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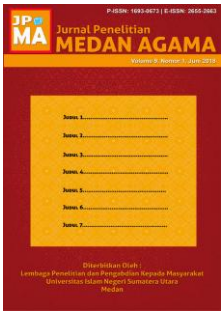

Neurodawn: Prototipe neuromodulasi non-invasif berbasis EEG untuk penyakit Parkinson

Neurodawn: An EEG-Based Non-Invasive Neuromodulation Prototype for Parkinson's Disease

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Abstract

Parkinson's disease (PD) is a chronic neurodegenerative disorder that significantly affects patients' quality of life, thereby necessitating safe, adaptive, and accessible intervention approaches. This study aims to develop Neurodawn, an electroencephalography (EEG)-based non-invasive neuromodulation prototype as a health technology innovation to support Parkinson's disease management while strengthening a holistic approach aligned with ethical principles and humanistic values. The research employs a research and development (R&D) method, encompassing stages of system design, EEG device integration, signal processing, and initial performance evaluation of the prototype. The innovation of Neurodawn lies in the utilization of EEG signals as the foundation for developing a non-invasive neuromodulation system designed to minimize clinical risks and enhance user comfort. Beyond technical aspects, this study emphasizes key health ethics principles, including non-maleficence, beneficence, patient autonomy, equity in access to healthcare services, and the protection of neurophysiological data privacy as integral components of technology ethics. The spiritual perspective is understood as strengthening patient resilience through meaning, hope, and social support in coping with chronic illness. The development results indicate that Neurodawn can be implemented as a functional prototype and has the potential to be further developed as a supportive non-invasive intervention technology for patients with Parkinson's disease. The integration of science, ethics, and spirituality forms the foundation to ensure that this innovation is both beneficial and dignified.

Keywords : *EEG, Non-Invasive, Parkinson's Disease, tACS*

Abstrak

Parkinson's Disease (PD) merupakan gangguan neurodegeneratif kronis yang berdampak signifikan terhadap kualitas hidup pasien, sehingga diperlukan pendekatan intervensi yang aman, adaptif, dan mudah diakses. Penelitian ini bertujuan mengembangkan Neurodawn, sebuah prototipe neuromodulasi non-invasif berbasis Electroencephalography (EEG) sebagai inovasi teknologi kesehatan untuk mendukung penanganan Parkinson sekaligus memperkuat pendekatan holistik yang selaras dengan etika dan nilai kemanusiaan. Penelitian menggunakan metode research and development (R&D) melalui tahapan perancangan sistem, integrasi perangkat EEG, pengolahan sinyal, serta evaluasi awal performa prototipe. Inovasi Neurodawn terletak pada pemanfaatan sinyal EEG sebagai dasar pengembangan sistem neuromodulasi non-invasif yang dirancang untuk meminimalkan risiko klinis dan meningkatkan kenyamanan pengguna. Selain aspek teknis, penelitian ini menegaskan prinsip etika kesehatan seperti non-maleficence, beneficence, otonomi pasien, keadilan akses layanan, serta perlindungan privasi data neurofisiologis sebagai bagian dari etika teknologi. Perspektif

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spiritual dipahami sebagai penguatan ketahanan pasien melalui makna, harapan, dan dukungan sosial dalam menghadapi penyakit kronis. Hasil pengembangan menunjukkan bahwa Neurodawn dapat diimplementasikan sebagai prototipe fungsional dan berpotensi dikembangkan lebih lanjut sebagai teknologi pendukung intervensi non-invasif bagi pasien Parkinson. Integrasi sains, etika, dan spiritualitas menjadi dasar agar inovasi ini bermanfaat dan bermartabat.

Kata Kunci : EEG, Non-Invasif, Penyakit Parkinson's, tACS

1. PENDAHULUAN

Parkinson's Disease (PD) is a progressive neurodegenerative disorder driven by the loss of dopaminergic neurons in the substantia nigra, leading to widespread disruptions in the cortico-basal ganglia network that underlies both motor and non-motor dysfunctions. Patients experience symptoms such as bradykinesia, rigidity, resting tremor, and postural instability, as well as cognitive and emotional impairments that increasingly degrade quality of life over time. Despite advances in pharmacological therapy and deep brain stimulation, treatment remains largely symptom-focused and does not alter the underlying progression of neuronal degeneration.

Recent interest has grown around biofeedback and neurofeedback as non-invasive rehabilitation interventions for PD. A 2025 comprehensive review analyzed electromyographic (EMG), heart rate variability (HRV), and electroencephalographic (EEG) feedback techniques for PD, finding that EEG neurofeedback can modify abnormal cortical oscillations, particularly beta-band activity linked to motor control, and that these changes correlate with improvements in executive functioning and motor initiation. However, the technical complexity and heterogeneity of protocols in existing studies limit generalizability and clinical adoption. (Diotaiuti P et all., 2025).

Meta-analytic evidence has further demonstrated that EEG neurofeedback reliably modulates cortical activity in PD patients, producing significant changes in targeted EEG features across studies. However, the downstream effects on functional motor outcomes remain inconclusive, suggesting that while the neuromodulatory potential of EEG feedback is promising, more rigorous and larger-scale studies are needed to determine clinical efficacy. (von Altdorf et all., 2025)

In addition to neurofeedback, non-invasive brain stimulation methods such as transcranial alternating current stimulation (tACS) have shown positive effects on neurophysiologic motor function in PD. A 2025 systematic review reported that tACS interventions significantly improved motor evoked potentials and intracortical inhibition in PD patients compared with non-stimulated controls, providing growing evidence for the therapeutic value of frequency-specific cortical stimulation in modulating pathological oscillations associated with motor dysfunction. (Ye et all., 2025).

Beyond cortical neurofeedback and tACS, combined neuromodulation approaches are being investigated. A 2024 randomized controlled trial compared high-frequency repetitive transcranial magnetic stimulation (rTMS) and EEG-guided neurofeedback — alone and in combination — revealing that multimodal strategies may produce larger effects on motor symptoms and quality of life than single modalities, though improvements in mobility and stability metrics were limited. (Romero et all., 2024).

Recent research has also explored deep brain neurofeedback in more invasive contexts, showing that Parkinson's patients using fully implanted deep brain stimulation (DBS) systems can achieve significant reductions in pathological beta oscillations through real-time neurofeedback control of subthalamic activity. This work

highlights the feasibility of targeted oscillatory modulation via feedback loops, although clinical translation remains constrained by invasiveness and logistical complexity. (Rohr-Fukuma et all., 2024).

Despite these encouraging directions, most current neuromodulation research in PD relies on either clinical-grade equipment or invasive systems, and there is a scarcity of work focusing on wearable, low-cost, and accessible solutions for real-world use. Wearable EEG-based systems like brain–computer interfaces (BCIs) show promise in motor rehabilitation and personalized neurotherapy but have yet to achieve widespread applicability due to challenges in signal quality, real-time responsiveness, and contextual integration with feedback or stimulation modules. (Ortega-Robles et all., 2025).

The NeuroDawn prototype is positioned within this emerging landscape. Unlike most prior work, which relies on expensive clinical stimulators, high-density EEG, or invasive electrodes, NeuroDawn aims to integrate consumer-grade EEG sensing with programmable, closed-loop stimulation in a wearable, low-cost format. While traditional EEG neurofeedback studies demonstrate cortical modulation potential, and tACS research supports oscillation-targeted stimulation, NeuroDawn proposes a combined feedback and stimulation loop that could — in principle — provide personalized neuromodulation outside clinical environments. In contrast to high-equipment-cost approaches and invasive neurofeedback, NeuroDawn emphasizes accessibility, portability, and iterative R&D validation.

However, unlike formal large-scale PD interventions previously reported, NeuroDawn leverages low-cost hardware with inherent limitations. For example, consumer EEG devices have lower signal resolution than clinical systems, and compatibility issues can disrupt real-time feedback pipelines. Nonetheless, this research explores whether such constraints can be overcome or mitigated in future iterations to provide meaningful, real-time modulation of EEG biomarkers associated with dopamine dysregulation.

The goal of this research is to develop, document, and evaluate the feasibility of a wearable, EEG-informed neuromodulation system capable of detecting and responding to real-time brainwave patterns related to dopaminergic signaling. While not intended as a definitive clinical intervention, NeuroDawn seeks to bridge the gap between high-end neuromodulation research and accessible, everyday technology that could one day support early PD intervention or generalized cognitive support.

2. METHODS

This study employs a Research and Development (R&D) methodology integrated with the ADDIE instructional development model to design, build, and evaluate a neuromodulation prototype intended to stabilize dopamine-related neural activity. The R&D method is appropriate for studies aimed at producing innovative technological solutions and validating their effectiveness through systematic development and testing stages. (Siregar, Torang., 2025).

Research and Development is defined as a structured process used to generate new knowledge and transform it into functional products or systems through iterative design, testing, and evaluation. (U.S. and international sources., 2022) This approach is commonly applied in engineering and technology-based research to develop prototypes and assess their feasibility prior to real-world implementation. (Bichachi., 2024)

The ADDIE model—consisting of Analysis, Design, Development, Implementation, and Evaluation—was selected as the framework for structuring the prototype's development process due to its systematic and iterative nature in guiding product creation and refinement. (Nugraha., 2025). The model ensures that each stage

of development is aligned with user needs and technical objectives, enabling continuous improvement throughout the research cycle. (Martatiyana, Usman, Lestari., 2023).

This combination of R&D methodology and the ADDIE model allows the study to progress logically from problem identification to prototype validation, ensuring that both technical and functional requirements are addressed comprehensively.

The research methodology was divided into five progressive phases:

1. Analysis Phase

The analysis stage focuses on identifying the need for a non-invasive neuromodulation device capable of stabilizing dopamine activity in individuals at risk of Parkinson's disease. Literature review findings and technological feasibility assessments were conducted to determine functional requirements, safety constraints, and limitations of existing neuromodulation solutions.

This stage is essential because the ADDIE framework begins with a needs assessment to ensure that the developed product addresses a real and well-defined problem. (Nugraha., 2025)

2. Design Phase

During the design phase, the conceptual architecture of the prototype was created. This included:

- Selection of the NeuroSky EEG headband as the neural data acquisition device
- Arduino-based control system design
- Dopamine-stabilization logic flow
- Feedback mechanisms

The design stage ensures that system specifications are clearly defined before physical development begins, which is a core principle of structured development models. (Martatiyana, Usman, Lestari., 2023).

3. Development Phase

In this phase, the prototype was physically assembled and programmed. Hardware integration, signal acquisition coding, and feature implementation were conducted.

The development stage in R&D typically involves building a functional prototype and conducting internal testing to determine whether the system operates as intended. (Bichachi., 2024)

The main hardware elements included:

1. EEG Acquisition: The NeuroSky MindWave Mobile 2, a consumer-grade single-channel EEG headset (FP1), was selected for its affordability, portability, and Bluetooth data streaming capability.
2. Microcontroller Unit: An Arduino Nano 33 BLE Sense was used for real-time data processing, stimulation control, and communication with the EEG system.
3. Stimulation Circuit: A custom-built tACS module was developed using an AD9833 waveform generator, current limiter, and isolation circuitry capable of safely delivering ±1 mA sinusoidal waveforms.

All firmware and software code were written in Arduino IDE and Python. EEG data from the headset was streamed wirelessly, processed via a custom pipeline, and used to control stimulation triggers based on real-time neural biomarkers.

4. Implementation Phase

The implementation phase involved preparing the prototype for functional testing, including safety testing on non-human subjects such as a dummy or arm to ensure electrical safety. This phase also included limited operational trials to observe system behavior in real-time conditions.

The implementation phase is critical to determine whether the developed system functions effectively in practical settings. (Nugraha., 2025)

Key procedures included:

1. Current Limiting Verification: Output current was tested to ensure it remained under 1 mA at all times, per non-invasive brain stimulation safety standards.
2. Thermal and Contact Testing: The system was activated on a mannequin head and then on the researcher's arm to detect possible overheating or discomfort at electrode contact points.
3. Impedance Monitoring: Electrode impedance was checked using a multimeter to ensure safe and consistent contact during operation.

This phase ensured the system met essential safety criteria before advancing to human testing.

Following safety clearance, the prototype will be tested for functionality in healthy adult users (n=5). The primary focus will be on validating that each core feature performed as intended:

1. EEG Signal Processing: Raw data were filtered (1–45 Hz), denoised, and segmented using rolling time windows. Key features such as beta power (13–30 Hz), theta/beta ratio, and Phase Synchrony Index were extracted.
2. Closed-Loop Control: If EEG metrics indicated excessive beta synchrony, the system automatically triggered Stabilization Mode, applying 20 Hz anti-phase tACS. Conversely, low beta activity activated Enhancement Mode, delivering in-phase 20 Hz stimulation.
3. User Interface: A Python-based GUI allowed manual override, visualized real-time data, and logged session information for analysis.

After all feature tests confirming the system's ability to detect EEG patterns and initiate appropriate stimulation protocols, it will then advance to the final phase.

5. Evaluation Phase

The evaluation phase involved analyzing system performance, identifying technical failures, and assessing whether the prototype met its intended objectives.

Evaluation is an essential component of ADDIE to determine effectiveness and guide further refinement of the developed product. (Martatiyana, Usman, Lestari., 2023).

The goal is to evaluate whether NeuroDawn can induce measurable changes in EEG biomarkers and/or observable symptom relief.

1. Baseline Collection: EEG activity and symptom observations will be recorded before device use.
2. Intervention Period: The patient will use the device over a controlled timeframe, following stimulation protocols established in Phase 3.
3. Post-Session Evaluation: EEG and subjective data will be collected to compare pre- and post-use states.

This phase will serve as a feasibility trial, offering preliminary evidence of clinical relevance for further development and trials.

Table 1. Materials

Component	Estimated Price (IDR)	*Notes*
NeuroSky MindWave Mobile 2	Rp4.480.000	*Official price in Indonesia may vary slightly*
ESP32 Dev Board	Rp 40.000 – Rp 60.000	*With USB connector*
MCP4725 DAC Module	Rp 30.000 – Rp 50.000	*I2C DAC breakout*
LM324 Op-Amp (1 pc)	Rp 5.000 – Rp 10.000	*Quad op-amp*
Resistors (assorted pack)	Rp10.000	*10–20 pcs*
Capacitors (100nF, 10uF)	Rp10.000	*Per small assortment*
Li-Ion Battery (3.7V 1000mAh)	Rp 40.000 – Rp 70.000	*Rechargeable*
Battery Holder + Switch	Rp 10.000 – Rp 20.000	*With JST cable or connector*
Breadboard or protoboard	Rp 15.000 – Rp 30.000	*For circuit assembly*
Electrodes (gel or sponge pair)	Rp 50.000 – Rp 150.000	*Reusable*
Wires, jumpers, connectors	Rp20.000	*Miscellaneous wiring*
3D-Printed Headset Frame	Rp 80.000 – Rp 150.000	*Based on local service (e.g., Tokopedia/3D printing shops)*
Misc. plastic parts/clips	Rp 20.000 – Rp 40.000	*Optional accessories*
Total Cost	4.810.000 - 5.100.000	

Table 2. Additional Expenses for Sensor

Component	Estimate Price (IDR)	*Note*
1x Arduino (like Uno, Nano, etc.)	Rp30.000 - 120.000	*Microcontroller for controlling the stimulation system. Can use Uno or Nano.*
1x LED (or a small buzzer)	Rp500 - 20.000	*Light Emitting Diode to Indicate Stimulation.*
1x 220Ω resistor (for LED safety)	Rp2000 - 20.000	*Used to limit the current to the LED to avoid damage.*
Arduino USB cable	Rp10.000 - 20.000	*For connecting Arduino to your PC for programming.*
Total Cost	Rp42.500 - 180.000	

Safety Equipment:

- *Digital Multimeter*: Used to measure voltage, current, and impedance for safety verification.
- *Non-conductive mannequin head and human forearm*: Used during Phase 2 testing to assess safety without risk to a live subject.

Software And Data Tools:

- *Python 3.11* with libraries:
  - MNE-Python for EEG processing
  - NumPy and SciPy for signal analysis
  - PySerial for Arduino communication
  - Tkinter for user interface
- *Arduino IDE*: Used to program the Arduino Uno.
- *Bluetooth module*: Integrated within both EEG and microcontroller subsystems for wireless connectivity.

Participants

The participants involved in this research were divided into three groups:

1. Researcher/Developer – responsible for prototype design, assembly, and programming.
2. Technical Validators – individuals with basic knowledge of electronics or biomedical engineering who reviewed the prototype design for feasibility and safety.
3. Future Target Participant Group (Planned) – a Parkinson's disease patient for trial testing, which was intended but not conducted due to time and technical constraints.

The inclusion of participants at different stages ensures both technical accuracy and ethical responsibility in the development of biomedical devices.

Data Collection Method

This research uses a mixed data collection approach, including:

- Experimental testing data from the prototype's EEG readings and system performance
- Observational data during assembly and feature testing
- Technical diagnostic logs from the Arduino and EEG software

Experimental testing is commonly used in R&D studies to evaluate prototype functionality and performance. (Nurrahman., 2016)

Type Of Data Collection

- Quantitative experimental data were collected through EEG signal recordings and system-logged stimulation events during real-time trials.
- Qualitative data included observational notes (e.g., user reactions, usability issues) and feedback from participants regarding comfort and perceived cognitive or emotional changes.

Procedures In Data Collection

Data were collected through the following procedures:

1. Recording EEG signal stability during prototype operation.
2. Monitoring electrical output levels for safety compliance.
3. Logging system errors and compatibility failures.
4. Documenting system behavior during each testing phase.

These procedures align with the iterative testing and refinement cycle typical of R&D methodologies. (Afriani , Mutmainnah , Sunarni., 2025)

Ethical Considerations

- All participants are informed of the experimental nature of the prototype.
- Safety measures, including limiting stimulation amplitude to ≤1 mA, are strictly followed.
- Data is anonymized, with no personally identifying information recorded.

This multi-channel data collection strategy ensures both the technical performance and user-centered impact of the NeuroDawn prototype are thoroughly evaluated under controlled yet realistic conditions.

Data Analysis Strategy

The data were analyzed using a descriptive and diagnostic analysis approach, including:

- Comparison of expected vs actual system performance

- Identification of hardware and software failure points
- Evaluation of signal reliability and compatibility issues

R&D studies often use descriptive analysis during prototype testing to determine feasibility prior to full-scale experimental validation. (Afriani , Mutmainnah , Sunarni., 2025)

Rational For Methodological Choices

The R&D method with the ADDIE model was selected because:

1. The study aims to develop a new technological product, not only test a hypothesis.
2. ADDIE provides a structured development framework suitable for iterative engineering design.
3. Experimental testing ensures technical feasibility before human trials.
4. Descriptive analysis is appropriate because the prototype did not reach clinical testing stage.

Together, these choices ensure that the methodology aligns with the exploratory and developmental nature of neuromodulation technology research.

3. RESULST AND DISCUSSION

The results of this study are presented according to the Research and Development (R&D) methodology using the ADDIE model, reflecting outcomes from each development phase. As the study focused on prototype development and feasibility assessment, results are reported descriptively rather than through inferential statistical analysis.

1. Analysis Phase Results

The analysis phase successfully identified a practical research gap: while non-invasive neuromodulation has shown promise in Parkinson's Disease management, most existing systems rely on expensive, research-grade hardware and controlled laboratory environments. The needs analysis confirmed the feasibility of exploring a low-cost, wearable EEG-informed neuromodulation prototype using consumer-grade components.

Key requirements identified during this phase included:

- Real-time EEG signal acquisition
- Safe electrical output
- Wearable and portable design
- Closed-loop feedback capability

However, early risk assessment also revealed a dependency on legacy EEG hardware, which later became a critical limitation during development and implementation.

2. Design Phase Results

During the design phase, a complete conceptual architecture of the *NeuroDawn* prototype was produced. The system design included:

- EEG acquisition using the NeuroSky MindWave Mobile 2
- Arduino-based signal response control
- Dual-mode neuromodulation logic (stabilization and enhancement)
- Vibrotactile feedback as a non-invasive stimulation mechanism

Flowcharts and logic diagrams were successfully created to represent system behavior under different EEG conditions. At the design level, the system met all predefined functional objectives. However, the design assumed uninterrupted

compatibility between EEG hardware, operating system, and software drivers—an assumption that later proved problematic.

3. Development Phase Results

The development phase resulted in partial prototype completion. Hardware assembly and basic coding were successfully executed, including:

- Physical integration of EEG headset, microcontroller, and feedback module
- Initial Arduino programming
- Preliminary EEG data reception scripts

Despite these achievements, full system integration could not be completed. EEG signal acquisition failed due to driver incompatibility and operating system **constraints**, as the NeuroSky device is dependent on outdated Windows 10 drivers that were no longer reliably functional following recent system updates. As a result, closed-loop EEG-triggered stimulation could not be validated.

4. Implementation Phase Results

This phase was not conducted. Ethical and methodological standards require a fully operational and safety-validated system prior to clinical or human testing. Due to unresolved technical constraints and incomplete feature validation, Parkinson's Disease trials were deemed inappropriate and were therefore omitted.

The outcome of this study highlights the practical challenges inherent in early-stage neurotechnology development, particularly when utilizing consumer-grade and legacy hardware. While the NeuroDawn prototype was successfully conceptualized and partially constructed, several limiting factors prevented full functional evaluation.

5. Evaluation Phase Results

The evaluation phase focused on diagnostic assessment rather than performance measurement. The primary findings included:

- Confirmation that hardware dependency on legacy EEG systems poses a significant risk
- Identification of software-platform incompatibility as the main point of failure
- Recognition that consumer-grade EEG devices are not always sustainable for long-term R&D projects

The evaluation phase fulfilled its role in identifying development constraints and informing future improvements, even though functional validation was not completed.

Discussion

The outcomes of this study illustrate the practical challenges inherent in applying R&D methodologies with the ADDIE model to emerging neurotechnology. While the ADDIE framework provided a clear and structured pathway for development, the results emphasize that successful progression through each phase depends heavily on technological sustainability and resource availability.

Alignment With R&D and Addie Framework

Within the context of R&D research, failure to reach full implementation does not invalidate the study. Instead, it provides valuable insight into feasibility and system constraints. The ADDIE model functioned effectively as a guiding framework, particularly in the Analysis and Design phases, where system requirements and conceptual architecture were clearly defined.

The breakdown occurred primarily between the Development and Implementation phases, underscoring a key limitation of applying instructional development models to rapidly evolving technological ecosystems. This highlights the importance of incorporating technology lifecycle analysis into the early stages of ADDIE-based R&D studies.

Technical And Platform Limitations

The reliance on the NeuroSky MindWave Mobile 2—an EEG device released in 2016—proved to be the most significant limitation. Although widely cited in earlier neurofeedback studies, the device's dependency on deprecated drivers and operating systems rendered it incompatible with current computing environments. This constraint halted EEG data acquisition and prevented real-time closed-loop testing.

Additionally, the use of single-channel, consumer-grade EEG hardware limited signal fidelity and reduced robustness for neuromodulation applications, further reinforcing the need for modern, actively supported platforms in future research.

Implications For Future Neuromodulation R&D

The findings suggest that future research should:

- Prioritize hardware with long-term software support
- Employ cross-platform EEG solutions
- Allocate extended development timelines
- Conduct incremental validation at each ADDIE stage before proceeding

Despite the incomplete prototype, the study contributes meaningfully by documenting development risks and reinforcing best practices for accessible neuromodulation system design.

In summary, while the *NeuroDawn* prototype did not achieve full functional deployment, the study successfully met the objectives of Research and Development research using the ADDIE model. The project demonstrates how structured development frameworks can guide innovation, identify system vulnerabilities, and inform future improvements in neurotechnology design.

4. CONCLUSION

This research aimed to design and develop a low-cost, wearable neuromodulation prototype informed by electroencephalography (EEG) signals, with a long-term goal of contributing to early-stage Parkinson's Disease intervention. The study adopted a Research and Development (R&D) methodology using the ADDIE model as a structured framework to guide the systematic analysis, design, development, implementation, and evaluation of the proposed system.

Overall, the study demonstrates that the ADDIE model is suitable for guiding neurotechnology-oriented R&D projects, particularly those focused on early-stage prototyping and feasibility exploration. Although the prototype did not reach full functional implementation, the research successfully fulfilled its methodological and exploratory objectives.

During the Analysis phase, the research successfully identified a gap in existing neuromodulation solutions, particularly the lack of affordable and portable systems that integrate EEG-based feedback mechanisms. The needs analysis confirmed the relevance of developing a consumer-accessible device, while also revealing critical dependencies on hardware compatibility and software support.

In the Design phase, a complete conceptual system architecture was produced, detailing EEG acquisition, signal processing logic, dual-mode neuromodulation

behavior, and user feedback mechanisms. At this stage, the prototype met all predefined functional requirements in theory, indicating that the proposed design was technically sound at a conceptual level.

The Development phase resulted in partial prototype construction. Hardware assembly and preliminary coding were completed; however, full system integration was not achieved due to incompatibility between the NeuroSky MindWave Mobile 2 EEG device and current operating system environments. This prevented reliable EEG signal acquisition and halted closed-loop neuromodulation testing.

The Implementation phase was therefore limited to non-functional safety testing, while the Evaluation phase focused on identifying design constraints, platform limitations, and systemic risks rather than performance outcomes. These evaluations provided valuable insight into the practical challenges of low-cost neuromodulation development.

Research Contributions

Despite the incomplete implementation, this research contributes meaningfully in several ways:

1. It demonstrates the applicability of R&D methodology with the ADDIE model in neurotechnology development.
2. It highlights the risks of relying on legacy, consumer-grade EEG hardware in contemporary research.
3. It provides a documented development pathway for future low-cost neuromodulation prototypes.
4. It contributes practical knowledge on hardware–software dependency management in wearable medical device research.

The study reinforces that in R&D-focused research, developmental constraints and failures are valid and informative outcomes that advance understanding within the field.

Limitations Of Study

The primary limitation of this research was the reliance on an EEG device that lacked long-term software and operating system support. Additionally, constraints related to time, funding, and access to higher-grade equipment limited the scope of development and testing. The use of a single-channel EEG system also restricted signal quality and reduced the feasibility of advanced neuromodulation algorithms.

Furthermore, ethical considerations prevented human testing in the absence of a fully functional and validated system, which limited empirical outcome measurement.

Recommendations For Future Research

Based on the findings and limitations of this study, future research is recommended to:

- Utilize modern, multi-channel EEG devices with active software support
- Incorporate cross-platform compatibility during the Analysis phase
- Allocate extended development timelines for iterative testing
- Conduct staged validation at each ADDIE phase
- Explore alternative neuromodulation modalities with stronger empirical backing

These improvements would significantly increase the likelihood of successful implementation and clinical relevance.

Final Remarks

In conclusion, this study demonstrates that the failure to achieve full prototype functionality does not negate the value of structured R&D research. By systematically applying the ADDIE model, the research successfully identified design strengths, technological constraints, and pathways for future improvement. The findings provide a solid foundation for subsequent development efforts and contribute to the broader discourse on accessible, non-invasive neuromodulation technologies.

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