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Development and Preliminary Feasibility Assessment of a Low-Cost EEG-Based System for Sleep Paralysis Detection

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Abstract | **Original Research Article**

Sleep paralysis is a transient state in which awareness returns while the muscle atonia associated with rapid eye movement (REM) sleep persists. This project investigated the feasibility of developing an affordable electroencephalography (EEG)-based prototype intended to identify a possible sleep-paralysis episode and provide an auditory alert. The proposed detection approach was informed by published descriptions of mixed alpha- and theta-frequency EEG activity during sleep paralysis and by a reported alpha-to-theta power ratio of approximately 0.412 from Mainieri *et al.,* (2021). A low-cost EEG acquisition kit (Upside Down Labs BioAmp EXG Pill) was interfaced with an Arduino Uno microcontroller and a Python-based signal-processing program. The system was designed to sample EEG at a nominal rate of 512 Hz, filter the signal within 0.5-30 Hz, estimate spectral power using Welch's method, calculate alpha/theta power, and activate an alarm when a specified ratio range persisted. Published EEG traces were also digitised from samples in Takeuchi *et al.,* (1992), and Mainieri *et al.,* (2021) and analysed as an exploratory exercise. During pilot testing in awake participants, the prototype produced unstable alpha/theta values and unexpectedly high delta and theta activity. Attempts to reduce interference through electrode preparation, conductive cream, unplugged operation, notch filtering and bandpass filtering did not resolve the problem. The manufacturer's example relaxation/concentration classification code also failed to produce consistent state-dependent outputs in the project tests. The work outlines the prototype development and pilot testing, though testing did not progress past this stage, so no sleep paralysis episodes were recorded. The work demonstrates an engineering proof of concept and identifies signal-acquisition validation, reproducible spectral analysis and ethically approved clinical evaluation as necessary next steps.

Keywords: Electroencephalography, sleep paralysis, EEG signal processing, Welch method, biomedical engineering, brain-computer interface.

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1. INTRODUCTION

Sleep paralysis (SP) is a transient inability to move or speak that occurs during transitions between sleep and wakefulness. The individual may be aware of the surrounding environment while the skeletal-muscle atonia normally associated with rapid eye movement (REM) sleep persists. Episodes may be accompanied by vivid perceptual experiences, fear or a sensation of an impending threat. Isolated sleep paralysis is distinguished from episodes occurring in the context of narcolepsy or another sleep disorder. Reviews describe sleep paralysis as a phenomenon with potential psychological and sleep-related consequences, although its clinical significance varies between individuals (Sharpless, 2015; Stefani & Högl, 2021).

The original project set out to investigate whether a relatively inexpensive wearable or bedside system could identify a sleep-paralysis episode and provide an alert intended to interrupt it. An initial hypothesis considered heart rate as a possible indicator because episodes can be frightening. However, the project's review of the sleep-paralysis literature did not identify a sufficiently consistent heart-rate change to support heart rate as a stand-alone detection feature. The project consequently shifted towards EEG, which provides a direct measure of cortical electrical activity.

The project documents describe EEG recordings during sleep paralysis as containing a mixture of alpha- and theta-frequency activity, particularly in posterior or occipital recordings. Mainieri *et al.,* (2021) reported an alpha/theta ratio of approximately 0.412 during sleep paralysis for 30 seconds of 3 second epochs. The project tested this value by analysing published EEG traces from Takeuchi *et al.,* (1992) and Mainieri *et al.,*

(2021). Digitised values were reported to produce alpha/theta ratios ranging from approximately 0.412 to 1.172. These values were used to define a provisional detection interval; they should not be interpreted as a validated diagnostic threshold because they were derived from a limited literature base and, in the case of the EEG traces, digitised published figures rather than original raw EEG data.

A practical detector would require both a signal-acquisition system capable of recording EEG with adequate fidelity and an algorithm able to distinguish the proposed sleep-paralysis pattern from other sleep and wake states. EEG signals are non-stationary and can be affected by movement, eye activity, electrode contact and electrical interference. Spectral estimation must therefore be selected and implemented with care. The project considered the Fast Fourier Transform (FFT), Welch's method and empirical mode decomposition (EMD). Welch's method was selected for the prototype because segmenting and averaging the signal can reduce the influence of random variation and windowing can reduce spectral leakage. EMD was explored but not retained in the final processing pipeline (Vinjamuri, 2020). The objective of this study was to document the design and preliminary testing of a low-cost EEG-based prototype intended to calculate alpha/theta power and provide an auditory alert when the ratio entered a provisional range. The evaluation focused on whether the system produced plausible and stable EEG-derived measurements during wakefulness. The study did not aim to establish clinical diagnostic accuracy, because no confirmed sleep-paralysis episodes were recorded.

2. MATERIALS AND METHODS

2.1. Study Design

This work was an engineering development project with exploratory signal-processing analysis and preliminary testing under awake conditions. The project proceeded in three broad stages: (i) review of published EEG descriptions of sleep paralysis and selection of a candidate spectral feature; (ii) development of an EEG acquisition and processing prototype; and (iii) pilot testing and troubleshooting when the prototype did not produce stable outputs.

2.2. EEG Hardware and System Architecture

The project selected a commercially available low-cost EEG/neuroscience kit from Upside Down Labs after considering two alternatives: constructing an EEG amplifier and filter circuit from discrete components, and modifying a Mattel Mindflex toy. The selected system was the Upside-Down Labs Explorer Pack, which included a BioAmp EXG Pill amplifier board using the Texas Instruments TL084PW op-amp. The hardware arrangement consisted of EEG electrodes and a reference electrode positioned at the ear. The electrode configuration utilised an occipital channel (O1) and two ear electrodes (A1 and A2), with A1 used as the reference.

The EEG signal was acquired by the BioAmp EXG Pill, which amplified and filtered the raw signal, before being sampled by an Arduino Uno board via its analog input. The digitised signal was then transferred through a serial connection (USB, 115,200 baud rate) to a Python program running on a laptop for processing. The Python program calculated frequency-domain features and could play a sound file when the alarm condition was met.

The nominal sampling frequency was 512Hz. The Arduino implementation used a timer-based sampling approach rather than a simple fixed delay to prevent cumulative timing drift. The Arduino code used the micros () function to calculate the time interval between samples, ensuring a sample was taken exactly every 1953 microseconds to approximate 512 Hz, regardless of minor delays in code execution.

2.3. EEG Signal Processing

The processing objective was to estimate power in the EEG frequency bands and calculate the ratio of alpha to theta power. The project documents define alpha as 8-14 Hz and theta as 4-8 Hz.

Welch's method was selected for the final intended processing pipeline to reduce the influence of random fluctuations and spectral leakage. The project's Python code used the scipy.signal.welch procedure. Specifically, the signal was buffered into 10-second windows. The Welch function was configured to divide this window into parts = 10 segments, meaning nperseg (segment length) was set to 512 samples (1 second), and noverlap was set to 256 samples (50% overlap). A default Hann window was applied by the SciPy function.

The code documentation reports implementation of a $0.5 - 30$Hz bandpass filter (4th-order Butterworth) and a 50Hz notch filter (IIR notch). The filters were applied using scipy.signal.filtfilt for zero-phase digital filtering, ensuring the timing of the EEG features was not shifted. The bandpass filter was intended to retain the EEG frequency range of interest, while the notch filter was intended to reduce mains interference.

Band power was calculated by summing the Power Spectral Density (PSD) values over the frequency bins belonging to each band. The final implemented code triggered the alarm if the ratio fell between 0.412 and 1.045 within a 10-second window buffer.

2.4. Exploratory Analysis of Published EEG

To explore whether the proposed feature could be extracted from a published sleep-paralysis recording, the developer used EEG traces reproduced in Takeuchi *et al.,* (1992) and Mainieri *et al.,* (2021). A high-resolution screenshot of the trace was imported into an online graph-digitisation tool (Automeris), and points were extracted to create a comma-separated-value file.

The resulting time-series approximation was processed using the project's signal-analysis code.

2.5. Preliminary Awake Testing and Troubleshooting

The prototype was first tested while the developer was awake. The expected direction of change was that alpha activity would increase during relaxed eyes-closed wakefulness. Instead, the calculated ratios fluctuated substantially over short periods and did not show the expected stable response. When the program was modified to output individual band powers, delta and theta activity appeared unexpectedly high during wakefulness. The planning record reports an alpha/theta ratio of approximately 0.4 in this awake test, which was substantially below the approximate reference values of 1.7-2.1 that the developer had extracted from adolescent awake EEG literature (Howsley & Levita, 2018; Lar'kina & Kirenskaya, 2005).

Several troubleshooting measures were attempted: testing with the laptop disconnected from mains power; applying a 50Hz notch filter; applying a $0.5-30$Hz bandpass filter; cleaning the skin before electrode placement; and using conductive cream to improve electrode contact. These measures did not resolve the unstable or implausible outputs. The developer subsequently tested the manufacturer's example relaxation/concentration classification code, which also failed to produce reliably controllable or state-dependent outputs.

After these tests, the device was tried on a small convenience sample. The participants were female and aged 14, 16, and 17 years.

2.6. Ethics and Participant Safeguards

The planning record states that participants were informed about the device, the type of recording, potential risks, the voluntary nature of participation and their right to withdraw. Participants signed a consent form. Parental or guardian consent was obtained for the participants under 18 years of age. No formal institutional or school research ethics approval was granted or required for this internal, non-invasive pilot project. The raw participant EEG data were deleted following the recordings at the explicit request of the participants to ensure privacy; therefore, no raw data are available for secondary analysis.

3. RESULTS

3.1. Exploratory Spectral Analysis

The project's exploratory digitisation of the EEG trace reproduced in Takeuchi *et al.,* (1992) produced alpha/theta ratios ranging from approximately 0.412 to 1.172. These findings informed the provisional ratio interval used in the prototype.

3.2. Awake Testing

During awake testing, the alpha/theta ratio varied markedly over short intervals and did not demonstrate the expected consistent increase during relaxed eyes-closed conditions. The developer then examined the individual band-power outputs and observed unexpectedly high delta and theta power during wakefulness. An alpha/theta ratio of approximately 0.4 was reported in the planning journal. The result was inconsistent with the awake reference values used by the developer, which were approximately 1.7-2.1 (Howsley & Levita, 2018; Lar'kina & Kirenskaya, 2005).

3.3. Troubleshooting and Additional Participant Testing

The application of conductive cream, skin cleaning, disconnection from mains power, 50 Hz notch filtering and 0.5-30 Hz bandpass filtering did not produce an apparent improvement in signal stability. Subsequent tests on the three additional participants reportedly produced similar unexpected delta/theta activity and did not reach the awake alpha/theta benchmark. The manufacturer's example relaxation/concentration classification code also failed to produce consistent results in the project's hands.

3.4. Prototype Performance

The prototype did not progress to testing during confirmed sleep-paralysis episodes. No true-positive, false-positive or false-negative classifications can therefore be calculated. The data from the pilot test is given.

Evaluation stage	Observation documented	Interpretation supported by the evidence
Digitised published EEG trace	Reported alpha/theta values approximately 0.412–1.172.	Exploratory feature extraction only; image digitisation limits precision.
Developer awake pilot	Unstable alpha/theta ratio; unexpectedly high delta/theta power; ratio reported around 0.4.	The acquisition/processing chain did not produce plausible, stable awake measurements.
Troubleshooting	No apparent resolution after skin preparation, conductive cream, unplugged laptop, notch and bandpass filtering.	The cause of the abnormal signal was not isolated.
Additional awake participants	Similar qualitative abnormalities reported; n=3 (F, 14, 16, 17); data deleted on participant request.	Preliminary observations only; not a formal validation study.
Manufacturer example classifier	Relaxed/attentive output reportedly inconsistent.	An additional hardware/software diagnostic check also failed in this setup.
Sleep-paralysis testing	Not conducted.	Clinical detection performance cannot be estimated.

4. DISCUSSION

This project describes the development and preliminary evaluation of a low-cost EEG-based prototype intended to identify a possible sleep-paralysis episode using spectral EEG features. The principal result was that the signal processing pipeline held potential, but was limited by the low-cost EEG hardware.

The initial choice of EEG rather than heart rate was a reasoned change in project direction. The literature identified by the project suggested that EEG may provide a more direct measure of the cortical state relevant to REM-wake transitions. However, the available literature base was limited, and the proposed alpha/theta ratio was derived from a small number of reports.

The proposed ratio threshold should be regarded as provisional. A value shown by a few studies cannot be assumed to generalise across EEG systems, electrode locations, reference configurations, age groups, sleep stages or individuals. The ratio also depends on the definitions of the alpha and theta bands, the spectral estimator, the length of the analysis window, artefact handling and the method used to integrate power across frequency bins. These parameters must be standardised before the feature can be evaluated as a candidate detector.

The use of Welch's method was a reasonable engineering choice for estimating average spectral power from finite EEG segments. Segment averaging and windowing can reduce the influence of random fluctuations and spectral leakage compared with a single periodogram. Nevertheless, Welch's method does not itself solve the problem of non-stationarity or remove physiological artefacts.

The awake pilot was an important diagnostic step because a detector intended for sleep use should first be shown to produce plausible EEG measurements under controlled, known conditions. The failure to observe a stable response during relaxed eyes-closed wakefulness suggests that the prototype's output could not be trusted as a measure of the intended EEG feature.

The filtering strategy requires further technical review. The use of a digital filter cannot correct all sources of poor signal quality. Electrode contact, common-mode rejection, grounding, cable movement, amplifier input range and analogue front-end characteristics should be measured or checked against manufacturer specifications.

The project's participant testing was exploratory and involved a small convenience sample of adolescent volunteers. The findings therefore cannot support statistical inference or generalisation. Furthermore, the participants were awake and did not experience confirmed sleep paralysis during the recordings. Their data can inform preliminary checks of signal plausibility but cannot be used to estimate detection performance during sleep paralysis.

The most appropriate next stage is a structured engineering validation against a known-good EEG acquisition system. Simultaneous recordings should be obtained from the prototype and a reference EEG device. Only after the signal acquisition system has been validated should the provisional ratio be tested on appropriately annotated sleep recordings and, eventually, on confirmed sleep-paralysis episodes under an approved research protocol.

5. LIMITATIONS

Some limitations restrict the conclusions that can be drawn. First, the prototype did not produce stable or plausible awake EEG-derived measurements. Second, the prototype and signal processing pipeline wasn't tested on clinical-grade EEG samples, instead relying on the prototype's recordings and digitisations of published EEG traces. Third, the pivotal testing stage was never reached, so no sleep paralysis episodes were tested on the prototype. Fourth, the lack of institutional ethics approval limits the formal generalisability of the pilot testing.

6. CONCLUSION

A low-cost EEG-based prototype was developed to explore whether alpha/theta spectral power could be used as a candidate feature for identifying sleep paralysis and triggering an auditory alert. The work has given a basis for how a sleep paralysis detection system may work, serving as a proof of concept. However, it highlights the need for further research on sleep paralysis as the work was limited by the lack of open-source sleep paralysis recordings. Future research should aim to perform spectral analysis on a greater number of sleep paralysis EEG recordings, potentially looking into other polysomnogram features like GSR or finger plethysmogram.

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DECLARATIONS

Ethics approval and consent to participate: The project documents describe voluntary participation and signed participant forms. Parental/guardian consent was obtained for participants under 18. No formal institutional ethics approval was granted for this internal, non-invasive pilot project.

Consent for publication: No identifiable participant information or images are included.

Availability of data and materials: The raw EEG data are not available, as the data were deleted at the participants' request. The analysis code is available from the corresponding author upon reasonable request.

Competing interests: The author declares that they have no competing interests.

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Author contributions: Saisha Sanaka conceived the project, designed the prototype, collected and analysed the data, and drafted the manuscript.

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