Movement-based seizure detection

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Movement-based seizure detection

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Summary
This is a critical review and comment on the use of movement detection in epileptic seizures. The detection of rhythmic movement components, such as the clonic part of tonic–clonic seizures, is essential in all seizure detection based on movement sensors. Of the many available movement sensor types, accelerometric sensors are used most often. Eleven video-electroencephalographic (EEG) and 1 field study have been carried out. The results of these clinical trials depend on the population, study design, and seizure evolution. In video-EEG monitoring units, sensitivity for tonic–clonic seizures varied from 31\% to 95\%, and positive predictive value from 4\% to 60\%. In a field trial in a residential adult population with intellectual disability, sensitivity was 14\% and positive predictive value was 82\%, whereas in patients admitted to an epilepsy clinic, a bed sensor had a sensitivity of 84\% (no positive predictive value was given). The algorithms using the “rhythmic movement” component at the end of a tonic–clonic seizure are reliable (few false-positive alarms) but miss less typical seizure patterns that are mostly present in people with associated brain development disturbances. Other modalities (heart rate and electromyography) are needed to increase the detection performance. Advanced accelerometric techniques allow us to gain greater insight into seizure evolution patterns, possibilities for neuromodulation, and the influence of antiepileptic drugs on specific seizure components.

KEYWORDS
accelerometry, epilepsy, movement, seizure monitoring

1 | INTRODUCTION

Movement is the most intuitive way to detect motor seizures, and it is the first of all nonelectroencephalographic seizure detection modalities to be widely used in clinical practice.\textsuperscript{1} Figure 1 shows an accelerometric recording of a classical tonic–clonic seizure.

The tonic phase, recognizable by a slow baseline drift at the beginning of the seizure, is followed by a rhythmic series of accelerations during the clonic phase of the seizure. In this example, the beginning of the seizure is preceded by an isolated short movement due to a myoclonus. The central theme in movement detection of tonic–clonic seizures is the rhythmicity that represents the clonic phase.

Many sensor types are available to record movement.\textsuperscript{1–4} Contact sensors, fixed on the body, are, by definition, nearer to the source of the movements and thus more sensitive than noncontact sensors, which are less obtrusive.

Validation of the sensors has been performed, primarily in video-electroencephalographic (EEG) monitoring units (EMUs), as verification with video-EEG is the gold standard. This type of verification does, however, have a

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number of drawbacks, and field studies are needed to establish the performance of sensors in clinical practice.

An important but underestimated research area is the detailed, more experimental, analysis of the semiology of the various types of motor seizures.\textsuperscript{5–7} This requires a special setup but may reveal unusual seizure patterns, not only limited to elementary movement patterns—myo(clonic), tonic—but also including more complex hyperkinetic and other stereotyped movements.

Although movement analysis has been shown to contribute to the detection of epileptic seizures, it has become clear that movement, the first of all non-EEG modalities, has several successors, such as heart rate, electromyography (EMG), skin conductance, and respiration-related signals, which have complementary properties. Although future sensors will combine more members of this family, movement analysis is likely to remain an essential and stable component of future devices that detect epileptic seizures.

2 | BACKGROUND OF RHYTHMIC MOVEMENTS DURING EPILEPTIC SEIZURES

The elementary motor components of seizures (myoclonic, clonic and tonic, International League Against Epilepsy classification of 2017\textsuperscript{8}) differ from each other in the frequency of the “epileptic” impulses from the brain to the muscles. Due to the mechanical inertia of the musculoskeletal system,\textsuperscript{5} low-frequency impulses (<6 Hz) will lead to isolated (myoclonic) or rhythmical (clonic) jerks, whereas the high-frequency ones (>10 Hz) are visible as “continuous” muscular (tonic\textsuperscript{6}) contractions. This phenomenon is comparable to the distinction between a series of photographs and a movie.

The rhythmic clonic movement pattern during tonic–clonic seizures (see Figure 1 and Figure S1) is the cornerstone of movement and seizure detection in most systems. It is the most specific and easiest to recognize sign during these seizures (see the section on clinical trials). The differences between the various systems are mainly determined by the required duration of the rhythmic movements, varying from 2 seconds during video analysis\textsuperscript{9} to 10-16 seconds in current bed sensors (Emfit,\textsuperscript{10} Epi-Care). An interesting phenomenon, the systematically decreasing frequency of the jerks during the clonic phase,\textsuperscript{11} has not yet been used in current movement sensors.

**FIGURE 1** A 3-dimensional accelerometric “fingerprint” of a tonic–clonic seizure preceded by an isolated myoclonia. The last part of the seizure (starting at 20 seconds) is the clonic phase; this is used for the detection of “rhythmic movement” episodes. The y-axis represents the acceleration (A) of the x-, y-, and z-axes in gravity units.
Types of Movement Sensors

The most frequently used sensors are accelerometers (Table 1). Some examples and references to their websites and manufacturers are shown in the supporting material (Figure S2).

Accelerometers are easy to fix on the body and hardly ever fail to provide an adequate signal (ie, suited for analysis). Because tonic–clonic seizures have a generalized character and the arms move more prominently than the legs (Figure S3) due to the organization of the pyramidal tract, one sensor on one arm is sufficient. Almost invariably, 3-dimensional accelerometers are used, measuring 3 movement axes (Figure 1). Placement at the wrist is often considered adequate, but pilot experiments for our new multimodal device showed that the upper arm is more suitable because of fewer disturbances by small voluntary movements that cause noisier signals.

Magnetic sensors can identify the direction of the movement, but these sensors are almost exclusively used for experimental movement analysis.

Piezoelectric sensors are frequently used in the form of bed sensors placed under or sometimes on top of the mattress. They are less obtrusive but also less sensitive than the accelerometers because of the distance from the body. Furthermore, the varying thickness of the mattress makes their response less predictable.

EMG is a special case because it does not measure movement itself, but the muscular activity that initiates it. EMG is important in measuring epileptic seizures; it is very sensitive to tonic contractions and complementary to the detection of rhythmic (clonic) movements by the other sensors. For a review of the value of EMG in epilepsy see Beniczky et al.

The noncontact sensors “video” and “radar” allow movement detection by analysis of the optic flow signal or of the variation in reflections. The algorithms to extract the movements are comparable to those for accelerometry or bed sensors, because rate and amplitude of the signal variations are the primary detection parameters. Video and radar are the least obtrusive of all sensor types.

Clinical Trials on Seizure Detection Using Movement Sensors

We performed a systematic review of current non-EEG detection systems. Of the selected studies (n = 15), 11 used movement analysis: accelerometry (n = 7) and piezoelectric bed sensor (n = 4). As a measure of specificity, positive predictive values (independent of time) or false alarm rates (time dependent) are used but not usually both, which makes comparisons across studies more difficult.

Most studies were carried out in EMUs and focused on generalized tonic–clonic seizures with sensitivities around 90% and false negative alarm rates ranging from 1 to 10 per 24 hours. The duration of these EMU trials is limited to <1 week, which is too short for chronic monitoring studies. EMU populations are highly selected, the majority of patients being epilepsy surgery candidates with focal, often temporal lobe, seizures, sometimes evolving into bilateral tonic–clonic seizures. Studies over a longer period (weeks to months) in patients with a high sudden unexpected death in epilepsy (SUDEP) risk, including video as reference standard and a variety of different seizure types, are scarce. In these patients, seizure evolution is much more variable than in EMUs.

Table 1

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Movement</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact sensor</td>
<td>Obtrusive</td>
<td></td>
</tr>
<tr>
<td>Accelerometer</td>
<td>Acceleration</td>
<td></td>
</tr>
<tr>
<td>Magnetic sensor</td>
<td>Direction</td>
<td></td>
</tr>
<tr>
<td>Electromyography</td>
<td>Muscle tone</td>
<td></td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>Pressure</td>
<td>Unobtrusive</td>
</tr>
<tr>
<td>Noncontact sensor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Video</td>
<td>Optic flow</td>
<td></td>
</tr>
<tr>
<td>Radar</td>
<td>Reflections</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2

Evolution of motor seizures in persons with an intellectual disability. Simple, only 1 characteristic motor element was present during each seizure; composed, more elementary motor components were present during each seizure. The y-axis represents the number of epileptic seizures. Adapted from Nijsen et al.
It is to be expected that population differences will influence the performance of the movement sensors. Table 2 shows the performance of movement sensors tested under various conditions.

Sensitivities of movement sensors are high for most trials in EMUs, with reasonable false alarm rates and positive predictive values. This only holds for generalized tonic–clonic seizures and is only demonstrated in EMUs. In a large, as yet unpublished field study of the Emfit bed sensor, we found a low sensitivity (median = 21%, 95% confidence interval [CI] = 13%-33%), good positive predictive value (82%, 95% CI = 51%-88%), and reasonable false alarm rate per night (median = 0.30, 95% CI = 0.19-0.55).12,13 In a recently published study,14 the Emfit sensor performed well in patients admitted to a Scottish epilepsy clinic (42 of 50 tonic–clonic seizures detected).

Caution is, therefore, warranted when extrapolating results from short-term clinical trials in EMUs to other populations with different seizure semiologies and long-term usage of the detection systems. Results from clinical studies confirm the potentially high positive predictive value that is possible with accelerometric12 or piezoelectrical13 sensors compared to EMG analysis.14 The required duration of the rhythmical movements is critical. In a residential population (28 patients for a period of 2-3 months) Arends J (unpublished data) found that no false alarms were generated by the software of a piezoelectric bed sensor when warning after a minimum rhythmic movement duration of 15 seconds. In a sample taken from the same population, Geertsema et al9 found that video analysis with a minimum rhythmic movement period of 2 seconds was associated with a significant number of false alarms (0.78 per night).

The large heterogeneity of trials has led to the introduction of new standards of clinical trials for seizure detection.20 Key features in future studies are subjects, recordings, data analysis, alarms, and reference standard. Together with the outcome measures, this results in a proposal for 5 phases of seizure detection studies.

### EXPERIMENTAL MOVEMENT ANALYSIS

Experimental, more analytical, movement analysis is mostly carried out using multiple accelerometers (at all limbs and the trunk) together with video-EEG and electrocardiographic recordings (Figure S4). Other modalities, such as EMG, may be added. In the studies by Nijsen et al,5,6,19 we started with a visual analysis of the seizure patterns, which is needed for an accurate annotation of the seizures (Figure S4).

### TABLE 2 Performance of movement sensors tested under various conditions

<table>
<thead>
<tr>
<th>Number of patients</th>
<th>Seizure type</th>
<th>Seizure number</th>
<th>Sensitivity, %</th>
<th>PPV, %</th>
<th>Trial design</th>
<th>Population</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Video-EEG unit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bed sensor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poppel 201310</td>
<td>45</td>
<td>tc</td>
<td>29</td>
<td>79</td>
<td>?</td>
<td>prosp.</td>
<td>Children</td>
</tr>
<tr>
<td>Wrist watch (accelerometer)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beniczky 201314</td>
<td>73</td>
<td>tc</td>
<td>39</td>
<td>91</td>
<td>0.2</td>
<td>prosp. DB</td>
<td>6-68 y</td>
</tr>
<tr>
<td>Cuppens 201415</td>
<td>7</td>
<td>hk</td>
<td>?</td>
<td>95</td>
<td>60</td>
<td>Children</td>
<td>4 sensors (limbs)</td>
</tr>
<tr>
<td>Lockman 201116</td>
<td>40</td>
<td>tc</td>
<td>8</td>
<td>88</td>
<td>?</td>
<td>prosp.</td>
<td>3-85 y</td>
</tr>
<tr>
<td>Patterson 201517</td>
<td>41</td>
<td>tc</td>
<td>51</td>
<td>31</td>
<td>?</td>
<td>prosp.</td>
<td>5-41 y</td>
</tr>
<tr>
<td><strong>At home (video control)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bed sensor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arends 2017*</td>
<td>28</td>
<td>tc</td>
<td>289</td>
<td>14</td>
<td>0.3</td>
<td>prosp. B</td>
<td>Adults (ID) Multimodal</td>
</tr>
</tbody>
</table>

B, blinded; DB, double blinded; EEG, electroencephalography; FAR, false alarm rate (false alarms per 24 hours); hk, hyperkinetic; ID, intellectual disability; PPV, positive predictive value; prosp., prospective; tc, tonic–clonic; ?, unknown.

*Unpublished data; for preliminary data, see Cluitmans et al.13

### TABLE 3 Performance of models of elementary motor seizure patterns

<table>
<thead>
<tr>
<th>Movement type</th>
<th>Sensitivity, %</th>
<th>PPV, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myoclonic</td>
<td>Nijssen 20105</td>
<td>80</td>
</tr>
<tr>
<td>Nijssen 20086</td>
<td>80</td>
<td>35</td>
</tr>
<tr>
<td>Hyperkinetic</td>
<td>Van de Vel 20137</td>
<td>96</td>
</tr>
<tr>
<td>Summary</td>
<td>High</td>
<td>Low/moderate</td>
</tr>
</tbody>
</table>

PPV, positive predictive value.
This recording method is well suited to the analysis of seizures with complex movement patterns (hyperkinetic seizures\(^7\)) or a short duration. Also, models of elementary motor seizure patterns can be tested (tonic\(^6\) or myoclonic\(^5\) seizures). The results of these analyses are summarized in Table 3.

Myoclonic movements showed a very low positive predictive value, which has, until now, precluded clinical application. Tonic movements are suited to accelerometric detection, but due to the small accelerations, 4 sensors, 1 on each limb, remain necessary for meaningful results.\(^6\) Complex, hyperkinetic movements showed the best results, making them suitable for accurate detection with a minimum of 2 sensors.

Seizure evolution can also be studied in detail. Nijsen et al\(^{19}\) (Figure 2) showed a variable evolution of motor seizures in a residential population with an intellectual disability. Among tonic seizures, 80% had a composed character with a myoclonic or clonic component. Among tonic–clonic seizures, 40% showed additional components, such as an initial myoclonia (see Figure 1). These atypical seizure evolutions may interfere with movement detection based on fixed algorithms.

Potential applications of experimental movement analysis may be:

1. Preventive intervention (inhibitory central feedback\(^{21}\)). If a myoclonus precedes a tonic–clonic seizure (Figure 1), the interval between the myoclonic event and the start of the tonic phase can be used for inhibitory central electrical stimulation. The performance of detection of myoclonic movements has to improve substantially for this application.

2. Measurement of specific antiepileptic (drug) effects, such as reduction of tonic but not myoclonic seizure phases by sodium channel blockers. One might expect an inhibition of tonic phases of seizures by sodium-channel blockers without or with limited effect on (myo)clonic seizure components. Appropriate accelerometric seizure detection techniques might allow us to measure this effect. It may also be clinically relevant that shortening of the tonic phase of a tonic–clonic seizure without complete seizure abolition might effectively reduce clinical complications such as SUDEP.

Only a few centers have carried out experimental movement analysis of epileptic seizures. We believe that this type of research deserves more attention.

6 | CONCLUSIONS

The detection of rhythmic movements components, such as the clonic part of tonic–clonic seizures, is essential in all movement sensors. Accelerometric (around the arm) and piezoelectric sensors (in the bed) are used most often. Variation in the required length of the rhythmic component is an important cause of performance differences. The results of clinical trials are variable depending on the population, study design, and seizure evolution patterns. Sensitivities of detection of tonic–clonic seizures in EMUs vary from 31% to 95%. Multimodal detection may be necessary to overcome the limitations of the detection of rhythmic movement patterns. Advanced accelerometric techniques allow us to gain greater insight into seizure evolution patterns, possibilities for neuromodulation, and the influence of antiepileptic drugs on specific seizure components.

ACKNOWLEDGMENT

I would like to thank the members of the Dutch Tele-Epilepsy Consortium for the work\(^{1,5,6,11,14,21–23}\) on which this paper is based.

CONFLICT OF INTEREST

The author is part of the Dutch Tele-Epilepsy Consortium, which has an agreement with Livassured, the company developing the Nightwatch device, a multimodal seizure detector based on heart rate and (accelerometric) heart rate analysis.\(^{1,2}\) Livassured has obtained an exclusive license for future commercial exploitation of the data. No one from the Tele-Epilepsy Consortium, including the author, has any direct financial links with LivAssured, or holds shares. We confirm that we have read the Journal’s position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

REFERENCES


