Original Article

A Scoring Framework and Apparatus for Epilepsy Seizure Detection Using a Wearable Belt

Abstract

Background: To develop a wearable device that can detect epilepsy seizures. In particular, due to their prevalence, attention is focused on detecting the generalized tonic-clonic seizure (GTCS) type. When a seizure is detected, an alert phone call is initiated and an alarm SMS sent to the nearest health-care provider (and/or a predesignated family member), including the patient's location as global positioning system (GPS) coordinates. **Methods:** A wearable belt is developed including an Arduino processor that constantly acquires data from four different sensing modalities and monitors the acquired signal patterns for abnormalities. The sensors are a heart rate sensor, electromyography sensor, blood oxygen level (oxygen saturation) sensor, and an accelerometer to detect sudden falls. Higher-than-normal threshold levels are established for each sensor's signal. If two or more signal measurements exceed the corresponding threshold value for a predetermined time interval, then the seizure alarm is triggered. **Results:** Clinical trials were not pursued in this study as this is the initial phase of system development (phase 0). Instead, the instrumented belt seizure detection prototype was tested on nine healthy individuals mimicking, to some degree, seizure symptoms. A total of eighteen trials took place of which half had <2 sensor thresholds exceeded and no alarm, whereas the other half resulted in activating the alarm when two or more sensor thresholds were exceeded for at least the predetermined time interval corresponding to each of the higher-than-normal sensor readings. For each trial that triggered the alarm when a seizure was detected, the on-board GPS and global system for mobile communication (GSM) units successfully initiated an alert phone call to a predesignated number in addition to sending an SMS message, including GPS location coordinates. **Conclusion:** Continuous real-time monitoring of signals from the four different sensors allows the developed wearable belt to detect GTCS while reducing false alarms. The proposed device produces an important alarm that may save a patient's life.

Keywords: *Alarm system, electromyography, epilepsy seizures, heart rate, smart health-care system, wearable*

Submitted: 08-Jul-2021 **Revised:** 04-Jan-2022 **Accepted:** 28-Jan-2022 **Published:** 09-Nov-2022

Salah Eldeen Mofleh Falah Alzghoul[1], Sa'ed Ahmad Qwaiteen Alajlouni[2]

Departments of [1]Biomedical Engineering and [2]Mechatronics Engineering, Faculty of Engineering, The Hashemite University, Zarqa, Jordan

Introduction

According to the World Health Organization, epilepsy is one of the most prevalent neurological disorders, affecting around 50 million patients worldwide.[1] Epilepsy has a prevalence rate of approximately 50 per 100,000 adults per year. It is caused by neural activity hyper-excitability that results from hyper-synchronization. That is, epileptic seizures are caused by an increase in brain excitability of nerve cells and by repetitive excitation of neurons.[2,3] By taking anti-seizure treatment drugs, around 61% of patients will become seizure-free, whereas 31% will suffer from at least one seizure per month or per week and the remaining 8% will have daily seizures.[4]

Seizures are classified into three major categories: (1) generalized, (2) focal, and (3) epileptic spasms. Generalized seizures are divided into four major subtypes: absence; myoclonic; atonic; and generalized tonic–clonic seizures (GTCS). Absence seizures are initiated with a lack of response to verbal stimuli as well as head wobbling or eye blinking.[5,6] Myoclonic seizures are characterized by unexpected fast contractions of a certain muscle or group of muscles without loss of consciousness. Furthermore, in most cases, myoclonic seizures cause a reduction in heart rate (HR). Atonic seizures result in loss of body balance, consequently

How to cite this article: Alzghoul SE, Alajlouni SA. A scoring framework and apparatus for epilepsy seizure detection using a wearable belt. J Med Sign Sens 2022;12:326-33.

Address for correspondence:
Dr. Salah Eldeen Mofleh Falah Alzghoul,
Department of Biomedical Engineering, Faculty of Engineering, The Hashemite University, Zarqa, Jordan.
E-mail: alzghoul@hu.edu.jo

Access this article online

Website: www.jmssjournal.net

DOI: 10.4103/jmss.jmss_138_21

Quick Response Code:

leading to a fall or a head injury; however, with atonic seizures, there is no significant change in HR or body temperature. GTCS is the most common type of seizures[7] and is characterized by stiff and jerky movements of the upper and lower limbs, increased sweating, and increased cardiac activity. Moreover, patients suffering from GTCS are susceptible to sudden unexpected death in epilepsy.[4,6-8]

As for the second major category of seizures, focal seizure patients are not usually responsive to normal stimuli, such as verbal or tactile, with loss of attention, emotion, and memory in addition to sweating and elevated HR.

The last category, epileptic spasms, is recognized by unexpected extension and flection of the limbs for a few seconds without any change in body temperature or cardiac activity. When epileptic spasms start very early in life, they are called "infant spasms."[4,5]

Administration of the appropriate epilepsy medical treatment is associated with the accurate and early detection of the seizure type and will decrease mortality caused by seizures and increase the patient's quality of life as well as that of their family. Wearable seizure detection devices increase the level of awareness and decrease response time, which will reduce any harmful effects. The type of seizure associated with the physiological changes that occur during such events is the main consideration in selecting the appropriate device. Each seizure type can be detected by multiple sensors that monitor physiological changes, sudden body movements, and/or falling.[4,9] These phenomena are measured by different sensing technologies, including electroencephalography (EEG), electrocardiography (ECG), HR sensors, electromyography (EMG), blood oxygen level (oxygen saturation [SpO_2]), video monitoring, accelerometers, electro-dermal activity sensors (EDA), mattress sensors, and eye movement detection.[10] Many commercial devices are available for seizure detection, with each device measuring one or more seizure biometric activity (e.g., sudden movements, muscle contractions, increase in HR, etc.). In particular, for clinical seizure detection, the gold standard has been the use of EEG in association with video monitoring; nevertheless, for wearable devices, different techniques are used as will be explained in the following subsection.

Seizure detection using wearable devices

In Poh *et al.*,[11] the authors utilized real-time EDA and accelerometer measurements to detect GTCS. A support vector machine was used as the detection algorithm. Other wearable devices like the one proposed in Ahmed *et al.*[12] can detect general seizures without being able to identify the seizure type. From here on, we will use the word "detection" to mean the ability to detect the presence of a seizure, whereas we will use "identification" to denote the ability to discern the correct seizure type. In Ahmed *et al.*,[12] four sensing technologies were used: ECG, tri-axial accelerometer for sudden fall measurement, EDA, and a breathing rate sensor as a force-sensor attached to the chest area.

In Patterson *et al.*,[13] the accuracy of seizure detection and seizure-type identification was evaluated for a commercially available smartwatch (manufactured by SmartMonitor, based in California, USA). The specific smartwatch instrumentation and algorithm used for seizure detection and identification were not mentioned in the study. Video EEG was used as a reference for detecting and identifying the correct seizure type of 191 seizures (41 patients). The smartwatch in[13] was able to identify only 16% of the seizures. The highest detection and identification accuracy of the smartwatch was associated with GTCS, with a 31% detection rate. Therefore, the study in McKenzie *et al.*[14] established the need for wearable devices with better accuracy seizure detection and identification.

An alternative wearable technology was utilized in McKenzie *et al.*[14] for the detection of generalized and focal seizures. The neuroheadset EPOC+ (by Emotiv Systems, Sydney, Australia), which contains a 14-lead EEG wirelessly connected to a smart tablet, was used for seizure detection. This detection system has no safety concerns but has low accuracy with high precession;[14] i.e., high accuracy of measuring biometric activity, but low accuracy in correlating the measured activity to a seizure. Another wearable device that uses surface EMG to detect GTCS (by placing the IctalCare detector on the biceps muscle) was studied in Beniczky *et al.*[15] This device is small and accurate with fast response time.[15] The wearable e-patch ECG device in Jeppesen *et al.*[16] was also relatively accurate with around one false alarm per day.

In addition to using wearables for seizure detection and as another way of protecting epilepsy patients and alerting nearby caregivers, an alternative category of methods exists for early seizure detection. These methods depend on monitoring behavioral changes in the patient, such as using a seizure alert dog for alerting caregivers in case the patient experience changes in behavior, which could be early signs of a seizure.[17]

Most wearables that detect seizures and alert the patient/caregiver, especially watches, do not use an EMG sensor to detect generalized seizures. EMG is one of the most important features to identify this type of seizure. Although many seizure detection wearables are sensitive to seizure-related biometric changes (e.g., sudden movements, increase in HR, etc.), these wearables lack specificity of seizure detection; that is, they have a high chance of false-positive detection due to interpreting biometrics from a nonseizure event as a seizure. For example, a watch that measures EDA, HR, and sudden falls may signal a false seizure alarm if the patient is doing a physical activity that increases HR and sweating

or that generates fast and sudden movements. False alarms are expected to appear if the device relies on <3 biometric conditions to send alerts, which is an observation supported by the results in Ahmed *et al.*[12] Therefore, there is a need for detection techniques that rely on more than two biometric conditions and presumably have higher seizure detection accuracy.

Contribution

Due to the previously stated need for more accurate seizure detection, this paper presents a framework for GTCS detection that uses four simultaneous biometric signals: EMG, HR, SpO2, and sudden fall signal as measured by an accelerometer. Because each seizure type has a specific biometric signal pattern - like cardiorespiratory changes, muscle contractions, falls, and changes in behaviour - it is important to identify the seizure type to be detected. The focus of this paper is on the detection of GTCS as it is the most common seizure type. For GTCS, many physiological changes appear during the seizure and the seizure duration typically lasts more than 10 s, which helps in seizure detection.

Roughly speaking, for each of the four biometric signals used, the proposed GTCS detection framework utilizes both the biometric signal level and the sustained level duration associated with GTCS.

The proposed prototype includes instrumentation components and a processor (Arduino).

Using the proposed framework and prototype, it is expected to decrease the probability of false seizure alarms. Furthermore, the proposed framework allows for the addition of more sensors to measure biometric signals in an easy and straightforward manner.

Because this concept is the initial phase of system development, the system was tested with healthy individuals mimicking the symptoms of a seizure patient, which was precisely achieved using nine test subjects. The results are presented in Section 3.

Methods

General scope

Before building the framework, major seizure detection features were specified as shown in Figure 1. The methodology of GTCS detection is as follows: Given the threshold value associated with a GTCS for each of the four measured biometric signals (EMG, HR, SpO_2, and accelerometer signal), the signals will be monitored/processed in real-time. If a biometric signal exceeds the threshold value for a prescribed duration, then a flag will be raised. If two or more flags are raised out of the four sensors, then a seizure is recorded and an alarm message/call sent to the nearest health-care facility and caregiver. It is worth mentioning that the threshold values

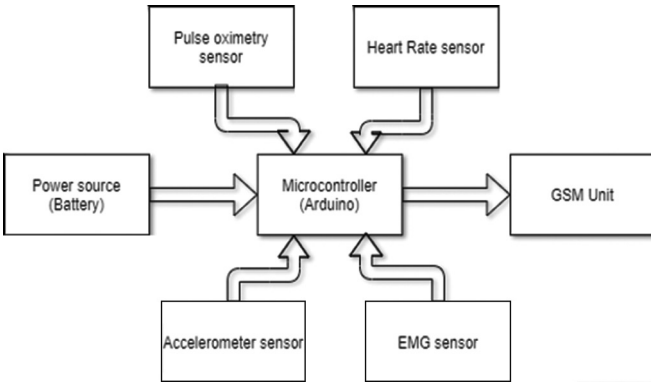

Figure 1: Framework flow diagram

of each of the four biometric signals used in this study are based on values reported in the literature.

The prototype is shown in Figure 2. It consists of a bag strapped to the waist and thigh. The Arduino control unit, batteries, global positioning system (GPS), and global system for mobile communications (GSM) units are placed inside that bag and the HR/SpO_2 sensor is attached to the forefinger. EMG electrodes are placed over the biceps muscle and an accelerometer is located on the back or around the chest. Because the proposed prototype involves wire connections, it may be difficult for patients to deal with the device the first time they wear it, but the reduced likelihood of false alarms to identify GTCS when employing four measured biometric signals outweighs this difficulty.

Detection sensors and conditions

Surface electromyography electrodes

By harvesting signals from muscles during seizure through EMG electrodes, muscle activation can be monitored. During GTCS, the EMG signal has high amplitude with frequency (>150 Hz).[15] The most appropriate locations to place electrodes for home detection systems are the tibialis muscles, deltoid muscles, triceps, and biceps.[18] Two Ag/AgCl electrodes are attached to the belly of biceps muscle and the third electrode is grounded to the elbow joint. An Advancer Technologies EMG Muscle Sensor Kit V3.0 was used in this framework. The kit outputs an enveloped EMG signal after applying necessary signal conditioning to the raw continuous muscle activity signal.

The main two features for raising the EMG flag are the amplitude of the EMG signal's upper envelope and the duration of muscle contractions.[19] It has been reported in the literature that during a GTCS, EMG electrodes recorded signal amplitudes well above the noise floor, reaching above 1.5 mV and lasting more than 10 s [Figure 3].[15,18,19]

In the proposed design, output of the Advancer Technologies EMG muscle sensor was amplified by a gain of 1,000 before passing the resulting signal to a 10-bit analog-to-digital converter (ADC). The ADC

maps a voltage value between 0 and 9 volts (the ADC's supply voltage) into integer values between 0 and 1023, where an ordinate amplitude of 200 represents amplitude of 1.75 mV before amplification.

In the current framework, the EMG flag is raised if the amplitude sustains a value ≥1.75 mV for a duration ≥10 s. Thus, there is high probability that the patient is experiencing a seizure. The chosen amplitude threshold of 1.75 mV is a conservative (a bit high) threshold; nevertheless, it has been chosen to avoid false EMG alarms, i.e., raising the EMG flag when there is no actual GTCS.

Heart rate and blood oxygen saturation sensor

To reduce the number of components, the MAX30102 Pulse Oximeter Heart-Rate sensor was selected. This sensor measures HR and SpO_2 by Reflective LED technique. It is a fast-response sensor with small dimensions and has low power consumption and a high signal-to-noise ratio. The sensor is firmly attached to the patient's finger to avoid readings caused by motion artifacts or light disturbances.

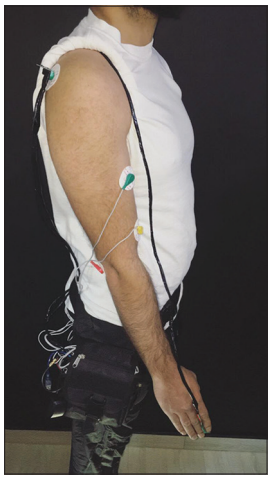

Figure 2: Prototype attached to the human body. The bag is strapped to the thigh and waist. Heart rate and oxygen saturation sensor are attached to the forefinger. Electromyography electrodes are placed over the biceps muscle, and an accelerometer is located on the back or around the chest

HR and oxygen saturation levels are significantly changed during GTCS for both children and adults,[20] and they are key factors associated with sudden death in epilepsy. Many studies showed that during a GTCS, HR will increase by more than 10 beats per min (bpm) and may increase to over 30 bpm.[16,20-22] An incremental increase in HR during a seizure leads to the secretion of catecholamine, an increase in limb activity through neuronal and motor activities, and tachycardia in most patients.[23,24]

The threshold level for HR is patient-dependent and based on their long-term average HR. Two HR values are calculated and compared: a long-term HR average and a short-term HR average calculated over the latest few seconds. If the patient's current (short-term) HR value increases above the long-term average value by 10 bpm, then a flag is raised.

Literature shows that SpO_2 readings play a key role in detecting GTCS.[21,25] Data from previous studies showed that oxygen blood saturation during a seizure may drop from 95% to <90%; in some cases, it can drop to around 60%. The duration of SpO_2 level reduction lasts from 3 s to up to 5 min.[21,25] The most important reason that detection devices do not use SpO2 readings as a significant threshold for their alarm systems is that there is a delay between seizure initiation and the onset of decreasing of oxygen blood saturation levels and that delay time has an average of 43 s.[20] As a result, this physiological change is not effective for detecting short-term seizures. However,

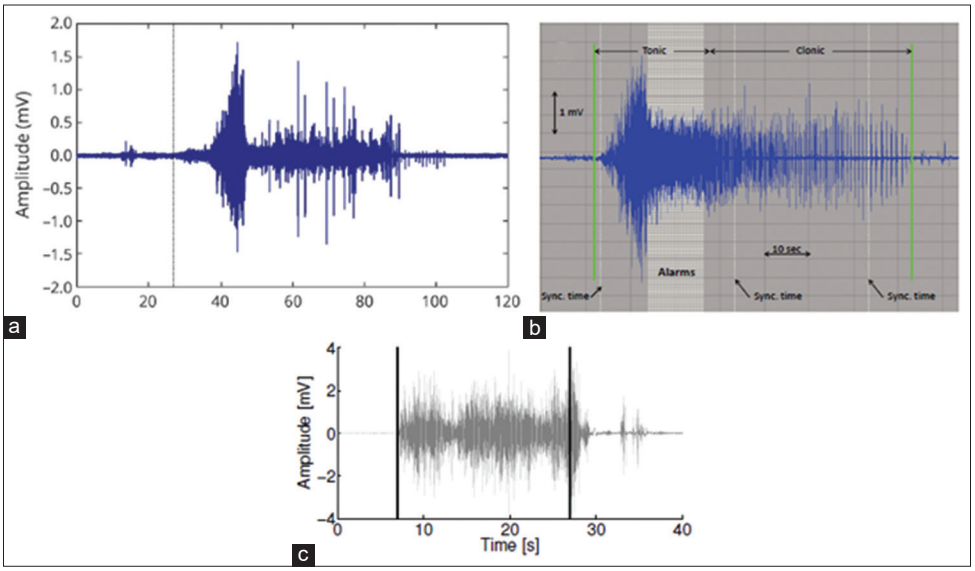

Figure 3: Raw surface electromyography (EMG) signals monitored from real seizure cases. (a) Epileptic seizure EMG signal by EDDI.[15] (b) Generalized tonic-clonic seizure (GTCS) muscle signal and conversion from GTCS to clonic seizure.[18] (c) High amplitude and duration of muscle contraction for seizure patient[19]

GTCS average duration is around 2 min and, in some cases, can last more than 10 min, which is more than the average time delay;[26] therefore, it is reasonable to use this clinical condition as an additional clause in the framework. The condition for raising the SpO2 flag in this system is when the SpO_2 level is ≤90% for 5 s or more as proved in a study of hypoxemia and its relation to seizures.[27]

Accelerometer

Using a wearable accelerometer sensor is common in seizure detection devices as it can detect sudden body movements such as jerking motions, stumbling movements, and rapid body falls, which are common phenomena for most seizure types, e.g., GTCS, tonic, clonic, myoclonic, and hypermotor. The accelerometers used in seizure detection systems are accurate, three dimensional, and consume low energy.[4] Most accelerometer applications in seizure detection appear as wearable devices such as the SmartWatch Inspyre, E4 wristband, Embrace wristband, NightWatch, and many other devices manufactured by well-known technology brands.[9,28,29] An accelerometer can be placed in many locations on the body (e. g., wrist, chest, back, and ankle). The threshold flag for the accelerometer will be raised if the absolute accelerometer signal value is ≥2 g.

Assembling the framework

Each sensing modality (SpO_2, HR, EMG, and accelerometer) will have its own conditions, which if satisfied will raise a sensor flag. If two flags out of the four available sensing modalities are raised, then a GTCS seizure alarm is produced. For example, in the case where a patient suffers a seizure without falling down or having reduced SpO_2 levels, other phenomena will be checked such as having higher than normal amplitudes of EMG and HR signals. If the patient falls down and their muscles become stiff, then it is expected that both the accelerometer and EMG signals will raise their corresponding flags as detecting a seizure regardless of the state of the two remaining flags associated with blood oxygen level and HR changes. By combining multiple flags (four sensor alarms) for seizure detection, the number of false seizure alarms is expected to be reduced.

Alarming nearby caretakers if generalized tonic clonic seizure is detected

To send a rapid warning to the nearest health-care facility or to the patient's caregiver, GPS and GSM units were connected to our module. Within seconds of a detected seizure, these modules send an alert phone call to a predesignated caregiver or facility along with an SMS message, including the GPS location of the patient. The alert system will keep sending warnings as long as the thresholds of physiological changes are remain exceeded.

Results

Testing the design required conditions mimicking the physiological conditions of a patient in seizure. This study recruited nine healthy individuals: 4 females with an average age of 22.5 ± 1 years and 5 males with an average age of 25 ± 2 years. Eighteen trials were conducted. In nine trials (half), the alarm was not triggered when a seizure was mimicked by the test subject. Long duration muscle contraction and falling down were the simplest conditions to emulate. As for mimicking the increase in HR that takes place during a seizure, this was achieved by climbing up 20 stairs over a relatively short time. In comparison, reaching the threshold level of SpO_2 and raising its corresponding flag was the hardest part; this was accomplished by asking the test subjects to hold their breath for around 30 s.

The results are shown in Table 1, where the red color represents an abnormal reading that raises a flag. In Table 1, the first nine rows represent trials that did not trigger a seizure alarm in the case where less than two flags were raised. The subsequent rows represent the trials that did activate the alarm when two or more flags were raised.

Figure 4 illustrates how the created system detected a seizure state due to SpO_2 and HR flags being raised while having no high muscle contraction or sudden body movement. As shown in Figure 5, a phone call was sent to a predesignated number in addition to a warning SMS message including the patient's location.

It is worth mentioning that it was very hard to mimic raising all four flags at once; however, it was possible to mimic a scenario where three flags are raised at the same time. Figure 6 describes the system's response to such a

Figure 4: The control system checking the physiological conditions. Electromyography contraction amplitude was below the threshold (200 divisions), IMU (accelerometer) did not detect any sudden fall, oxygen saturation level reached the threshold (90%), and the heart rate (HR) was 111 beats per min which are 10% higher than the normal (long-term average) HR. "State 1" means that the conditions for detecting a seizure has been met, and system will send the alarm message that contains location (latitude and longitude), in addition to an alarm phone call to the nearest hospital or patient's family member

Table 1: Nine healthy students stimulate the four conditions that will lead to seizure

Subject number	Age (years)	Gender	Weight (kg)	HR (bpm)	SPO_2 (%)	EMG value in volts after signal conditioning stage (V)	ACC (sudden fall)	Alarm
1	22	Female	51	60	97	0.8	No	No
2	22	Female	64	65	96	1.2	Yes	No
3	22	Female	55	73	99	1.6	No	No
4	24	Female	52	62	87	0.9	No	No
5	28	Male	67	57	98	1	No	No
6	24	Male	74	53	95	1.8	No	No
7	23	Male	63	67	96	0.7	Yes	No
8	24	Male	77	61	97	2.9	No	No
9	27	Male	82	111	95	1	No	No
1	22	Female	51	97	83	1.8	No	Yes
2	22	Female	64	62	89	0.6	Yes	Yes
3	22	Female	55	66	94	2.2	Yes	Yes
4	24	Female	52	113	98	1.3	Yes	Yes
5	28	Male	67	71	97	2.3	Yes	Yes
6	24	Male	74	111	90	0.87	No	Yes
7	23	Male	63	112	99	5.8	No	Yes
8	24	Male	77	102	89	1.9	No	Yes
9	27	Male	82	64	90	2.7	Yes	Yes

HR – Heart rate; EMG – Electromyography; SPO2 – Oxygen saturation; ACC – Accelerometer

Figure 5: (a) An emergency SMS with Google Maps location messages to alert that there is a seizure case. (b) Phone call to give more attention

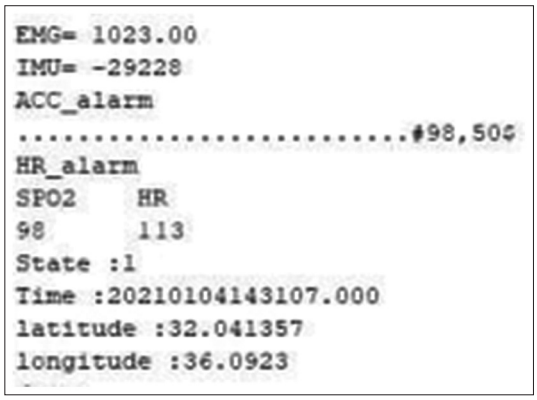

Figure 6: Three monitored readings reached warning levels, accelerometer hinted for a sudden fall, 113 beats per min for the heart rate, and very high muscle contraction (1023 divisions) as given by electromyography sensor. The system sent warning calls, messages, and accurate location

scenario, where the accelerometer (IMU), EMG, and HR flags are raised simultaneously.

Discussion and Conclusion

The multicondition framework and prototype presented in this paper for seizure detection show promising potential for detecting GTCS by monitoring the most common human signals for changes that occur during a seizure. The successfully implemented prototype detects four seizure flags: elevated HR, decay in oxygen blood saturation levels, rapid movements including sudden falls, and high muscle contraction. Following a detected seizure - when at least two flags are raised - a rapid alert is sent via a phone call and an SMS message including the patient's GPS location. A swift and accurate alarm system for detecting seizures will help save lives and reduce the number of sudden deaths caused by epilepsy and will reduce harmful circumstances that could happen during or after a seizure.

The importance of having more than one sensor to detect physiological changes during a seizure is to increase detection reliability effectively and thereby decrease the number of false alarms. False alarms are a major drawback for any detection device because they can cause distress to patients and their families. Reducing false positives by increasing the number of sensor modalities and conditions for seizure detection will help increase the quality of life for seizure patients and their families. Although this proposed system is tailored to GTCS detection, the flag conditions/thresholds can be modified easily to match

any seizure type that has effects on HR, EMG signal, HR signal, or causes body shakes and/or falls.

The proposed wearable belt has an implementation cost of about 140 US dollars, which is less than some currently used technologies, such as the EMFIT MMTM Movement Monitor (594 US dollars), the NightWatch, which is used for epilepsy seizure detection during sleep (460 US dollars), the Embrace 2 seizure detection watch (249 US dollars), and the SensAlert 200 system, which is a convulsive epileptic seizure detector (around 300 US dollars). It is worth mentioning that there are mobile-based applications available for the detection of seizures. These applications utilize the hardware available in the phone (phone prices and available sensors vary). The phone applications themselves, however, are fairly inexpensive and some are even free to download.

As a future modification, an additional accelerometer could be incorporated into the proposed system and placed on the thigh. The goal is to increase the accuracy of movement measurements and fall detection. Moreover, future work will include adding a memory card to expand the storage capacity of the current prototype. The additional data storage space will be used to record the patient's biometric signals over long periods. The recorded data, especially the part slightly preceding a recorded seizure event, will be postprocessed to develop methods of seizure prediction rather than merely creating a postseizure alarm. Parallel to the previously mentioned future work activities, the authors will keep refining the belt design in an effort to make the wearable system more convenient to wear. Our initial idea would be to reduce the wires involved in the current prototype.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

References

1. Forsgren L, Beghi E, Oun A, Sillanpää M. The epidemiology of epilepsy in Europe – A systematic review. Eur J Neurol 2005;12:245-53.
2. Abramovici S, Bagić A. Epidemiology of epilepsy. Neuroepidemiology 2016;138:159-71.
3. Aminoff M. Electrodiagnosis in Clinical Neurology. 3rd ed. Philadelphia: Elsevier Churchill-Livingstone; 1992.
4. Ulate-Campos A, Coughlin F, Gaínza-Lein M, Fernández IS, Pearl PL, Loddenkemper T. Automated seizure detection systems and their effectiveness for each type of seizure. Seizure 2016;40:88-101.
5. Stafstrom CE, Carmant L. Seizures and epilepsy: An overview for neuroscientists. Cold Spring Harb Perspect Med 2015;5:a022426.
6. Blume WT, Lüders HO, Mizrahi E, Tassinari C, van Emde Boas W, Engel J Jr., Glossary of descriptive terminology for ictal semiology: Report of the ILAE task force on classification and terminology. Epilepsia 2001;42:1212-8.
7. Gursahani R, Gupta N. The adolescent or adult with generalized tonic-clonic seizures. Ann Indian Acad Neurol 2012;15:81-8.
8. Sperling MR. Sudden unexplained death in epilepsy. Epilepsy Curr 2001;1:21-3.
9. Verdru J, Van Paesschen W. Wearable seizure detection devices in refractory epilepsy. Acta Neurol Belg 2020;120:1271-81.
10. Van de Vel A, Verhaert K, Ceulemans B. Critical evaluation of four different seizure detection systems tested on one patient with focal and generalized tonic and clonic seizures. Epilepsy Behav 2014;37:91-4.
11. Poh MZ, Loddenkemper T, Reinsberger C, Swenson NC, Goyal S, Sabtala MC, *et al.* Convulsive seizure detection using a wrist-worn electrodermal activity and accelerometry biosensor. Epilepsia 2012;53:e93-7.
12. Ahmed A, Ahmad W, Khan MJ, Siddiqui SA, Cheema HM. A wearable sensor based multi-criteria-decision-system for real-time seizure detection. Annu Int Conf IEEE Eng Med Biol Soc 2017;2017:2377-80.
13. Patterson AL, Mudigoudar B, Fulton S, McGregor A, Poppel KV, Wheless MC, *et al.* SmartWatch by SmartMonitor: Assessment of seizure detection efficacy for various seizure types in children, a large prospective single-center study. Pediatr Neurol 2015;53:309-11.
14. McKenzie ED, Lim AS, Leung EC, Cole AJ, Lam AD, Eloyan A, *et al.* Validation of a smartphone-based EEG among people with epilepsy: A prospective study. Sci Rep 2017;7:45567.
15. Beniczky S, Conradsen I, Henning O, Fabricius M, Wolf P. Automated real-time detection of tonic-clonic seizures using a wearable EMG device. Neurology 2018;90:e428-34.
16. Jeppesen J, Fuglsang-Frederiksen A, Johansen P, Christensen J, Wüstenhagen S, Tankisi H, *et al.* Seizure detection based on heart rate variability using a wearable electrocardiography device. Epilepsia 2019;60:2105-13.
17. Dalziel DJ, Uthman BM, Mcgorray SP, Reep RL. Seizure-alert dogs: A review and preliminary study. Seizure 2003;12:115-20.
18. Conradsen I, Beniczky S, Wolf P, Jennum P, Sorensen HB. Evaluation of novel algorithm embedded in a wearable sEMG device for seizure detection. Annu Int Conf IEEE Eng Med Biol Soc 2012;2012:2048-51.
19. Larsen SN, Conradsen I, Beniczky S, Sorensen HB. Detection of tonic epileptic seizures based on surface electromyography. Annu Int Conf IEEE Eng Med Biol Soc 2014;2014:942-5.
20. Blum AS, Ives JR, Goldberger AL, Al-Aweel IC, Krishnamurthy KB, Drislane FW, *et al.* Oxygen desaturations triggered by partial seizures: Implications for cardiopulmonary instability in epilepsy. Epilepsia 2000;41:536-41.
21. Goldenholz DM, Kuhn A, Austermuehle A, Bachler M, Mayer C, Wassertheurer S, *et al.* Long-term monitoring of cardiorespiratory patterns in drug-resistant epilepsy. Epilepsia 2017;58:77-84.
22. Vandecasteele K, De Cooman T, Gu Y, Cleeren E, Claes K, Paesschen WV, *et al.* Automated epileptic seizure detection based on wearable ECG and PPG in a hospital environment. Sensors (Basel) 2017;17:E2338.
23. Ramgopal S, Thome-Souza S, Jackson M, Kadish NE, Sánchez Fernández I, Klehm J, *et al.* Seizure detection, seizure prediction, and closed-loop warning systems in epilepsy. Epilepsy Behav 2014;37:291-307.
24. van Elmpt WJ, Nijsen TM, Griep PA, Arends JB. A model of heart rate changes to detect seizures in severe epilepsy. Seizure 2006;15:366-75.
25. Bergen DC. In a heartbeat: Autonomic changes during seizures. Epilepsy Curr 2005;5:194-6.
26. Jenssen S, Gracely EJ, Sperling MR. How long do most seizures

last? A systematic comparison of seizures recorded in the epilepsy monitoring unit. Epilepsia 2006;47:1499-503.
27. Rheims S, Alvarez BM, Alexandre V, Curot J, Maillard L, Bartolomei F, *et al.* Hypoxemia following generalized convulsive seizures: Risk factors and effect of oxygen therapy. Neurology 2019;92:e183-93.
28. Bruno E, Viana PF, Sperling MR, Richardson MP. Seizure detection at home: Do devices on the market match the needs of people living with epilepsy and their caregivers? Epilepsia 2020;61 Suppl 1:S11-24.
29. Regalia G, Onorati F, Lai M, Caborni C, Picard RW. Multimodal wrist-worn devices for seizure detection and advancing research: Focus on the Empatica wristbands. Epilepsy Res 2019;153:79-82.