity. The decision line (threshold) in bold (and black) is only indicative.

pdf was constructed using 67 normal movements. In the *test phase*, 33 normal and 2 epileptic (labeled based on video and EEG) movements were used. This meant that 100 normal and 2 epileptic movements in total were used per patient.

3. Results

Positive predictive value (PPV) is calculated next to specificity, as it is more sensitive to false positives and because the data sets contain a much higher frequency of true negative than true positive events. For seizure detection systems, it is important that there are no false negatives (sensitivity 100%), and that the amount of incorrectly detected seizures is as low as possible (high PPV).

The results of the testing on 2 seizures and 33 normal movements per patient are given in Table 1. Sensitivity was 100% in all patients except patient 5, with a PPV between 48% and 65%. For patient 5, a sensitivity of 70% and PPV of 55% were observed. This resulted in an average sensitivity of 95.71% and a PPV of 57.84% over the 7 patients.

4. Discussion

There is an obvious need for ambulant alarm systems that allow for long-term and home monitoring of seizures. The authors' research contributes by focusing on hypermotor seizure detection in pediatric patients using an accelerometer (ACM) attached to wrists and ankles. The seizure detection algorithm was tested on 7 patients and 51 seizures labeled based on video and electro-encephalography (EEG) and resulted in a mean sensitivity of 95.71% and a mean positive predictive value (PPV) of 57.84%.

To explain the variability in system performance between the patients (Table 1 and Fig. 4: normal activity and epileptic seizures are well separable in patient 3 [A] while not separable in patient 5 [B]), the authors looked once again at the video recordings and confirmed a clinical difference in seizure manifestations. For example, for patient 5, seizures were short in duration and subtle in intensity. Furthermore, this patient had the most hypermotor seizures, but the five nocturnal video/EEG measurements were spread over a period of two years and eight months, which could explain the variety in manifestation of both seizures and normal activity. For the other patients, the maximum spread between recordings was two months, and the maximum period between first recording and last recording was three months.

Relatively few teams are focusing on the use of ACM solely. Nijssen et al. (the Netherlands) used it on myoclonic jerks resulting in a maximal sensitivity of 80% but with a low PPV (16% and less) [19] and on tonic seizures resulting in a sensitivity of 80% and PPV of 35% [20]. Jallon (France) investigated epileptic seizures of an unspecified type in (only) two patients, resulting in a sensitivity of 88% and 89% and a false alarm rate of 25% and 45%, respectively [21]. Schulc et al. (Austria) focused on (only four) tonic-clonic seizures and got 100% sensitivity, specificity $\geq$ 88% and PPV $\geq$ 75% [22].

Two teams have developed a ACM-based system that will soon be commercialized: Lockman et al. (US) and Smart Monitor Corporation developed the SmartWatch which was successfully tested on a group of 40 adult patients. Seven of eight tonic-clonic seizures and 204 non-seizure events were detected, but there was only one false detection during sleep [23]. Kramer et al. (Israel) and BioLert developed the watch-like Epi-Lert for tonic, clonic and tonic-clonic

seizures, and a study resulted in a sensitivity of 91% (20 detected) and 8 false positives in 1692 h (all during the day) [24].

Overall, the algorithm has been tested on a larger group of patients and/or seizures compared to all groups except Nijssen. In addition, the authors focused on a pediatric patient group and hypermotor seizures and used the method of novelty detection.

Detecting hypermotor seizures is important given their often refractory nature and possible serious consequences. Furthermore, they often occur at night during which supervision is reduced. Finally, subtle or absent ictal patterns on scalp EEG make an extracerebral detection system particularly interesting for this type of seizures. The latter and the resemblance of the clinical manifestations of hypermotor seizures to those of non-epileptic parasomnias might make it difficult to distinguish both, but the question is to what extent a differential diagnosis is needed. Many patients have overlapping disorders, and non-epileptic events might also need care.

Novelty detection is interesting in situations with very low occurrence of abnormal events: no seizures are needed and the events should not be labeled (epileptic versus non-epileptic), as all events are used for modeling normal events. This allows immediate installation of the system in a new patient's room, without prior knowledge on the patient's seizures. Only enough data to model the normal events will be needed. Group-specific information in the algorithm, i.e. a subset of normal movement from other patients, will gradually be replaced by patient-specific movements as more data is collected on that patient. Furthermore, change of (ab)normal movement over time can be taken into account by replacing older movements used for building the model by new ones. This may have been a possible solution for patient 5.

Given that the authors were working on movement detection both by ACM and video, it seemed interesting to combine and compare these different methods. The engineers are now developing a home monitoring system with these two methods incorporated that detects and stores movement recorded during the night. Running the algorithm for hypermotor seizures is done offline (not real time) at the moment. Four patients have been monitored with this system and, currently, improvements are made.

In conclusion, this study is a contribution to the development of an ambulant seizure detection system. An international multicenter study would, in the opinion of the authors, be warranted.

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