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Accuracy and Cost Tradeoffs in Wearable Detection of Convulsive Seizures: A Comparative Study of Sensor Modalities

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***Abstract*— Objective: To systematically review and compare the diagnostic accuracy and relative cost of wearable multimodal detection systems for convulsive seizures.**

***Methods:* A comprehensive search of PubMed/MEDLINE identified studies published between 2015 and 2025 reporting diagnostic accuracy of wearable seizure detection using accelerometer (ACC), gyroscope (Gyro), electrodermal activity (EDA), photoplethysmography (PPG), electrocardiography (ECG), or electromyography (EMG). Only free-full text, English-language articles with quantitative outcomes were included. Data extracted included sensitivity, false alarm rate (FAR) and sensor modalities. Risk of bias was assessed using QUADAS-2, with studies at high risk of bias (n = 4; one responder-only ECG study, three using cross-validation with internal threshold optimization) excluded from the final synthesis.**

***Results:* Eleven studies met inclusion criteria; seven were retained after risk-of-bias assessment. Across retained studies, sensitivity for convulsive seizure detection was high (84.8–96.0%) with varying FARs (0.21–0.88 per 24 hours). Simpler accelerometer- and gyroscope-based devices performed as well as or better than more complex multimodal systems incorporating ECG, EMG, or EDA. Relative cost analysis grouped devices into three tiers: (1) low-cost ACC/Gyro, (2) mid-cost EDA/PPG, and (3) higher-cost ECG/EMG. On average, low-cost devices achieved comparable sensitivity with lower FARs than higher-cost modalities. Wearable detection of convulsive seizures shows remarkable accuracy across different sensor modalities, but cost and complexity do not necessarily enhance accuracy. Wrist-worn accelerometer-based systems offer a more practical and cost-effective solution for use in real-world settings, but additional prospective validation and improved standardized outcome reporting are required to establish a stronger evidence base.**

***Index Terms*— Accuracy and Cost Tradeoffs, Wearable Detection, Convulsive Seizures, Sensor Modalities**

I. INTRODUCTION

Convulsive seizures, including Generalized Tonic–Clonic Seizures (GTCS) and Focal-To-Bilateral Tonic–Clonic Seizures (FBTCS), are among the most dangerous seizure types due to their association with injury, sudden unexpected death in epilepsy (SUDEP), and significant impacts on quality of life. Reliable seizure detection is therefore critical for both clinical monitoring and patient safety. While inpatient video-EEG (vEEG) remains the diagnostic gold standard, patients need reliable monitoring solutions in real-world environments as well.

Wearable devices have emerged as a promising solution to this. Advances in sensor technology and machine learning have enabled the development of multimodal systems incorporating accelerometry, gyroscopes, electrocardiography (ECG), electromyography (EMG), electrodermal activity (EDA), and photoplethysmography (PPG). These approaches aim to capture both motor and autonomic features of convulsive seizures, offering noninvasive and continuous monitoring outside the hospital.

A key challenge, however, lies in balancing accuracy with cost and usability. High sensitivity and low false alarm rates are essential for clinical reliability, but complex multimodal systems often require costly sensors, greater power consumption, and reduced wearability. Conversely, simpler devices, particularly accelerometer-based wristbands, are inexpensive and accessible but may risk reduced specificity. Understanding these trade-offs is essential to inform future device development and guide clinical and commercial deployment.

Previous reviews have described the performance of wearable seizure detection technologies, but few have systematically compared diagnostic accuracy alongside relative sensor cost. This gap is particularly relevant for translating detection systems into real-world practice, where affordability is as important as technical performance.

This review synthesizes evidence from recent studies (2015–2025) on multimodal wearable detection of convulsive seizures. evaluate diagnostic accuracy metrics, including sensitivity and false alarm rates, and stratify devices by sensor modality into relative cost tiers. By comparing accuracy and cost simultaneously, this review aims to provide a practical perspective on the feasibility and future directions of wearable seizure detection.

II. METHODS

A search was conducted in the PubMed/MEDLINE

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database from 2015 to 2025 to identify studies evaluating multimodal wearable seizure detection systems. Only open access, full-text articles in English were considered for inclusion. The search strategy combined terms related to seizures (eg., Epilepsy), wearable sensors (eg., accelerometer, gyroscope, electromyography [EMG], electrocardiography [ECG], electrodermal activity [EDA], photoplethysmography [PPG]) and diagnostic accuracy (eg., sensitivity, specificity, false alarm, false-positive and accuracy). Studies were included if they reported diagnostic accuracy outcomes for convulsive seizures (generalized tonic–clonic and/or focal-to-bilateral tonic–clonic) using multimodal wearables. Exclusion criteria were non-human studies, studies published before 2015, non-English language reports, and lack of quantitative diagnostic performance metrics. This made sure only relevant studies were included in the final synthesis.

Data extraction and qualitative synthesis were performed at the individual level. Extracted data included study design, population, wearable sensor combinations and diagnostic performance (sensitivity, false alarm rate)

Risk of bias was assessed using the QUADAS-2 tool following the Cochrane Collaboration's guidelines. Four domains were evaluated: patient selection, index test, reference standard, and flow and timing, with signaling questions tailored to wearable seizure detection. During risk of bias assessment, four studies were excluded from the final evidence synthesis due to high risk of bias, ensuring only high-quality data was used for the evaluation.

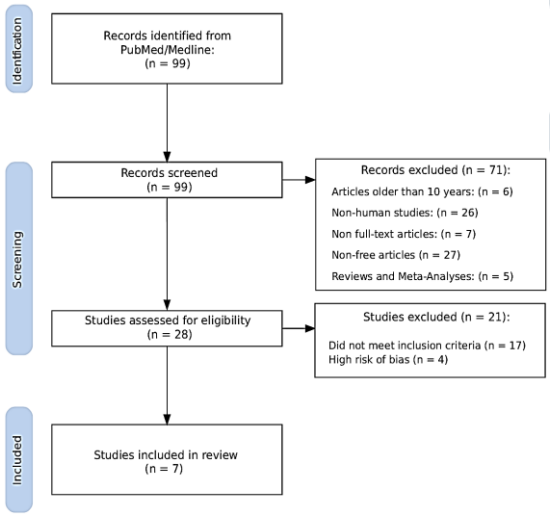

Figure 1. Flow diagram for the review and inclusion criteria

III. RESULTS

Risk of Bias

Risk of bias was evaluated for all 11 studies meeting initial inclusion criteria using the QUADAS-2 tool. Most studies prospectively enrolled patients undergoing video-EEG monitoring, reducing the likelihood of selection bias. However, one study using ECG to detect seizures, limited inclusion to **ECG "responders"** (patients with >50 bpm ictal heart rate increase). This exclusion criterion directly favored individuals with detectable autonomic change, introducing high selection bias. The study was therefore removed from the final synthesis.

Most studies evaluated wearable algorithms independently of the clinical gold standard. In most cases, reviewers interpreting the vEEG reference standard were **blinded** to the wearable detection output, minimizing index test bias. However, three studies used **cross-validation approaches** (10-fold CV or LOOCV) with threshold optimization performed within the training folds. This practice risks inflating sensitivity and underestimating false alarms due to lack of true external validation. These studies were excluded from the final synthesis for high index test bias.

Across nearly all studies, vEEG was used as the reference standard. In most cases, seizure annotations were conducted by expert reviewers blinded to the wearable data. A small number of reports did not clearly describe the blinding process, leading to an "unclear" rating in the reference standard domain.

The flow and timing domain was generally low risk. Most studies evaluated all enrolled patients and seizures within a defined monitoring period and ran index tests and the reference standard concurrently.

Diagnostic sensitivity for convulsive seizure detection was consistently high across all included wearable modalities, with results summarized in Table 1. Reported sensitivities ranged from 84.8% to 96%, with a pooled unweighted mean sensitivity of approximately 90.7%.

The highest sensitivity was achieved with a wristband accelerometer + gyroscope device (96%), while the lowest was reported for the connected shirt (ECG + accelerometer) system (84.8%). Other modalities, including wearable EMG (93.8%), bilateral wrist-worn accelerometers (90%), wristwatch accelerometers (92.3%), wrist-worn ACC + EDA (91%) and the off-the-shelf Samsung smartwatch (87%), demonstrated performance clustered around the pooled mean. Although sensitivity remained above 85% across all sensor modalities, the differences suggest that relatively simple motion-based systems (e.g., accelerometer + gyroscope) provide the most consistent detection of convulsive seizures. In contrast, multimodal systems incorporating ECG or EMG did not show clear sensitivity advantages, though they may contribute to other outcomes such as specificity or false alarm reduction.

Table.1 Sensitivity of Wearable Devices for Convulsive Seizure Detection Across Sensor Modalities

Study/Lead Author	Index Test Device/Modality	Sensitivity
Gharbi et al. (2024)	Connected Shirt ECG, ACC (Hexoskin)	84.80%

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Study/Lead Author	Index Test Device/Modality	Sensitivity
Larsen et al. (2024)	Wristband ACC + Gyro	96.00%
Beniczky et al. (2018)	Wearable EMG (EDDI)	93.80%
Velez et al. (2016)	Wristwatch ACC (SmartWatch)	92.30%
Johansson et al. (2019)	Bilateral Wrist-worn ACC (Shimmer3)	90.00%
Böttcher et al. (2021)	Wrist-worn ACC + EDA (Empatica E4)	91.00%
Vakilna et al. (2024)	OTS Samsung Watch HR, ACC, Gyro	87.00%

False Alarm Rates Across Devices

False alarm rates (FAR) varied more widely across modalities than sensitivity, as summarized in **Table 2**. Reported FARs ranged from **0.21 to 0.88 per 24 hours**, with a pooled unweighted mean of approximately **0.45 per 24 hours**.

The lowest FAR was observed in the off-the-shelf Samsung smartwatch (HR, ACC, gyroscope) at 0.21/24 h, closely followed by the bilateral wrist-worn accelerometers (0.24/24 h) and the wristband ACC + gyroscope device (0.23/24 h). In contrast, higher FARs were reported for the wristwatch accelerometer (0.88/24 h), wearable EMG (0.67/24 h), and connected shirt ECG + ACC (0.55/24 h). The wrist-worn ACC + EDA device (0.37/24 h) demonstrated intermediate performance.

Overall, these findings highlight greater variability in FAR than sensitivity across devices, with simpler accelerometer-based systems achieving the most favorable balance of high accuracy and low false alarms.

Table 2.: False Alarm Rates of Wearable Devices for Convulsive Seizure Detection Across Sensor Modalities

Study/Lead Author	Index Test Device/Modality	False Alarm Rate (FAR)
Gharbi et al. (2024)	Connected Shirt ECG, ACC (Hexoskin)	0.55
Larsen et al. (2024)	Wristband ACC + Gyro	0.23
Beniczky et al. (2018)	Wearable EMG (EDDI)	0.67
Velez et al. (2016)	Wristwatch ACC (SmartWatch)	0.88
Johansson et al. (2019)	Bilateral Wrist-worn ACC (Shimmer3)	0.24
Böttcher et al. (2021)	Wrist-worn ACC + EDA (Empatica E4)	0.37
Vakilna et al. (2024)	OTS Samsung Watch HR, ACC, Gyro	0.21

Relative-Cost Tier Analysis

To facilitate comparison between detection accuracy and hardware expense, the included devices were grouped into three relative cost tiers based on the underlying sensor modalities.

*Tier 1 (Low cost – accelerometer/gyroscope only)***:** Wristband ACC + gyroscope, bilateral wrist-worn ACC, wristwatch ACC, and the off-the-shelf Samsung smartwatch. These devices rely on widely available inertial sensors already embedded in consumer electronics, making them the most affordable.

Tier 2 (Moderate cost – EDA and/or PPG sensors): The wrist-worn ACC + EDA device (Empatica E4) falls into this tier, reflecting the added cost of biosensors beyond inertial motion detection.

Tier 3 (High cost – ECG or EMG sensors): The connected shirt (ECG + ACC) and wearable EMG system (EDDI) represent the highest-cost modalities due to the need for specialized electrodes and hardware.

Across these tiers, accuracy outcomes were generally comparable, with Tier 1 devices achieving the highest sensitivity and lowest false alarm rates despite lower cost. Tier 2 and Tier 3 systems did not demonstrate clear performance advantages relative to their higher hardware requirements, though they may offer unique utility in specific patient populations.

IV. DISCUSSION

Key Findings

This systematic review and comparative analysis identified seven wearable multimodal systems for convulsive seizure detection that met criteria for inclusion after risk of bias assessment. Several important findings emerged.

First, diagnostic sensitivity was consistently high across all modalities, with pooled estimates around 90%, and all devices exceeding 85%. The highest sensitivity was achieved by wrist-worn accelerometer + gyroscope systems, highlighting the strength of inertial sensors in detecting convulsive motor activity.

Second, false alarm rates varied more widely than sensitivity, with rates ranging from 0.21 to 0.88 per 24 hours. Simpler accelerometer-based devices achieved the lowest false alarm rates, while multimodal systems incorporating ECG or EMG tended to produce more false positives, likely due to non-seizure physiological artifacts.

Third, relative-cost analysis revealed that lower-cost systems (accelerometer/gyroscope alone) performed as well as or better than higher-cost modalities (EDA, ECG, EMG).

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Despite their greater technical complexity, the higher-tier devices did not demonstrate a consistent advantage in sensitivity or false alarm reduction.

Finally, by excluding studies at high risk of bias, the analysis provides a more reliable synthesis of wearable seizure detection performance. This strengthens confidence that the observed trends—high sensitivity across modalities, variable false alarm rates, and lack of accuracy advantage in higher-cost systems—reflect robust findings rather than methodological artifacts.

Clinical Implications

The findings of this review have several important implications for clinical practice and the deployment of wearable seizure detection systems.

First, the observation that low-cost accelerometer-based devices achieve accuracy comparable to or better than more complex multimodal **systems** suggests that affordable, readily available consumer-grade wearables could play a central role in real-world monitoring. This is particularly relevant for resource-limited settings, where cost has been a barrier to adoption of advanced seizure detection technologies.

Second, the consistently high sensitivity across all modalities supports the feasibility of using wearable systems to detect generalized tonic–clonic and focal-to-bilateral tonic–clonic seizures reliably. However, the variability in false alarm rates highlights the need for individualized device selection. For example, patients with high daily physical activity may experience greater false positives with EMG- or ECG-based systems, while simpler accelerometer-only devices may be more robust.

Third, these findings indicate that device selection should be guided not only by diagnostic accuracy, but also by cost, patient acceptability, and context of use. Consumer-level smartwatches, which already integrate accelerometers and gyroscopes, represent a particularly attractive solution, offering low-cost deployment, long-term wearability, and user familiarity.

Finally, given the rapid evolution of wearable technology, these results underscore the importance of **e**xternal validation studies and real-world testing in diverse patient populations. Further prospective trials will be essential to confirm whether the observed balance of high sensitivity, low false alarm rates, and low cost translates into meaningful improvements in patient safety and quality of life.

Limitations and Future Directions

This review has some important limitations that shape how the findings should be interpreted. The included studies were quite different in design, size, and reporting. Although all focused on convulsive seizures, some only evaluated generalized tonic–clonic seizures while others also included focal-to-bilateral tonic–clonic events. That variation makes it harder to directly compare results.

False alarm rates were also reported in inconsistent ways — some per hour, some per night, and some per day. All rates were converted to a standard 24-hour metric, but in several studies the monitoring periods varied across patients or were not fully reported. This means that the pooled FAR values should be viewed as approximate, not exact.

Looking ahead, several directions stand out. First, future work should focus on prospective, multicenter validation studies that test devices in real-world environments rather than controlled inpatient vEEG settings. Secondly, while this review emphasized accuracy and cost, future research should also examine practical issues such as battery life, comfort, wearability, and user acceptance, which will ultimately determine whether these systems can be integrated into everyday care.

There is a clear need for research that explores cost-effectiveness in real-world deployment. Our findings suggest that low-cost, accelerometer-based wearables perform as well as or better than more complex and expensive systems. Demonstrating this in large-scale prospective trials could accelerate adoption and improve seizure safety for patients worldwide.

V. Conclusion

This review highlights the trade-offs between accuracy and cost in wearable detection of convulsive seizures. Across studies, sensitivity was consistently high, but false alarm rates varied depending on sensor type and study design. Importantly, accelerometer-based systems performed as well as or better than more complex, multimodal devices that include ECG, EMG, or EDA, despite the lower cost

These findings suggest that effective seizure detection does not necessarily require costly or invasive sensors. Instead, practical, low-cost solutions like wrist-worn accelerometers may be the most realistic path toward widespread clinical adoption. At the same time, careful prospective validation and standardization of outcome reporting will be critical to ensure these devices meet patient and caregiver needs in everyday life.

In short, wearable seizure detection is already highly promising, but its success will depend not only on accuracy, but also on affordability, usability, and real-world validation.

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