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Review

Safe and sound? A systematic literature review of seizure detection methods for personal use

Caryn Jory [a], Rohit Shankar [a,b,*], Deborah Coker [c], Brendan McLean [d], Jane Hanna [e], Craig Newman [c,f]

[a] Cornwall Partnership NHS Foundation Trust Chy Govenek, Threemilestone Industrial Estate Truro TR4 9LD
[b] Exeter Medical School
[c] Plymouth Hospitals NHS Trust
[d] Royal Cornwall Hospital Trust
[e] SUDEP Action Charity
[f] Plymouth University

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ABSTRACT

Purpose: The study aims to review systematically the quality of evidence supporting seizure detection devices. The unpredictable nature of seizures is distressing and disabling for sufferers and carers. If a seizure can be reliably detected then the patient or carer could be alerted. It could help prevent injury and death.

Methods: A literature search was completed. Forty three of 120 studies found using relevant search terms were suitable for systematic review which was done applying pre-agreed criteria using PRISMA guidelines. The papers identified and reviewed were those that could have potential for everyday use of patients in a domestic setting. Studies involving long term use of scalp electrodes to record EEG were excluded on the grounds of unacceptable restriction of daily activities.

Results: Most of the devices focused on changes in movement and/or physiological signs and were dependent on an algorithm to determine cut off points. No device was able to detect all seizures and there was an issue with both false positives and missed seizures. Many of the studies involved relatively small numbers of cases or report on only a few seizures. Reports of seizure alert dogs are also considered.

Conclusion: Seizure detection devices are at a relatively early stage of development and as yet there are no large scale studies or studies that compare the effectiveness of one device against others. The issue of false positive detection rates is important as they are disruptive for both the patient and the carer. Nevertheless, the development of seizure detection devices offers great potential in the management of epilepsy

1. Introduction

One of the most disabling aspects of epilepsy is the unpredictability of epileptic seizures. During a seizure a person is generally unaware and unable to call for help. Many people with epilepsy or their carers keep seizure diaries, but there is a difference between recording and detecting seizures and diaries have been shown to be rather unreliable [1]. However, the use of a detecting devise linked to an electronic diary could be of practical benefit for the seizure management. The aim of this study is to systemically review the quality of evidence supporting seizure detection devices.

2. Theory

Seizure detection studies have focused on detecting physiological changes that occur before and during a seizure. Such as increased cerebral oxygen levels, alteration of movements, heart rate changes, electrical activity in muscles and changes in galvanic skin resistance. In addition there are also studies of dogs that appear to detect seizures. This review paper describes studies that have practical implications for clinical practice.

* Corresponding author. Tel.: +44 1872221553.
E-mail address: Rohit.shankar@nhs.net (R. Shankar).

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3. Material and methods

A literature search was carried out using the search terms: epilepsy, epileptic, seizure, alarm, monitor, device, sensor, safety, protection, mobile/smart phone, pillow, mat, mattress, physiologic, accelerometer, home, community, moisture, technology. The following databases – Medline, Cinal and Embase were used for this review. In addition 9 organisations were contacted for details of any relevant studies. Only one organisation provided a further study that was not included in the original literature search. Altogether, 120 studies were examined. 68 of the papers were excluded from the review because they involved the use of scalp electrodes to continuously record EEG data. Not only was this very intrusive and impractical for everyday life but the majority of patients would refuse to wear on a long term basis [2]. Similarly 4 studies were excluded because they involved implanted devices and were not relevant for most people with epilepsy.

The remaining 48 studies were then assessed using the guidance of the PRISMA [3] on the following 5 criteria for inclusion in this review:

1. use of control cases
2. confirmed diagnosis
3. 10 or more cases
4. identification of false positives
5. quality of life mentioned

The criteria was decided and confirmed by an expert focus group. None of the studies met all 5 of the inclusion criteria, but 19 met at least 3 and form the basis of this review. A further 16 studies were included because they added interesting information even though they failed to meet the inclusion standard. They are marked in the text with an asterisk.

4. Results

4.1. Movement sensors

A pressure sensor mat is placed under the sheet or mattress to detect abnormal movement or absence of movement. They can usually be adjusted to allow for the patient's weight and for normal sleep movements. Nevertheless they were very variable in their success in detecting seizures. The most successful device ($n = 79$) detected 89% of tonic clonic seizures [4]. But another study detected only 30% of nocturnal tonic clonic seizures ($n = 45$) [5]. In a study comparing two seizure movement alarms corroborated by vEEG, one alarm didn't detect any nocturnal seizures whilst the other detected 66% ($n = 15$) [6].

The specificity of movement monitors is questionable. One study ($n = 64$) recorded 269 false positive results [7]. While another study noted numerous false alarms and 28 patients had to be excluded from the study due to faulty sensors, false positives and difficulties differentiating seizures from movements associated with getting out of bed [4].

In spite of these problems, this type of sensor is currently the first choice for many people, perhaps because of its simplicity [8]. A study carried out by the Maxwell Muir Foundation found that 90% of parents were satisfied with bed sensors for their children and believed that most seizures were detected in spite of false alarms (Panwar, unpublished) [40].

4.2. Accelerometers

An accelerometer is a device that measures both motion and changes in velocity in either 2 or 3 dimensions. For example, smart phones have a 3-way axis which detects when they are tilted, rotated, or moved. A study [9] pointed out that vEEG was too uncomfortable for long term use and that wearing small accelerometers on the limbs was user friendly and able to provide long term monitoring of tonic clonic seizures. A sensitivity of 95% was observed in a study ($n = 7$) using four accelerometers, but with noticeable inter-patient difference [10]. This was supported by the finding of another study ($n = 73$) which showed a sensitivity of 91% using a single wrist worn unit [11]

The specificity and sensitivity of an accelerometer is dependent on the associated algorithm to analyse the rate, amplitude, intensity, duration and rhythm of the motor component of the seizure and it has been suggested that a minimum of two accelerometers are needed to reliably detect nocturnal convulsive seizures [12]. However it was reported on a commercially available smart watch that could be worn on any limb and had the advantage of communicating with a smartphone via Bluetooth and the ability to set the sensitivity [13]. 15 patients were monitored with vEEG and all generalised tonic clonic seizures (GTCS) were identified. A similar set up with a single wrist attached device and vEEG monitoring detected 87% of GCTS but with multiple false positives [14]

Most studies report on small numbers of cases with variable specificity (correctly identifying genuine seizures). Ceulemans et al. [15] noted a specificity of 84% ($n = 3$) with clearly marked motor manifestations in their nocturnal seizures, but Van De Vel et al. [16] noted a specificity of only 58% for nocturnal hyper motor seizures in seven patients. In a larger study of 49 patients Van De Vel et al. [17] found that no parameter setting was 100% sensitive or specific for all patients. They observed a specificity between 35% and 100% in detecting seizures.

False positive rates also vary. Beniczky et al. [11] observed a very low false positive rate of once every 5 days ($n = 73$) while Sabesan et al. [18] found a higher mean false positive of 2.1 per night in a multi-modal device incorporating both an accelerometer and ECG. The speed of seizure detection is also an important factor and Kramer et al. [19] found that 91% of seizures were detected within a median period of 17 s, and all events were identified within 30 s.

4.3. Devices that measure physiological change

Seizure onset can be detected by changes in the autonomic nervous system [20]. A pilot study by Poh et al. [21] observed that epileptic seizures induce a decrease in skin resistance due to increased sweating. A further study based on galvanic skin resistance and accelerometers in seven patients found that the device detected 94% of the generalised tonic clonic seizures (GTCS) with a false positive rate of 0.74 per 24 h. [22]

Seizure detection using heart rate has been observed to correlate well with electrocorticoencephalography (ECoG) However, this varied from person to person and its clinical relevance is unproven [23]

Physiological signals of movement and heart rate were assessed for home seizure detection in 92 patients, but a high sensitivity was found to be necessary for algorithms to be implementable [24]. Kroner et al. [25] measured heart rate, respiration and electromyography ($N = 7$) and concluded that cardiac parameters alone were able to identify 100% of GTCS and 94% of myoclonic seizures. Other physiological approaches for detecting seizures have been investigated such as the use of an apnoea device worn over the trachea which identified 88% of sleep apnoea events in 10 subjects and a specificity of 99% (Rodruigez-Villegas et al., 2014) [39].

4.4. Electromyography (EMG)

Electromyography measures changes in the electrical activity in muscles. There is no current EMG device available for home use but the potential for this device is good with high levels of specificity. In a study of 29 subjects, corroborated by vEEG, the EMG algorithm being developed detected all GTCS within 30 s with no false positives [26]. In a larger study of 118 people a similar high level of specificity was observed. The Sensitivity was comparable to United States Federal Drug Agency cleared, automated EEG seizure detection algorithms [27].

4.5. Video and infrared devices

Chan et al. [28] concluded that video monitoring for seizure detection is feasible but needs further development ($n = 5$). A study of video surveillance by Cuppens et al. [29] specifically looked at the detection of nocturnal myoclonic jerks in 8 subjects and found a sensitivity of over 75% but this was uncorroborated by EEG. The use of infrared movement monitors has been reported by Shankar et al. [30] Shankar et al. [31]. They found that movements correlate well with carer reports of seizures ($n = 5$). A study that measured changes in haemoglobin oxygenation using infrared spectroscopy was found to be unsuitable for seizure detection [32].

4.6. Seizure alert dogs (SAD)

The ability of some dogs to detect seizures minutes or hours before a seizure has been reported. A case study of an untrained pet dog reported by Lyons et al. [33] observed that the dog was able to detect seizures with 100% accuracy and no false positives. This was corroborated by EEG. Another study found 9 dogs that responded to a seizure but only 3 of these alerted to seizure onset [34]. Whether the dogs can anticipate true epileptic seizures has been questioned, since they have been observed to alert to both epileptic and non-epileptic seizures, but the same study found that patients with a SAD experience a reduction in the number of seizures. [35].

5. Discussion

Given the importance of seizure detection there is a lack of large scale studies and few that compare the effectiveness of available devices. There are a number of innovative technologies that have been considered but the findings are rarely corroborated by vEEG. Also the numbers in some of the larger studies can be deceptive. For example a study by Narachania et al. (2013) reported on 79 patients but only 18 seizures were recorded. Similarly, Carlson et al. [7] reported on 64 patients, but with only 8 GTCS recorded.

Care must be taken in the interpretation of results. For example, studies are often carried out by the team that developed the device or are sponsored by the manufacturer and the results are often favourable raising the question of possible bias. We noted that the studies are mostly confined to just a few centres with some reports using the same clinical sample in several papers. In addition, the device manufacturer's web sites may give misleading information supporting their product. For example, one website advertised a seizure alert device and cited numerous studies supporting their device but only one paper actually referred to epilepsy. Of great concern is that social media marketing of some commercial devices specify that the device is designed to prevent SUDEP without any supporting evidence.

False positives and missed seizures are an important issue, but by their nature are difficult to accurately record and some studies were not corroborated by EEG monitoring. Seizure reporting by carers may also be subjective and inaccurate which adds to the uncertainty about the efficiency of the devices. Algorithms and device design also differ widely so it is difficult to say with any certainty how effective a particular device might be for an individual patient as there was notable inter-patient difference in detection rates within some studies [36].

Although some of the studies state that the device improved quality of life, it was unclear how this was measured and frequent disturbance by an alarm at night may have a detrimental impact on patients and carers. It was interesting to note that there are no studies of a simple baby listening device or CCTV which is both cheap and readily available. These devices might offer some reassurance to parents and carers but are not yet tested for sensitivity or specificity.

5.1. Future trends

As technology advances, particularly the personal ownership of powerful devices such as smartphones and smart-watches, innovations in the self-monitoring of seizures and related variables are on the increase. For example, *Embrace*, a smart watch based App, has recently been developed to support the self-monitoring of stress and activity levels with additional claims that it can capture convulsive seizures and alert others via its link to an smartphone (www.empatica.com/embrace-watch-epilepsy-monitor). However any studies to establish this are yet to be published.

Another, newer example of using smart-watches for epilepsy is *EpiWatch*, an app designed for use on an Apple Watch with its paired iPhone (http://www.hopkinsmedicine.org/epiwatch#.Vkel7dLhBdh). EpiWatch is using Apple's ResearchKit framework to develop a multi-modal seizure detector based on seizure-related movements, heart rate changes, and patient interactions with the app. While participating in research, patients are rewarded with helpful and engaging tools to track their condition. Again research is needed to establish its advantages and disadvantages.

Although this article excluded implantable devices, livaNova/Cyberonics have recently developed a Vagal Nerve Stimulator which can be linked with an ECG to identify ictal tachycardia and provide automated therapy by stimulating the vagal nerve at a predetermined heart rate. [37]

Increased awareness of risk, including SUDEP, amongst people with epilepsy, carers and organisations is also influencing future trends on safety devices. A statement of research need on epilepsy deaths from UK research teams in 2014 flagged up detection devices that may prevent SUDEP as an important area for funding (https://www.sudep.org/statement-research-need).

Ultimately, the best protection against injury or fatality due to epilepsy is early recognition of risk and appropriate clinical intervention. *EpSMon* (Epilepsy Self-Monitor) www.sudep.org//epilepsy-self-monitor, a smartphone based App [38], provides a translation of the clinicians' SUDEP and Seizure Safety checklist https://www.sudep.org/checklist ([30], [31]) into a self-administered questionnaire, which monitors changes in risk over time, provides appropriate education and recommends clinical contact when appropriate. It works on the principle that worsening of seizures are a function of cumulative increase in seizure, biological, social and psychological factors.

6. Conclusion

The body of work in this literature review represents the best information available at this time. It is not surprising that people with epilepsy and their carers recognise the potential benefit of seizure detection devices. Appropriate communication between doctors and patients about new technologies needs to be well supported. Professionals need to be able to assess the evidence and offer realistic advice to people with epilepsy and their carers to reduce their exposure to risk. For this reason, it is important that that the available evidence on the risks and benefits of this technology is set out clearly for open access preferably via mainstream peer reviewed scientific journals.

But ultimately the choice of a device is down to seizure type, personal circumstances, lifestyle and acceptance of risk. As far as we are aware, none of the devices is registered as a medical device and although seizure alarms may offer some peace of mind, clinicians need to be clear about what the device is detecting and that seizures may be missed or falsely reported.

We conclude that it is important to exercise caution when recommending or providing a commercially available device that claims to detect seizures and to bear in mind that there is no evidence that any of them could prevent SUDEP. Care providers should also be careful when requesting a seizure alert device and advice should always be sought beforehand from an epilepsy specialist and the risks discussed and understood.

The review does not look into other related factors such as problems in practically setting up devices, recognition and addressing any malfunction and the issue of servicing the device.

In references an asterix (*) after an author's name in the text indicates that the study did not meet the criteria set for the systemic review but the paper was included because it was pertinent to the manuscript subject

Conflict of Interest

Mrs. Jory, Dr Shankar, Dr McLean, Ms. Hanna and Dr Newman all belong to organizations which have developed EpSMon a self-monitoring of risk mobile app for people with epilepsy which has been included in this review. It is important to note that the individuals and organizations involved are nonprofit organizations i.e. national health service, University and Charity. The App is free to download.

SUDEP Action has provided/will be providing financial support for the research and development of EpsMon; the SUDEP and Seizure Safety Checklist and WADD.

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Professor Stephen Brown

Appendix A

Study	Authors	Publication	Year	No	Aim of Study	Strengths/Limitations of study	Findings
Detection Of Generalised Tonic Clinic Seizures By A Wireless Wrist Accelerometer: A Prospective Multi-centre Study'.	Beniczky, S.Polster, T.Kjaer, TW. & Hjalgrim, H.	Epilepsia	2013	73	Assess the clinical reliability of a wrist-worn, wireless accelerometer sensor for detecting generalized tonic–clonic seizures (GTCS)	• A prospective double blinded multicentre study. • Ref standard was seizure identified by experienced neurophysiologists using EEG data and blinded to accelerometer data. • One wrist worn 3D accelerometer.	• 39 GTCS in 20 pts recorded and 35 detected. • 149 other seizure types did not trigger alarm • mean sensitivity of 91%. • In 16 pts all seizures detected. • Mean latency of alarm 55 seconds. • False positives 0.2 per day Tooth brushing and other voluntary rhythmic movements. • Detects GTCS with high sensitivity and specificity.
Detection of epileptic seizure using wireless sensor networks.	Borujeny et al.	Journal of medical signals and sensors	Apr-13	3	Propose a seizure detection system based on accelerometry.	• X3 2D sensors used. (arms and thigh) • Only 3 Patients • Classifies abnormal movements as seizure • Seizures uncorroborated with EEG or observation. • Used 2 different algorithms to interpret data with differing results. • May not record some types of seizures. • Must be close to the base unit (attached to wireless network)	• System can be used for patients living in a clinical environment or at their home. • Algorithm does not need to be patient specific.
Can Seizure-Alert Dogs predict seizures?	Brown SW, Goldstein LH.	Epilepsy Res	2011			• A review of the effectiveness of SAD	

Appendix A (*Continued*)

Study	Authors	Publication	Year	No	Aim of Study	Strengths/Limitations of study	Findings
* Detecting Nocturnal Convulsions: Efficacy Of The MP5 Monitor'.	Carlson, C. Arnedo, V., & Devinsky, O	Seizure	2009	64	To investigate the efficacy of the Medpage bed seizure monitor to detect generalized tonic-clonic seizures.		• Five of eight tonic-clonic seizures were detected. • There were 269 false positive alarms. • The sensitivity and specificity of the alarm were 62.5% and 90.4%, respectively. • The negative predictive value of 99.8% illustrates the potential for this device to provide additional security for patients with tonic-clonic seizures, however individual calibration would likely be necessary to improve the positive predictive value of 3.3%,
Novel Ambulatory EM-G Based GTC Seizure Detection Device For Home And Hospital Use'	Cavazos, J.Girouard, M., & Whitmire, L.	Neurology	2015	118	To validate effectiveness of a novel EM-G based real-time detection system that can be discreetly worn	• Double blind controlled trial • 6000hrs of recording • Interpretations. Viability, bias	• Sensitivity is comparable to FDA cleared automated EEG seizure detection algorithms.
Automated EMG based seizure detection and quantification for the home and the EMU, a prospective multicentre study	Cavazos et al.	Epilepsy Currents	Jan-15	26	Validate the effectiveness of a novel EMG based GTCS detection system.	• Test of a not yet fully developed system • phase 3 double blind trial. • Full study of 120 subjects not yet published • Only reviewed 1598 h (on average 61 h per subject)	• Results of Device performance and study of 120 patients not yet presented.
Detection Of Nocturnal Frontal Lobe Seizures In Paediatric Patients By Means Of Accelerometers:	Ceulemans, B. Cuppens, K. Lagae, L. Van Huffel, S., & Vanrumste,	European Journal Of Paediatric Neurology	2009	3		• Small numbers • Paediatric	• A sensitivity of 91.67% and a specificity of 83.92% • Nocturnal frontal lobe seizure detection based on three axis accelerometers attached to the wrists and ankles is reliable.
Automated Marker less Video Seizure Detection'.	Chan, D. Lu, H. Mandal, B. Ling Ng, Y., & Lung Eng, H		2012	5	To aid seizure detection in the home using automated markerless video	• Small sample • Paediatric	• prototype shows promise in the detection of seizures.
Seizure onset detection based on one sEMG channel	Conradsen et al.	IEEE Conference	Jan-11	6	To evaluate a new method to detect seizure onset of tonic clonic seizures based on sEMG DATA.	• Small numbers • Generic	• Sensitivity of 100%. • Median latency of 7.6 s. • Median false detection rate 0.04 per hour.
Seizure onset detection based on a Uni- or multi-modal intelligent seizure acquisition (UISA/ MISA) system	Conradsen et al.	Annual International Conference of the IEEE Engineering in Medicine and Biology Society	2010	?	proposed algorithm for use with EMG.	• Corroboration unclear	• Superiority of multi modal approach. • Patient specific. • Algorithm has a sensitivity of 91-100%.
Multimodal intelligent seizure acquisition (MISA) system. A new approach towards seizure detection based on full body motion measures.	Conradsen et al.	IEEE conference	2009	3	To test MISA system based on full body motion data.	• Low numbers • Simulated seizures - undefined. • Subject specific. • Not tested on people with epilepsy	• 98% of simulated seizures including 4 false alarms. • Untested on people with genuine seizures.
Evaluation of novel algorithm embedded in a wearable sEMG device for seizure detection	Conradsen et al.	Annual International Conference of the IEEE Engineering in Medicine and Biology Society.	2012	5	To evaluate a modified version of an algorithm for detection of GTC seizures into a prototype wireless service, electro myography (sEMG) recording device.	• 5 patients monitored for 2-5 days. • Small no's, • ?bias as previously had algorithm	• Device detected 4 of the 7 seizures. • False detection rate of 1 in 12days. • Patient specific.

Accelerometers-based Home Monitoring For Detection Of Nocturnal Hypermotor Seizures Based On Novelty Detection'	Cuppens, K. Karsmakers, P. Van De Vel, A. Bonroy, B. Milosevic, M. Luca, S. Croonenborghs, T. Ceulemans, B. Lagae, L.Van Huffel, S., & Van Rumste	IEEE Journal Of Biomedical And Health Informatics	2014	7	Nocturnal hypermotor seizure detection based on accelerometers.	• Paediatric study. • Low numbers • Accelerometers x 4 attached to extremities • Classifies abnormal movements as seizure • Seizures uncorroborated with EEG or observation • Patient specific modelling	• Notable inter patient difference in detection rates. • Mean performance over 7 patients sensitivity of 95.24%. • Positive prediction of 60.04%.
Using Spatio Temporal Interest Points (STIP) For Myoclonic Jerk Detection In Nocturnal Video'	Cuppens, K. Chen, C.W. Wong, K B .Van De Vel, A. Lagae, L. Ceulemans, B. Tuytelaars, T. Van Huffel, S.Vanrumste, B., & Aghajan, H	Annual International Conference Of The IEEE engineering In Medicine And Biology Society 2012,	2012		Detection of nocturnal myoclonic jerks using video. The algorithm is based on spatio-temporal interest points	• No numbers • No comparison with EEG. • Only one seizure type detected. ? Unfeasible	• with optimal parameter setting this resulted in a sensitivity of over 75% and PPV of 85% on combined patient data.
Extraction of features for myoclonic shock detection in video based on mean shift clustering for constructing motion tracks	Cuppens et al.	European Journal of Paediatric Neurology	May-11	8	Make the monitoring of epileptic children feasible in a home situation	Paediatric Small sample size. Still in development	detection via video monitor is possible
Seizure Alert Dogs: A Review And Preliminary Study'.	Dalziel, D. Uthman, B. Mcgorray, S., & Reel, R	Seizure	2003	63	Gather data on incidence of canine alerting/responding behaviour with a defined patient population	29 owned dogs of who 9 responded to seizure Review of the literature was performed. A qualitative questionnaire was completed by epilepsy patients	Findings suggest some dogs have innate ability to alert and/or respond to seizures Warrants further research to aid in the selection of patients who may benefit from seizure-assist dogs
A seizure response dog: video recording of reacting behaviour during repetitive prolonged seizures	Di Vito L et al.	Epileptic disorders, international epilepsy journal with video tape	2010	1	A case study of a not previously trained dog showing complex seizure response behaviour on home video.	• One case study	
Prospective Study Of 2 Bed Alarms For Detection Of Nocturnal Seizures'.	Fulton, S. Poppel, K V. McGreggor, A. Ellis, M. Patters, A., & Wheless, J	Journal Of Child Neurology	2013	15	To evaluate the sensitivity and specificity of the medpage bedalarms ST2 and MP5	• Small numbers • EEG records reviewed to detect any seizures missed by the bed alarms or carers records.	• In 15 patients 69 seizures were recorded by video EEG. The ST 2 didn't detect any nocturnal seizures. • The MP5 detected 1 in 15 seizures in sleeping patients (A generalised Tonic Clonic seizure.) • The Medpage alarms did not appear to adequately detect tonic clonic seizures.
EMG Based Seizure Detector: Preliminary Results Comparing A Generalised Tonic Seizure Detection Algorithm To Video EEG Recordings'	Girouard, M. Moreno, L. Morgan, L. Karkar, K. Leary, L. Lie, O., & Szabo, C.	Epilepsy Currents	2014	29	To validate an EMG- based GTCS detection algorithm to be used later in a seizure detection system.	• EMG recordings averaged 42.4 h per patient.191 seizures recorded in 29 subjects	• No false positive detections. • 84 myoclonic, 34 tonic,12 absence, 37 focal seizures with impairment and 3 seizures without impairment were recorded by VEEG and EMG but none triggered a GTCS alarm. • GTCS can be reliably detected using an arm worn device analysing EMG signals. • The sensitivity and Positive Predictive Value appears to be superior to other devices.
Seizure alarm dogs for Children's nocturnal seizures. Feasibility and consumer involvement	Jeavsons et al.	Archives of diseases in Childhood	May-12	46	To evaluate whether to pilot a study of training dogs to act as nocturnal seizure alarm dogs was feasible.	• Questionnaire on whether people had a dog or would consider having one.	• Only 35% of families asked said they wouldn't consider having a dog.
New Modified Heart rate Variability Analysis as Detector Of Epileptic Seizures'	Jeppesen, J. Beniczky, S. Johansen, P. Sidenius, P. & Fuglsang-Frederiksen, A	Clinical Neurophysiology	2014	11	Can focal seizures be detected by short term heart rate variability analysis?	• Study over 1–5 days • Focal seizures only • Small numbers	• Patient specific. • Seizure onset in certain patients can be detected by changes in the autonomic nervous system.

Appendix A (*Continued*)

Study	Authors	Publication	Year	No	Aim of Study	Strengths/Limitations of study	Findings
Exploring The Capability Of Wireless Near Infrared Spectroscopy as a Portable Seizure Detection Device For Epilepsy Patients'	Jeppesen, J. Beniczky, S. Johansen, P. Sidenius, P., & Fuglsang-frederiksen, A.	Seizure	2015	33	Evaluate the use of NIRS in patients being monitored with LT vEEG to measure changes of oxygenation and haemoglobin in rt and Lt temporal lobe.	• In development	• Did not seem suitable technology for general seizure detection given the device, settings and methods used in the study.
A Novel Portable Seizure Detection Alarm System: Preliminary Results'	Kramer, U. Kipervasser, S. Shilitner A., & Kuzniecky R.	Journal Of Clinical Neurophysiology	2011	31	To develop a small portable wearable device capable of detecting seizures.	• Small numbers -31 • 3D X1 accelerometer one wrist.	• Can identify most motor seizures with high sensitivity and low false alarm rate. • 91% of seizures within 17 seconds and all seizures. over 30 s were identified. The system failed to identify 9% of seizures. • 8 false alarms during 1692hrs of monitoring.
Physiologic sensor array to identify generalized seizures in children in a residential setting	Kroner et al.	Epilepsy Currents	2011	3	Measure the physiological responses arising from changes in the autonomic nervous system activity.	• Small sample size 3 • Drug resistant epilepsy in a residential setting • Parents given commercially available, non invasive and unobtrusive sensors. • Seizures defined by care giver observation.	• multiple physiological changes correlated with seizures. • Changes in heart rate and rhythm are key components in a seizure detection device. • Ground breaking impact with 7/7 detection of GTC and 15/16 myoclonic seizures, with detection rate of 94%. • Seizure onset detected by a direct trend in muscle activity along the muscle fibre in one patient.
Detection of seizure-like movements using a wrist accelerometer.	Lockman J., Fisher R.S., Olson D.M.	Epilepsy and behaviour	2011	40	to determine if a wrist-worn motion detector could detect tonic-clonic seizures	• Device detected rhythmic movements. • Detected non seizure movement 204 times	• Six of 40 patients had a total of eight tonic-clonic seizures. • detected 87.5% of GTCS (7 of 8) but also detected non-seizure activity 204 times but only once during sleep.
Seizure Alert Dog As An Effective 'seizure Detection Device' In Refractory Symptomatic Localisation Related Epilepsy: A Case Report'	Lyons, P. Bodamer, M. Lyons, E., & Harry, L.	Epilepsy Currents	2014	1	A case study of a puppy without any specific training was able to detect with 100% accuracy and no known false alerts	• Only one person one dog • Cost effectiveness?	• Patient and care givers reported a significant improvement in quality of life. • Dog could anticipate 100% of seizures from 10–60 min prior to clinical seizure. • corroborative evidence with ambulatory vEEG.
Towards long-term home monitoring of epileptic children	Milosevic et al.	Epilepsy Currents	Jan-14	10	The detection of motor convulsions using user friendly motion sensors	X4 3D Accelerometers attached to extremities. Low numbers x 10 Paediatric	24 clonic seizure not detected Accelerometry is capable of detecting motor seizures with a repetitive rhythm. Poor detection of more subtle seizures/ movements.
Assessment Of A Quasi-piezoelectric Mattress Monitor As A Detection System For Generalised Convulsions'	Narechania, A .Garic, I. Sen-Gupta, I. Macken, M .Gerard, E ., & Schuele, S	Epilepsy And Behaviour	2014	**79**	investigates an under-mattress device which is triggered by rhythmic motor activity of a specifiable duration, frequency, and intensity	• Only 18 GTCS recorded. • 15 months of recording. • 28 patients excluded because of faulty sensor (6 times) • Bed absence alarm was turned on and recorded data couldn't differentiate bed absence from seizure. • Sensitivity accidently increased in three patients.	• Sixteen of the 18 seizures detected (89%) resulted in activation of the device. • 21 false alarms detected. • ?reliability.
To evaluate the use and effectiveness of Seizure Alarms (bed alarm) amongst the representative paediatric population	Panwar N.	(unpublished) Maxwell Muir Trust		50	To evaluate the use and effectiveness of Seizure Alarms (bed alarm) amongst the representative paediatric population	• Questionnaire results from 50 families. • Results uncorroborated by EEG so subjective view of device	• 90% of the families found alarm to be useful. • 60% found that alarm pick up a genuine seizure at least 7 or more times out of 10. • 280% had difficulty with use of alarm. • 62.5% had false alarms or non detection of a seizure. • Advantages – early seizure detection, less worry more sleep for carers and easier sleeping arrangements.

Continuous monitoring of electrodermal activity during epileptic seizures using a wearable sensor'	Poh, M.Z. Loddenkemper, T. Swenson, N.C . Goyal S. Madden, J.R. Picard, R.W.	Annual International Conference of the IEEE Engineering in Medicine and Biological Society.	2010		To investigate the relationship between seizures and autonomic alterations.	• pilot study implies low numbers. • No numbers • Seizures uncorroborated with EEG or observation • Novel method –untested before	• Preliminary results suggest that epileptic seizures induce a surge in EDA. • The changes are greater in GTCS which reflects a massive sympathetic discharge.
Convulsive Seizure Detection Using Wrist Worn Electrodermal Activity And Accelerometry Biosensor	Poh, M.Z. Loddenkemper, T. Reinsberger, C. Swenson, N.C. Goyal, S. Sabtala, M.C. Madden, J.R., & Picard RW.	Epilepsia	2012	80	To evaluate the performance of an algorithm of automatic detection of GTCS based on EDA and Accelerometry.	• ? bias in study –authors own device. • limited goal - to define a seizure according to 19 features extracted from EDA and accelerometry recordings - ? is this a seizure.	• Patient specific. • 130 false alarms which is on average 1 false alarm per 24 h. • 15 out of GTCS detected. • Found EDA and accelerometry perform better when used together. • Can potentially provide a convulsive seizure alarm.
Portable device for realtime monitoring and warning of epileptic seizures	Popescu et al.	Epilepsy and behaviour	Aug-13		Evaluate the use of spectral analysis of abnormal cerebral currents.	• ? numbers • Authors own device -Bias • Needs specific software • Device attached to the neck • Sends emergency text message which isn't available at the moment	• In development.
Apnoea Detector To Prevent SUDEP	Rodriguez-villegas, E. Aguilar-pelaez, E. Chen, G., & Duncan, J.	Epilepsia	2009			• Simulated seizures during trials • Low no of hours recorded 51 hrs • Fitted over trachea – 2x2 cm square device ?tolerability • ?trailed in a domestic or clinical setting?	• Found it well tolerated and adhesion over trachea was robust. • WADD can reliably identify apnoea. • Long term use of WADD offers the possibility of averting some instances of SUDEP.
'A Pilot Study Of A Wearable Apnoea Detection Device'.	Rodriguez-villegas E, Chen G, Radcliff J & Duncan J.	BMJ open	(2014)	10	Evaluate a novel wireless Apnoea Detection Device (WADD)	• Pilot study • Tested on people with sleep apnoea not epilepsy • Device tested against clinician observations	
Improving Long-Term Management Of Epilepsy Using Wearable Multi-modal Seizure Detection System'	Sabesan S. Rose, K. Carlson,G. Mueller, A. Sankar R., & Wheless, J	Epilepsy Currents	2015		Evaluation of multimodal accelerometers and ECG in the detection of seizures .	• ECG and accelerometers in a chest worn sensor. • ECG data and accelerometer data evaluated separately • a retrospective study using data from 581 hrs of ECG data collected from epilepsy monitoring units.	• Overall performance was reasonable. • Greater than 80% mean sensitivity. • a mean sensitivity of 80% and a mean false positive of 2 per night. • Seizures detected by the cardiac algorithm were largely complex focal seizures with or without secondary generalisation. • The accelerometer detected 97% of seizures with movement.
The Patients View On EEG-based Seizure Prediction Devices'.	Schulze-Bonhage, A.Wagner, K.Carius, A.Schelle, A., & Ihle, M.	Epilepsia	2010				
Monitoring Nocturnal Seizures In Vulnerable Patients'.	Shankar, R.Jory, C.Trip, M., & Hagenow, K	Learning Disability Practice	2013	5	Evaluate if infra red movement detection can be used to detect seizure activity.	• small study . • No corroboration with EEG – Reliant on carer observation	Movement detection did correlate with carers findings Larger study required
Seizure Alert Dogs - Fact Or Fiction?'.	Strong, V.Brown, S., & Walker, R.	Seizure	1999	6	To investigate the possibility that dogs may be able to anticipate and respond to seizures in their owners.	Low numbers Seizure frequency subjective reporting	only dogs which have been selected for their suitability are trained for seizure detection work. All dogs successfully trained in 6 months Each dog had a specific and reliable prediction time which did not vary once training was complete. Strong subjective impression from subject reports that seizure frequency reduced.

Appendix A (*Continued*)

Study	Authors	Publication	Year	No	Aim of Study	Strengths/Limitations of study	Findings
SmartWatch® – monitoring and detection of convulsive movements caused by seizures	Sullivan J, (University of California)		2013	15	To determine whether the could be use SmartWatch® to effectively detect abnormal motion patterns associated with GTCS.	• Study by SmartMonitor of their own product ?bia • Paediatric • Over 19 months 7 GTCS seizures were detected. • EEG corroborated • 99% sensitivity • 95% specificity • One false positive	• Study concluded SmartWatch®. • Effectively met the aims.
Feature Comparison For Realtime Detection Of Nocturnal Seizures Using Accelerometry'.	Ungureanu, C.Van Bussel, M.Tan, I Y.Arends, J B., & Aarts, RM.	Epilepsia	2012	18	Monitor in real-time patients with broad spectrum epileptic seizures.	• Small numbers -18 • Classifies abnormal movements as seizure • Seizures uncorroborated with EEG. • ?bias as own algorithm used.	• two accelerometer sensors represent the minimum requirement for the detection of nocturnal convulsive seizures.
Usefulness Of Movement And Heart Rate As Physiological Signals To Detect Nocturnal Epileptic Seizures'	Van Andel, J.Leijten, F.Rose, K., & Arends, J.	Clinical Neurophysiology	2014	92	Investigate the usefulness of movement and heart rate as physiological signals to detect nocturnal epileptic seizures	• Observed nocturnal seizures only • All seizure types involved • 'Seizures observed for clinical relevance by expert panel' -?subjective view • 'Clinical relevance' undefined.	• sensitivity of 61%. • False alarm 1.3 per 24 hrs. • Clinically relevant seizures had a sensitivity of 73%. • Higher sensitivity and lower false alarm rates needed for algorithms to be 33implementable. • Combination of non EEG physiological signals movement and heart rate seems feasible for automatic seizure detection in a home setting.
Using					photoplethysmography in heart rate monitoring of patients with epilepsy.	van Andel, Judith, Ungureanu, Constantin, Aarts, Ronald, Leijten, Frans, Arends, Johan	Epilepsy & behavior
Apr-15	7	To evaluate the usefulness of green light			photoplesmyography in comparison to ECG in 7 people with epilepsy OHR-Optical heart rate HRECG heart rate ECG	• Small numbers • Not tested during seizures but at random 10 minute intervals –did capture 2 seizures	• Limits of agreement were higher during wakefulness and during the occurrence of two seizures possibly because of less reliable HRECG measurements due to motion artefacts. • ? HRECG measurements acknowledged as being unreliable during seizures but OHR less sensitive to motion artifacts. • OHR may be useful in seizure detection.
Tele-epilepsy: Developing a multi-modal device for non eeg, extramural, nocturnal seizure monitoring	Van Andel J.,	Epilepsy Currents	Mar-13	100	Develop a multi modal device using audio/automated video frame analysis/ECG/3D accelerometry.	• Involved paediatric patients adolescents with Learning Disability and adults with nocturnal seizures.	• No conclusions published in this study.
Long Term Home Monitoring Of Hypermotor Seizures By Patient Worn Accelerometers'	Van De Vel, A.Cuppens, K.Bonroy, B.Milosevic, M.Van Huffel, S.Van Rumste, B.Lagae, L., & Ceulemans, B.	Epilepsy And Behaviour	2013	7	Nocturnal hyper motor seizure detection in paediatric patients based on an accelerometer.	• Accelerometers attached to extremities. • Small sample 7 • Paediatric • Author development - ?bias • Specific algorithm	• Positive predicative value of 57.84%. • sensitivity of 95.71%. • Can be installed without prior knowledge of seizure presentation.
Accelerometers For Detection Of Motor Seizures During Sleep In Pediatric Patients With Epilepsy'	Van De Vel, A.Cuppens, K.Bonroy, B.Milosevic, M.Kris, R.Gijsemans, L.Vervisch, J.Lagae, L.Van Huffel, S.Vanrumste, B., & Ceulemans, B.	European Journal Of Paediatric Neurology	2011	49	Evaluation of accelerometers for detection of motor seizures during sleep	• 3 Accelerometers attached to wrists and ankle synchronised with audio/EEG/EMG/ACM/ECG • ?Bias, non-standardised algorithm, • retrospective study, • patient specific set up.	• Promising results for detecting hypermotor seizures but patient specific set up is required. • No parameter setting was 100% for all patients. • Further development of algorithm req.

Critical Evaluation Of Four Seizure Detection Systems Tested On One Patient With Focal And Generalised Tonic And Clonic Seizures.'	Van De Vel, Anouk. Verhaert, Kristien ., & Ceulemans, Bergen.	Epilepsy And Behavior	2014	1			
Clinical impact of long-term nocturnal home monitoring for detection of epileptic seizures in pediatric patients	Van De Vel et al	European Journal of Paediatric Neurology	Sep-13	4	Evaluating efficiency/comfort user friendliness of seizure monitoring using 3D accelerometers, radar and video	• 4 patients monitored for 1 month. • Considerable amount of equipment required. • Seizures uncorroborated with EEG. • Comparative data reliant on carer observation	• More than the witnessed seizures by carers were detected. •Increase in better management and efficiency of carers. • Further study required.
Prospective Study Of The Emfit Movement Monitor'	Van Poppel, K.Fulton, S P.McGregor, A.Ellis, M.Patters, A., & Wheless, J.	Journal of Child Neurology	2013	45	To evaluate the sensitivity and specificity of the Emfit movement monitor	• Paediatric	• Of the 45 patients 26 experienced a combined total of 78 seizures. • 28 seizures whilst the subject was asleep. Emfit monitor captured 23 (30%) of these.15 of which detected during sleep (53.6%). • The Emfit monitor detected 84.6% (11 of the 13) generalised tonic clonic seizures during sleep and 12 of the 16 when the subject was awake. • Emfit is designed to detect generalised tonic clonic seizures when the person is asleep and authors felt it met its objective.

Name of device	Company/Contact	What type of device?	Mode of action	What hardware is required?
Accelerometers				
Epicare and android app	www.possum.co.uk	3 Axis Accelerometer in a wrist sensor	Accelerometers detect seizure movements which connects to smart phone app (Epicare) via blue tooth. Will alert registered friends.	Wrist band Smart phone
Epicare with pager	www.possum.co.uk	.3 Axis Accelerometer in a wrist sensor	Accelerometers detect seizure movements which connects to control device and alerts a Pager.	Pager
Epicare with careline alarm	www.possum.co.uk	3 Axis Accelerometer in a wrist sensor	Accelerometers detect seizure movements which connects to control device which alerts a careline alarm via phone socket	Wrist band Control device Communicates with a Careline (telecare24) who will contact family members/emergency services
Ep DETECT	www.epdetect.com	Accelerometer in a wrist sensor	Accelerometers detect seizure movements which connects to smart phone app will alert registered friends	Wrist band Smart phone
SMART watch	www.smart-monitor.com	Wrist sensor	Detects repetitive shaking motion Records time duration, duration and location of any unusual movement patterns.	Wrist Band
Heart rate changes				
Pulseguard	www.pulseguard.org	Wrist sensor measures pulse changes	Detects changes of pulse outside predetermined parameters blue tooth connection to ipad	Wrist band ipad (which has to be within a few metres of the sensor)
Bed Movement Sensors				
Ep-it monitoring systems	www.alert-it.co.uk	A range of bed sensors designed to detects abnormal movement, sound Incontinence, Vomiting and Bed Vacation	Alarms are transmitted through a radio link to a pager	Mattress sensor, control device Alerts • a pager with a 450m range.

Appendix A (*Continued*)

Name of device	Company/Contact	What type of device?	Mode of action	What hardware is required?
Emfit with pager/care line	www.emfit.com	A bed sensor using an electroactive polymer that detects electromechanical changes.	detects abnormal movements including hyperventilation and bed absence bedside control unit can alert a pager or a careline System also includes a wireless pendant which user can press to speak to operator	Bed sensor mat, bedside control unit Alerts • pager (rage up to 150m) • Or a careline. Wireless pendant.
Armeco	aremco@onetel.com	Bed sensor includes	Motion detection Pillow Moisture Body Moisture Distress Call Microphone bed occupancy detection sensor	Movement sensor plate – body movements outside set parameters/ respiration movements microphone for' transient sounds'
Medpage MP5V2	www.medpage-ltd	Bed alarm	Movement sensor Microphone Alarms via radio pager	Bed mat Control device pager
Medpage MP5 ULTRA	www.medpage-ltd	Bed alarm	Claims to detect nocturnal seizure movement from patient's of all ages who experience non-typical convulsive seizures. Suitable for complex epilepsy	Bed mat Control device pager
Medpage Model MP2V2 Multiple Patient Seizure Monitoring	www.medpage-ltd	Bed alarm	MP2V2 epilepsy care system can be expanded to include patient call pendants or nurse call cords, PIR movement sensors, door alarms, enuresis sensors, bed occupancy sensors, and specialist disablement adaptations	Bed mat Control device Desk top alarm For multi use – care homes
SensAlert 200	www.sensorium.co.uk	Bed alarm	Under mattress sensor pads detecting unusual movement	Bed pads Control device pager
SPTX-EP200	www.sensorium.co.uk	Bed alarm		Bed pads Control device pager
Epilepsy Sensor		fine strip of foil-like material, a control unit and a radio transmitter	sensor are based on monitoring the person's movements including respiration and heartbeat.	
Smart Phone App				
Alert5	Alert 5	emergency contact app	Phone app that will send an alert including GPS to registered friends if activated	An app for iPhone and android which can alert up to 5 people from contact list
CCTV with night vision				
Sami	www.samialert.com	Night vision monitor	Detects unusual events Alarms and video records	Infa red video camera Smart phone/app
Babyping	www.babyping.com	CCTV with night vision listening device		Camera – infa red night vision. MICROPHONE Smart phone
Electrodermal Conductivity				
Empatica	www.empatica.com	accelerometers, electro dermal conductivity, temperature changes	Measures electro dermal activity – stress levels that rise pre seizure.	Smart watch blue tooth connection to smart phone
Prototypes				
SMART belt-(Seizure Monitoring and Response Transducer) A prototype belt developed by RICE University Students.	http://www.futurity.org/epilepsy-belt-alerts-caregivers-of-kids-seizure/	Body sensors	Wearable sensors that measure – elastic fabric measures respiration. Two sensors measure electrodermal activity (skin conductivity)	
Prototype Smart Clothing		Smart Clothing The medical device consists of a long-sleeved T-shirt fitted with electromyograms, a pulse oximeter, accelerometers and temperature sensors with a cap integrating the latest generation sensors, which carry out EEGs	Data is sent from the garment via Bluetooth for analysis and processing in an innovative smartphone application. Data gathered by a secure cloud-based (remote IT servers) system can be analysed in detail and shared with doctors	

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