Spring 6-14-2024

Technologies for Wearable Seizure Detection: A Systematic Review

Rhema Losli
Portland State University

Technologies for Wearable Seizure Detection: A Systematic Review

by

Rhema Losli

An undergraduate honors thesis submitted in partial fulfillment of the

requirements for the degree of

Bachelor of Science

in

University Honors

and

Electrical Engineering

Thesis Advisor

Dr. James McNames

Portland State University

2024

***Abstract*—Knowing when a seizure occurred is helpful because this information can be used to evaluate the effectiveness of seizure interventions and possibly alert caregivers to emergency situations. The current practice for recording seizures outside of a hospital and without sensors is through keeping a self-reported seizure diary. This practice may be unreliable if the diary is not updated or the person having the seizure does not realize it is happening. Wearable seizure detectors aim to solve this problem by reliably recording when a seizure happened and either sending out an alert or storing the data for later analysis. In this systematic review of the literature, 1,018 articles were evaluated to assess the current status of wearable seizure detection technology. A look into the challenges to developing such a device and how others have overcome some of these challenges is also discussed.**

***Index Terms*—Seizure detection device, wearable device, wearable sensors, automated seizure detection, systematic literature review.**

I. Introduction

Seizures can happen for many reasons including epilepsy which is a condition that causes recurring seizures and affects around 50 million people worldwide [1]. An important factor for managing and treating seizures is knowing when and how often they occur [2]. Many do this by keeping a seizure diary but this may be inaccurate since seizures can happen without the person being aware of it [2]. A wearable seizure detector can track seizures a person may not know is happening. Some seizure detection devices can also alert caregivers of active seizures [3].

This technology has several different use cases. Pharmaceutical companies may use it to monitor the effects of new therapies. Researchers may use it if they need to accurately count seizures when seizure diaries are unreliable. Clinicians may use it to help patients find therapies that work for them. Lastly, people with seizures may use it to alert caregivers or for their own tracking of when seizures tend to happen.

The purpose of this review is to determine what is available in terms of wearable seizure detectors, the current capabilities of wearable seizure detectors, and what improvements need to be made so that these devices provide reliable information. This systematic literature review is organized around the following research questions to summarize the current state of technology for wearable seizure detectors.

RQ1: What datasets are available that use ambulatory sensors and are recorded during daily activities?
RQ2: What is the standard for comparing wearable sensors for accurate seizure detection?
RQ3: How well do the wearable detectors perform?
RQ4: What types of seizures can be detected by the current technology?
RQ5: What challenges are researchers facing when developing a wearable device that can be used during daily activities?

II. Methods

This systematic review was conducted based on the PRISMA 2020 guidelines. The databases IEEE Xplore, PubMed, and ScienceDirect were searched on March 26, 2024 with the following search terms “(ambulatory OR wearable OR "daily activities" OR accelerometer OR "smart watch" OR "headband") AND seizure”. All databases were limited to results from 2014 to 2024 and articles written in English. IEEE Xplore was further limited to journals, magazines, and early access articles. ScienceDirect was further limited to these article type options: review articles, research articles, editorials, short communications, and other. The resulting articles were then assessed using the following inclusion/exclusion criteria.

1. Must include a wearable device
   a. Can be worn during daily activities
   b. An individual can place the device on themself
2. Must be intended for use in seizure detection
3. Must be tested on seizure data
   a. Data collected from patients doing daily activities
   b. Data collection must not come from wet electrodes
   c. Study must have 5 or more participants
4. Written in English
5. Study must be tested on humans
6. Must not be a supplemental article to a research article

One reviewer (R.L.) screened each article to determine if it met the inclusion criteria. Articles were included if it was a journal article that presented a wearable device that used sensors to capture signals and was intended specifically for seizure detection. The proposed device must also have been tested on data from people with seizures and the results of the testing are discussed in the article. These criteria were selected to answer the research questions.

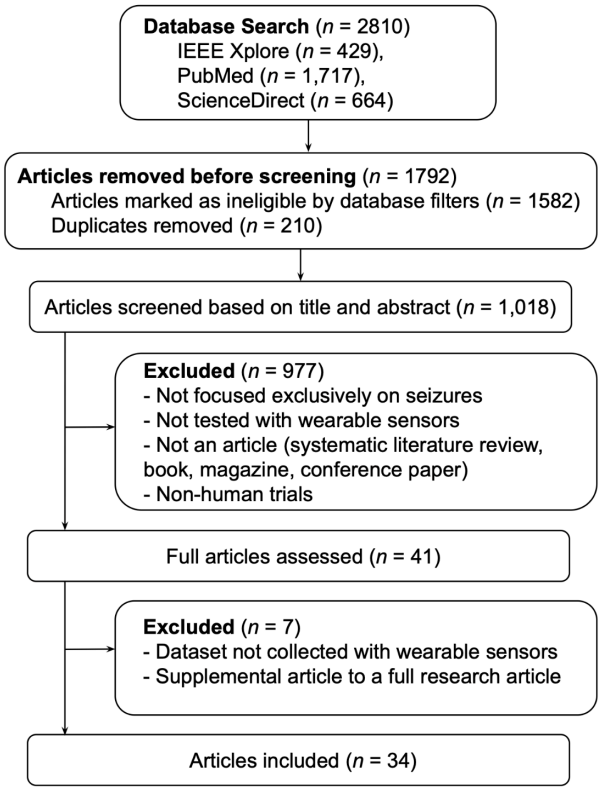

Fig. 1. Flow diagram of the article selection process.

Articles selected to be included in this review were read entirely by one reviewer (R.L.) and screened for information on the type of seizures detected, sensing technology used, the dataset used, performance, and the authors' discussion of the research. During the reading process, this information was recorded for further analysis.

The collected data was then displayed graphically. Any false alarm rate data given in units of per hour were converted to per day by multiplying by 24. Sensitivity and false alarm rate data are graphed to show the relationship between the two.

III. Results

This section describes and analyzes the results of information collected from the 34 relevant studies. Fig. 1 shows the process of evaluating which studies were included.

A. Datasets

Of the 41 articles fully read to assess if they fit the inclusion criteria, only two used data from public datasets [12], [31]. These two were ultimately excluded because some portion of the data used in each article was collected with non-wearable sensors. The result of this was that each study that met the inclusion criteria collected its own data from participants.

Of the 34 articles included in this review, two have made a way for others to gain access to their data [19], [8]. To get access to the data from Nasseri et al., a URL is provided in the data availability section of the article [19]. To get the data from Joyner et al., access is granted upon "reasonable request" of the corresponding author [8]. All other articles either stated that they were not able to share their data publicly or made no statement at all about the availability of their data.

Many of the participants in these studies were patients at epilepsy monitoring units who volunteered to be selected for a study. Studies selected participants based on unique inclusion/exclusion criteria typically having to do with participant age, seizure type, seizure duration, if seizures occurred during the monitoring period, and ability to wear the sensing device. The studies ranged in size from 10 to 243 participants, each collecting hundreds to thousands of hours of recordings (237 hrs to 15,888 hrs).

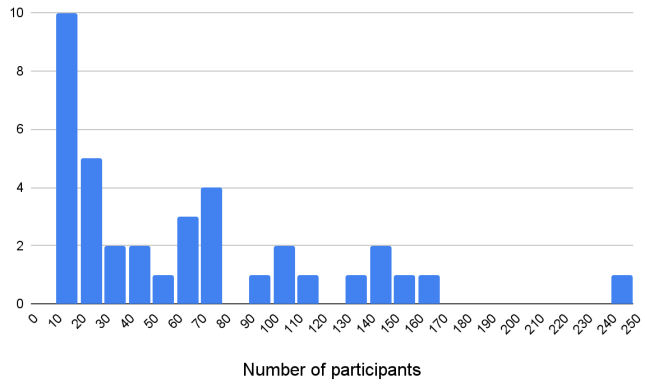

Fig. 3. Histogram of the number of participants in each study.

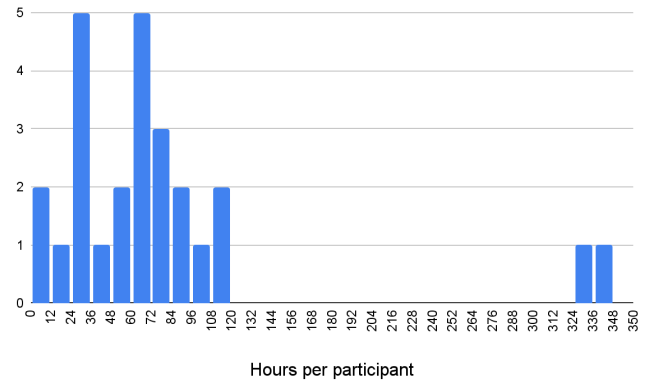

Fig. 4. Histogram of the number of hours per participant in each study.

B. Gold Standard Used

All but four of the studies collected EEG data from a standard scalp EEG system as the gold standard, in addition to their wearable sensors, for determining exactly when seizures started and stopped. This allowed for seizure detection from other sensors to be validated by expert-reviewed EEG data. However, this means that studies using scalp EEG as the gold standard must limit the activities the participants can do because scalp EEG is not wearable.

The four exceptions to the scalp EEG gold standard are [19], [40], [25], and [8]. Intracranial EEG was used in [19] which allowed participants to use the wearable device for months in everyday situations while still having EEG data as a reference. In [8] and [25], behind-the-ear EEG sensors were used to provide EEG data as a reference while allowing participants to go about their normal activities. Participants of [40] self-reported the start and stop times of their seizures to provide a reference to the wearable device.

Of the studies that stated what the participants did during recordings, these studies instructed the participants to perform tasks such as using a stationary bike, making coffee and food, performing daily hygiene, and playing video games [15], [33], [29]. To induce seizures, some participants had their anti-seizure medication reduced, performed exercises to raise their heart rate, and were sleep-deprived [9]. Other studies did not restrict what the participants could do during the recording period [19], [18], [21], [10], [35], [25], [40]. The activity of the participants in almost every study could not fully reflect a person's daily life because of the limitations of scalp EEG.

C. Devices and Sensors

The devices reported in the selected studies use various wearable sensors to detect seizures. Sensors were used to measure electroencephalography (EEG), electromyography (EMG), electrocardiography (ECG), electrodermal activity (EDA), movement through accelerometers (ACC) and gyroscopes (GYRO), heart rate (HR), body temperature (TEMP), photoplethysmography (PPG) for blood pulse volume, respiration (RESP), sound through microphones (MIC), and blood oxygen saturation (SpO2). Some studies used off-the-shelf devices to collect data which are listed in Appendix A.

The form factor of the devices was typically an adhesive patch containing electrodes or a wrist band but there was also a headband, wired earbuds, a finger clip, and a vest containing sensors. Different sensors were required to be placed on specific parts of the body such as the forehead, in-ear, behind the ear, arm (bicep), chest (below the heart or clavicle), wrist, finger, waist, and ankle. Fig. 5 shows the location of the sensors along with how many studies used this location.

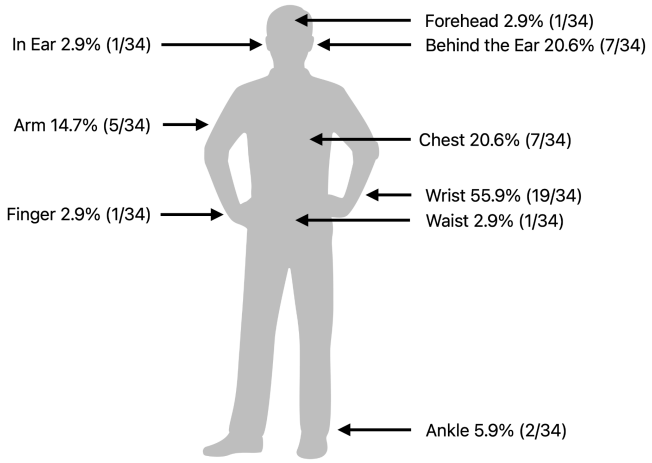

Fig. 5. Sensor locations on the body and associated number of studies.

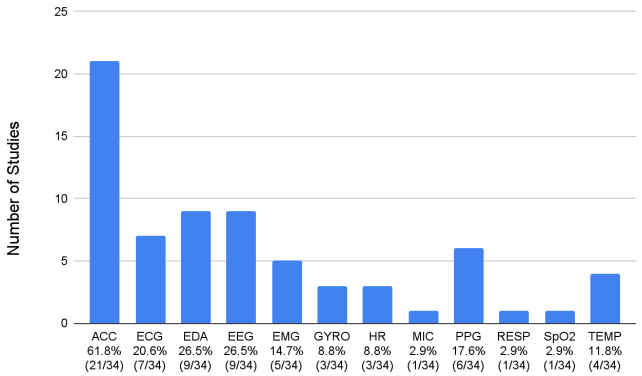

Fig. 6. Plot of how frequently each sensor type was used.

D. Seizure Types Detected

Looking into what seizure types were used to validate the wearable seizure detectors also offers insight into the state of the technology. Fig. 7 shows that most studies tested their device on seizures with motor manifestations. This seems to line up with Fig. 6 which shows that accelerometers are the most commonly used sensor. Fig. 7 also shows that only 3 studies were interested in non-motor only seizure data to test their device. This may be caused by non-motor seizures being more difficult to detect or because of less of a demand for wearable seizures that only detect non-motor seizures.

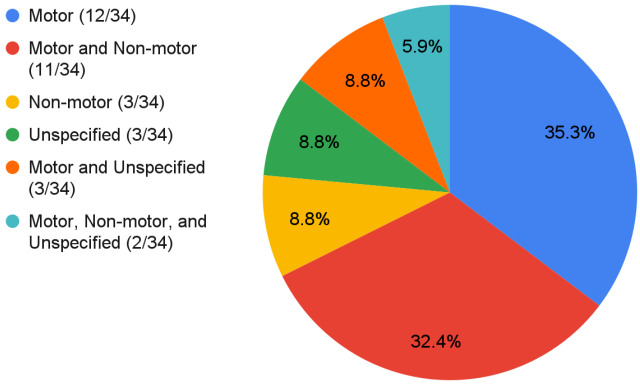

Fig. 7. Percentage of articles that use a combination of motor, non-motor, or unspecified seizure types.

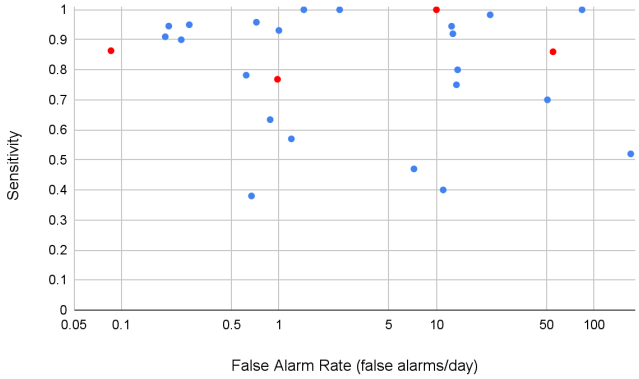

Fig. 8. Sensitivity vs. False Alarm Rate per Day from 26 articles.

It is important to note that Fig. 7 does not show how many participants had motor or non-motor seizures, but rather how many studies tested their device with motor or non-motor seizure data. A full list of seizure types and now many articles mention each type can be found in Appendix B.

E. Performance and User Experience

The selected studies were examined for statements about performance regarding the timing of seizure detection, latency (time from seizure start to detection), sensitivity, false alarm rate (FAR), positive predictive value, and area under the receiver operator characteristic curve. Few studies reported their system's latency, positive predictive value, or area under the receiver operator characteristic curve so these performance metrics will not be discussed in this review. Most did however report sensitivity and FAR. This data is shown in Fig. 8. Any studies missing either sensitivity or FAR data were not included in Fig. 8. Twenty-six studies did report this data. False alarm rates given in events per hour were converted to events per day by multiplying by 24. This may introduce error into the FAR since the FAR during the day versus during the night may be different and nothing was done to take this into account during conversion.

Fig. 8 shows that most seizure detection systems have a sensitivity better than 0.5 and a FAR less than 24 per day or 1 per hour. The red dots represent studies that did not use the traditional scalp EEG as their gold standard. From left to right, the red dots represent studies that used intracranial EEG, self-reporting, and the last two used behind-the-ear EEG as their gold standard.

F. User Experience

Some studies also collected information from the participants about their experience with the detection system. User experience reports from devices that used adhesive patches were mixed. Some studies reported that their participants were not worried about the look of the device and that it was comfortable to wear [5], [24]. Other studies with patches reported that the device could be uncomfortable and that users were worried about wearing the device in public [18], [25]. One thing that all studies reported was mild to moderate skin irritation or discomfort when wearing the device in the heat [5], [18], [24], [25], [28].

Adherence seemed to be high in studies where the device was in the form of a wrist band but one participant dropped out of their study due to the inconvenience of charging and managing the device [19] and three dropped out of another study due to discomfort caused by the device [10]. In [19] it was reported that the latency in detection was acceptable for most participants [21].

The study using an in-ear sensor reported that their participants rated the comfort level a 7.5 out of 10 and was overall well-liked [8]. Only minor adverse reactions were reported and there was no loss of hearing from the device [8].

G. Suggested Future Research

Almost all authors of the included articles made suggestions for future research. The trends of these suggestions are summarized here. Many authors wanted to continue testing their detection system at a higher study phase which would mean more participants and studying the performance in the participants' natural setting [5], [6], [8], [9], [13], [15]–[17], [23], [27], [28], [33]–[37], [39]. Many authors also suggested that more

research should be done to improve the performance of their systems. The proposed ways of doing this were to use detection algorithms tailored to an individual, to improve their methods of data processing, and to use more sensors, different sensors, or better sensors. [5]–[7], [10], [11], [14], [16], [18], [20]–[26], [28]–[30], [34], [35], [38], [40].

IV. Discussion

There are very few options for people with seizures to detect when they are having a seizure in a normal environment. Answering this review's research questions provides insight into why this may be. The first four research questions have been answered in the results section of this review. To answer RQ5, a look at why some of the prior research questions contributed to the challenges researchers face is discussed.

A challenge stemming from RQ1 is the limited amount of publicly available databases that use wearable sensors. The search performed for this review encountered only two articles where the authors made a way for others to get access to their data that was collected using wearable sensors. Anyone trying to develop this technology will most likely have to collect their own data from people with seizures in order to test if their seizure detection device is viable.

A challenge stemming from RQ2 is proving that any seizure detection system works in a natural environment because there are very few ways of knowing when a seizure truly happened. The current gold standard for seizure detection is video-EEG but this cannot be collected while a person is going about their daily activities. Of the four studies that did not use video-EEG as their gold standard, the use of intracranial-EEG seems the most likely to provide a true comparison for the wearable seizure detector being tested. However, the limited number of people with intracranial EEG may make it challenging to conduct a large enough study. Behind-the-ear EEG is another gold standard used in these articles. Vandercasteele et al. found that a neurologist visually reviewing behind-the-ear EEG data on average had a sensitivity of 65.7% and specificity of 94.4% [6]. They also found that the neurologist was better at detecting certain types of seizures so this may be a usable gold standard in certain applications [6]. Elger and Hoppe found that, on average, participants recorded fewer than 50% of their seizures in seizure diaries [41]. This shows that seizure diaries are not a useful gold standard for long-term monitoring.

A challenge stemming from RQ3 is achieving acceptable performance so that wearable seizure detectors provide useful information. It is unclear from the results of this review what the level of performance should be for use as a commercial or medical device. Certainly, users of the device will not tolerate a high false alarm rate if they are alerted every time. It is recommended by the author that the sensitivity be at least 90% and the false alarm rate be no more than 10% of the true number of seizures.

Lastly, it is a challenge to develop a device that is comfortable enough and unobtrusive enough to be worn almost every day. Many of the studies that reported the users' experience with the device had participants drop out of the study or not wear the device for long periods because of discomfort. No matter how accurate the device is, it can only provide useful information if the user is willing to wear it long enough for that information to be collected.

V. Summary

This systematic review sought to answer questions about what datasets are publicly available that use wearable sensors, what seizures can be detected, how well wearable detectors perform, what is the standard for checking data collected by these devices, and the challenges to developing a wearable seizure detector. Based on the information gathered from 34 articles, there are still significant challenges to developing a wearable seizure detector that can be used in a natural setting because current methods of validating data from wearable detectors in most cases cannot be done outside of a hospital. Other limitations to the technology are the performance of seizure detection and the ability for users to wear the device long-term.

Future research should strive to solve the problem of validating the proposed seizure detection device while being worn by a person during daily activities. This will allow devices in the clinical trial phase to progress to being used for their intended purpose. The wider the variety of seizure detectors available to those who want this technology, the more that can be learned about seizures in all settings.

APPENDIX A

List of off-the-shelf wearable devices used in the selected studies:

- 180 eMotion Faros
- Affectiva Q-curve
- Apple iPod Touch (4th generation)
- Biopac MP160
- Biopac MP36
- Bittium Faros 180
- Brain Sentinel
- Brainlink Lite device (Macrotellect) (Epihunter)
- Empatica E3
- Empatica E4
- ePatch
- Epileptic seizure Detector Developed by IctalCare (EDDI)
- Fitbit Charge 2
- iCalm
- Nonin WristOx2
- RISE Acreo
- Sensor Dot
- Shimmer3
- SmartWatch by SmartMonitor
- SPEAC System
- TrackIT T4a

APPENDIX B

List of seizure types used to test wearable devices divided into motor, non-motor, and unspecified seizure types [42]–[53]:

- Motor
  - Automatisms (2/34)
  - Bilateral tonic-clonic (1/34)
  - Clonic (2/34)
  - Epileptic Seizures (motor only) (1/34)
  - Focal automatisms (1/34)
  - Focal clonic (3/34)
  - Focal motor (2/34)
  - Focal motor tonic-clonic (2/34)
  - Focal to bilateral tonic-clonic (9/34)
  - Focal tonic (2/34)
  - Generalized epileptic spasms (2/34)
  - Hyperkinetic/hypermotor (3/34)
  - Motor element (1/34)
  - Myoclonic (3/34)
  - Partial motor (1/34)
  - Partial with secondary generalization (1/34)
  - Psychogenic nonepileptic seizures (motor only) (1/34)
  - Secondary generalization (1/34)
  - Tonic (4/34)
  - Tonic-clonic (18/34)
- Non-motor
  - Absence (4/34)
  - Autonomic (1/34)
  - Focal aware (2/34)
  - Focal behavior arrest (1/34)
  - Focal non-motor (1/34)
  - Focal subclinical (1/34)
  - Subclinical (1/34)
- Motor and/or Non-motor
  - Complex partial (3/34)
  - Dyscognitive (1/34)
  - Extratemporal lobe epilepsy (1/34)
  - Front-temporal lobe seizures (1/34)
  - Focal impaired awareness (2/34)
  - Psychogenic nonepileptic seizures (3/34)
  - Partial onset with minimal motor component (1/34)
  - Temporal lobe epilepsy (1/34)
- Unspecified (11/34)
  - Focal (5/34)
  - Generalized (3/34)
  - Unknown (3/34)

REFERENCES

[1] "Epilepsy," www.who.int, Jun. 20, 2019. https://www.who.int/en/news-room/fact-sheets/detail/epilepsy

[2] S. C. Schachter MD, "Tracking Seizures," epilepsy.com, Aug. 20, 2021. https://www.epilepsy.com/manage/tracking (accessed Apr. 16, 2024).

[3] "Role of Seizure Alerts," Epilepsy Foundation. https://www.epilepsy.com/complications-risks/early-death-sudep/role-seizure-alerts

[4] Cleveland Clinic, "Seizure: What It Is, Causes, Symptoms & Types," Cleveland Clinic, Apr. 13, 2022. https://my.clevelandclinic.org/health/diseases/22789-seizure

[5] R. Proost, J. Macea, L. Lagae, W. Van Paesschen, and K. Jansen, "Wearable detection of tonic seizures in childhood epilepsy: An exploratory cohort study," Epilepsia, vol. 64, no. 11, pp. 3013–3024, Nov. 2023, doi: 10.1111/epi.17756.

[6] K. Vandecasteele et al., "Visual seizure annotation and automated seizure detection using behind-the-ear electroencephalographic channels," Epilepsia, vol. 61, no. 4, pp. 766–775, Apr. 2020, doi: 10.1111/epi.16470.

[7] C. Baumgartner, L. E. Whitmire, S. R. Voyles, and D. P. Cardenas, "Using sEMG to identify seizure semiology of motor seizures," Seizure, vol. 86, pp. 52–59, Mar. 2021, doi: 10.1016/j.seizure.2020.11.013.

[8] M. Joyner et al., "Using a standalone ear-EEG device for focal-onset seizure detection," Bioelectron Med, vol. 10, no. 1, p. 4, Feb. 2024, doi: 10.1186/s42234-023-00135-0.

[9] M. Velez, R. S. Fisher, V. Bartlett, and S. Le, "Tracking generalized tonic-clonic seizures with a wrist accelerometer linked to an online database," Seizure, vol. 39, pp. 13–18, Jul. 2016, doi: 10.1016/j.seizure.2016.04.009.

[10] D. Johansson et al., "Tonic-clonic seizure detection using accelerometry-based wearable sensors: A prospective, video-EEG controlled study," Seizure, vol. 65, pp. 48–54, Feb. 2019, doi: 10.1016/j.seizure.2018.12.024.

[11] V. D. Naganur, S. Kusmakar, Z. Chen, M. S. Palaniswami, P. Kwan, and T. J. O'Brien, "The utility of an automated and ambulatory device for detecting and differentiating epileptic and psychogenic non-epileptic seizures," Epilepsia Open, vol. 4, no. 2, pp. 309–317, Jun. 2019, doi: 10.1002/epi4.12327.

[12] K. Vandecasteele *et al.*, "The power of ECG in multimodal patient-specific seizure monitoring: Added value to an EEG-based detector using limited channels," *Epilepsia*, vol. 62, no. 10, pp. 2333–2343, Oct. 2021, doi: 10.1111/epi.16990.

[13] A. L. Patterson et al., "SmartWatch by SmartMonitor: Assessment of Seizure Detection Efficacy for Various Seizure Types in Children, a Large Prospective Single-Center Study," Pediatr Neurol, vol. 53, no. 4, pp. 309–311, Oct. 2015, doi: 10.1016/j.pediatrneurol.2015.07.002.

[14] J. Tang et al., "Seizure detection using wearable sensors and machine learning: Setting a benchmark," Epilepsia, vol. 62, no. 8, pp. 1807–1819, Aug. 2021, doi: 10.1111/epi.16967.

[15] J. Jeppesen et al., "Seizure detection based on heart rate variability using a wearable electrocardiography device," Epilepsia, vol. 60, no. 10, pp. 2105–2113, Oct. 2019, doi: 10.1111/epi.16343.

[16] F. Onorati et al., "Prospective Study of a Multimodal Convulsive Seizure Detection Wearable System on Pediatric and Adult Patients in the Epilepsy Monitoring Unit," Front Neurol, vol. 12, p. 724904, 2021, doi: 10.3389/fneur.2021.724904.

[17] J. Jeppesen, J. Christensen, P. Johansen, and S. Beniczky, "Personalized seizure detection using logistic regression machine learning based on wearable ECG-monitoring device," Seizure, vol. 107, pp. 155–161, Apr. 2023, doi: 10.1016/j.seizure.2023.04.012.

[18] J. M. Nielsen et al., "Out-of-hospital multimodal seizure detection: a pilot study," BMJ Neurol Open, vol. 5, no. 2, p. e000442, 2023, doi: 10.1136/bmjno-2023-000442.

[19] M. Nasseri et al., "Non-invasive wearable seizure detection using long-short-term memory networks with transfer learning," J Neural Eng, vol. 18, no. 5, Apr. 2021, doi: 10.1088/1741-2552/abef8a.

[20] H. Chen et al., "Neonatal Seizure Detection Using a Wearable Multi-Sensor System," Bioengineering (Basel), vol. 10, no. 6, p. 658, May 2023, doi: 10.3390/bioengineering10060658.

[21] F. Onorati et al., "Multicenter clinical assessment of improved wearable multimodal convulsive seizure detectors," Epilepsia, vol. 58, no. 11, pp. 1870–1879, Nov. 2017, doi: 10.1111/epi.13899.

[22] D. Cogan, J. Birjandtalab, M. Nourani, J. Harvey, and V. Nagaraddi, "Multi-Biosignal Analysis for Epileptic Seizure Monitoring," Int J Neural Syst, vol. 27, no. 1, p. 1650031, Feb. 2017, doi: 10.1142/S0129065716500313.

[23] S. Böttcher et al., "Intra- and Inter-Subject Perspectives on the Detection of Focal Onset Motor Seizures in Epilepsy Patients," Sensors (Basel), vol. 22, no. 9, p. 3318, Apr. 2022, doi: 10.3390/s22093318.

[24] J. Macea, M. Bhagubai, V. Broux, M. De Vos, and W. Van Paesschen, "In-hospital and home-based long-term monitoring of focal epilepsy with a wearable electroencephalographic device: Diagnostic yield and user experience," Epilepsia, vol. 64, no. 4, pp. 937–950, Apr. 2023, doi: 10.1111/epi.17517.

[25] L. Swinnen et al., "Home recording of 3-Hz spike-wave discharges in adults with absence epilepsy using the wearable Sensor Dot," Epilepsia, vol. 65, no. 2, pp. 378–388, Feb. 2024, doi: 10.1111/epi.17839.

[26] J. Mittlesteadt et al., "Evaluation of an Activity Tracker to Detect Seizures Using Machine Learning," J Child Neurol, vol. 35, no. 13, pp. 873–878, Nov. 2020, doi: 10.1177/0883073820937515.

[27] A. M. Husain, A. R. Towne, D. K. Chen, L. E. Whitmire, S. R. Voyles, and D. P. Cardenas, "Differentiation of Epileptic and Psychogenic Nonepileptic Seizures Using Single-Channel Surface Electromyography," J Clin Neurophysiol, vol. 38, no. 5, pp. 432–438, Sep. 2021, doi: 10.1097/WNP.0000000000000703.

[28] J. J. Halford et al., "Detection of generalized tonic-clonic seizures using surface electromyographic monitoring," Epilepsia, vol. 58, no. 11, pp. 1861–1869, Nov. 2017, doi: 10.1111/epi.13897.

[29] S. Böttcher et al., "Detecting Tonic-Clonic Seizures in Multimodal Biosignal Data From Wearables: Methodology Design and Validation," JMIR Mhealth Uhealth, vol. 9, no. 11, p. e27674, Nov. 2021, doi: 10.2196/27674.

[30] Y. Gu et al., "Comparison between Scalp EEG and Behind-the-Ear EEG for Development of a Wearable Seizure Detection System for Patients with Focal Epilepsy," Sensors (Basel), vol. 18, no. 1, p. 29, Dec. 2017, doi: 10.3390/s18010029.

[31] M. Hegarty-Craver, B. L. Kroner, A. Bumbut, S. J. DeFilipp, W. D. Gaillard, and K. H. Gilchrist, "Cardiac-based detection of seizures in children with epilepsy," Epilepsy Behav, vol. 122, p. 108129, Sep. 2021, doi: 10.1016/j.yebeh.2021.108129.

[32] J. Gubbi, S. Kusmakar, A. S. Rao, B. Yan, T. OBrien, and M. Palaniswami, "Automatic Detection and Classification of Convulsive Psychogenic Nonepileptic Seizures Using a Wearable Device," IEEE J Biomed Health Inform, vol. 20, no. 4, pp. 1061–1072, Jul. 2016, doi: 10.1109/JBHI.2015.2446539.

[33] S. Beniczky, I. Conradsen, O. Henning, M. Fabricius, and P. Wolf, "Automated real-time detection of tonic-clonic seizures using a wearable EMG device," Neurology, vol. 90, no. 5, pp. e428–e434, Jan. 2018, doi: 10.1212/WNL.0000000000004893.

[34] K. Vandecasteele et al., "Automated Epileptic Seizure Detection Based on Wearable ECG and PPG in a Hospital Environment," Sensors (Basel), vol. 17, no. 10, p. 2338, Oct. 2017, doi: 10.3390/s17102338.

[35] S. Kusmakar, C. Karmakar, B. Yan, T. Obrien, R. Muthuganapathy, and M. Palaniswami, "Automated Detection of Convulsive Seizures Using a Wearable Accelerometer Device," IEEE Trans Biomed Eng, vol. 66, no. 2, pp. 421–432, Feb. 2019, doi: 10.1109/TBME.2018.2845865.

[36] G. Japaridze et al., "Automated detection of absence seizures using a wearable electroencephalographic device: a phase 3 validation study and feasibility of automated behavioral testing," Epilepsia, vol. 64 Suppl 4, pp. S40–S46, Dec. 2023, doi: 10.1111/epi.17200.

[37] A. Hamlin, E. Kobylarz, J. H. Lever, S. Taylor, and L. Ray, "Assessing the feasibility of detecting epileptic seizures using non-cerebral sensor data," Comput Biol Med, vol. 130, p. 104232, Mar. 2021, doi: 10.1016/j.compbiomed.2021.104232.

[38] S. Yu et al., "Artificial intelligence-enhanced epileptic seizure detection by wearables," Epilepsia, vol. 64, no. 12, pp. 3213–3226, Dec. 2023, doi: 10.1111/epi.17774.

[39] L. Swinnen et al., "Accurate detection of typical absence seizures in adults and children using a two-channel

electroencephalographic wearable behind the ears," Epilepsia, vol. 62, no. 11, pp. 2741–2752, Nov. 2021, doi: 10.1111/epi.17061.

[40] C. Dong et al., "A Two-Layer Ensemble Method for Detecting Epileptic Seizures Using a Self-Annotation Bracelet With Motor Sensors," IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1–13, 2022, doi: 10.1109/TIM.2022.3173270.

[41] C. E. Elger and C. Hoppe, "Diagnostic challenges in epilepsy: seizure under-reporting and seizure detection," *Lancet Neurol*, vol. 17, no. 3, pp. 279–288, Mar. 2018, doi: 10.1016/S1474-4422(18)30038-3.

[42] "Extratemporal Lobe Epilepsies." Accessed: Jun. 10, 2024. [Online]. Available: https://www.uclahealth.org/medical-services/neurosurgery/conditions-treated/extratemporal-lobe-epilepsies

[43] "Focal Aware Seizures (Simple Partial)," Epilepsy Foundation. Accessed: Jun. 10, 2024. [Online]. Available: https://www.epilepsy.com/what-is-epilepsy/seizure-types/focal-onset-aware-seizures

[44] "Focal Bilateral Tonic Clonic Seizures (Secondarily Generalized Seizures)," Epilepsy Foundation. Accessed: Jun. 10, 2024. [Online]. Available: https://www.epilepsy.com/what-is-epilepsy/seizure-types/focal-bilateral-tonic-clonic-seizures

[45] "Focal Dyscognitive Seizures – Epilepsy Ontario." Accessed: Jun. 10, 2024. [Online]. Available: https://epilepsyontario.org/about-epilepsy/types-of-seizures/complex-partial-seizures/

[46] "Focal Impaired Awareness Seizures," Epilepsy Foundation. Accessed: Jun. 10, 2024. [Online]. Available: https://www.epilepsy.com/what-is-epilepsy/seizure-types/focal-onset-impaired-awareness-seizures

[47] "Frontal lobe seizures - Symptoms and causes - Mayo Clinic." Accessed: Jun. 10, 2024. [Online]. Available: https://www.mayoclinic.org/diseases-conditions/frontal-lobe-seizures/symptoms-causes/syc-20353958

[48] "Generalized tonic-clonic seizure Information | Mount Sinai - New York," Mount Sinai Health System. Accessed: Jun. 10, 2024. [Online]. Available: https://www.mountsinai.org/health-library/diseases-conditions/generalized-tonic-clonic-seizure

[49] R. S. Fisher *et al.*, "Operational classification of seizure types by the International League Against Epilepsy: Position Paper of the ILAE Commission for Classification and Terminology," *Epilepsia*, vol. 58, no. 4, pp. 522–530, Apr. 2017, doi: 10.1111/epi.13670.

[50] "Psychogenic Nonepileptic Seizures | PNES," Epilepsy Foundation. Accessed: Jun. 10, 2024. [Online]. Available: https://www.epilepsy.com/diagnosis/imitators-epilepsy/psychogenic-nonepileptic-seizures

[51] "Subclinical Seizures," Cedars-Sinai. Accessed: Jun. 10, 2024. [Online]. Available: https://www.cedars-sinai.org/health-library/articles.html

[52] "Temporal Lobe Epilepsy (TLE)," Epilepsy Foundation. Accessed: Jun. 10, 2024. [Online]. Available: https://www.epilepsy.com/what-is-epilepsy/syndromes/temporal-lobe-epilepsy

[53] A. Wachtel, "Types of Epileptic Seizures," Barrow Neurological Institute. Accessed: Jun. 10, 2024. [Online]. Available: https://www.barrowneuro.org/resource/types-of-epileptic-seizures-2/