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Francisca Lavinia Bartha (Voicu), Ionel Șerban

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Abstract
This article presents a structured approach to the development of a vibrotactile wristband intended to improve speech comprehension and postural control in users of cochlear implants and hearing aids. Making use of the principles of multisensory integration and sensory substitution, this study reviews relevant literature, outlines methodological plans, and forecasts the impact of associating auditory and somatosensory stimuli for dual therapeutic benefit. The proposal seeks to bridge the gap in current assistive technologies by introducing a compact, wearable device capable of delivering speech-synchronized vibrotactile feedback in daily listening environments.

Keywords
Vibrotactile stimulation; cochlear implants; hearing aids; postural control; multisensory integration.

I. Introduction

Hearing loss is a major global health concern affecting an increasing number of individuals across all age groups. Beyond impairing communication, hearing loss has been linked to deficits in postural stability and spatial orientation. While cochlear implants and hearing aids have significantly improved speech perception and environmental awareness, they do not fully resolve difficulties in noisy environments or vestibular-related deficits.

The intersection between auditory and balance functions has gained attention in recent years, with studies showing that a decline in hearing is often accompanied by balance impairments and increased fall risk. Given the shared neurophysiological pathways and proximity of auditory and vestibular systems in the inner ear, it is essential to adopt a multisensory approach to rehabilitation.[1]

This research proposes a wearable solution, a vibrotactile wristband, that aims to provide auditory enhancement and improve postural stability simultaneously. The wristband delivers vibrotactile stimulation synchronized with the rhythm of speech. It is designed for daily use, at-home use and targets adult and child users of cochlear implants and hearing aids. The ultimate objective is to validate whether such stimulation improves speech-in-noise recognition and reduces sway in posture-graphic analysis, while also monitoring cortical responses through EEG analysis to better understand the neurophysiological effects of multisensory integration. If successful, this approach could introduce a paradigm shift in audiological rehabilitation and non-invasive technology.

The innovation in this study lies not only in the integration of vibrotactile stimulation with auditory input, but also in its ergonomic, user-friendly format suitable for real-world use. By combining two core rehabilitation goals: speech comprehension and postural control, the wristband provides a dual solution that may enhance patient outcomes and reduce reliance on fragmented therapeutic protocols.

Additionally, this research contributes to the growing field of wearable health technology, offering an interdisciplinary model that merges audiology, neuroengineering, and human factors. Insights from the pilot study will help refine both the technical design of the device and the therapeutic strategies employed in clinical audiology.

To support the validation of the dual impact of the proposed vibrotactile wristband, the study also incorporates electroencephalographic (EEG) monitoring to observe neurophysiological responses associated with auditory and somatosensory integration. EEG analyses will be used to assess neural entrainment to speech rhythm and to detect changes in cortical activity patterns before and after vibrotactile stimulation. This approach adds an objective neurophysiological perspective to the evaluation of the device’s efficacy, offering deeper insights into how multisensory feedback may modulate central auditory and balance processing. Such findings could inform future rehabilitation protocols, supporting more personalized and integrative strategies for individuals with combined auditory and vestibular deficits.

Our study addresses a current gap: there is no integrated, real-world wearable that targets both auditory and balance outcomes in cochlear implant and hearing aid users while concurrently quantifying cortical dynamics. We therefore pursue the aims: test whether a week of speech-synchronized vibrotactile stimulation improves word recognition in noise and reduces postural sway; and determine whether EEG indices of audio-tactile entrainment change alongside behaviour. By unifying dual rehabilitation goals within an ergonomic device and validating outcomes across behavioural and neural levels, this work seeks to advance multisensory, at-home audiological rehabilitation.

II. Methodology

This study is structured into several phases: literature review, prototype development, participant recruitment, experimental testing, data analysis and results interpretation. This research is currently in its early developmental stage and is being prepared within the Laboratory of the Faculty of Product Design and Environment, Transilvania University of Brasov, Romania. Ethical approval will be requested from the University's Research Ethics Committee prior to participant recruitment (approval number pending). All participants, or their legal tutors in the case of minors, will provide written informed consent in accordance with the Declaration of Helsinki.

A. Literature Foundation

Multisensory integration, particularly the interaction between auditory and tactile modalities, has emerged as a promising field for enhancing speech perception and balance control for individuals with hearing loss. Huang showed that cochlear implant users had significantly improved speech recognition in noise conditions when vibrotactile stimuli were temporally align with auditory input [2]. Luo further supported this by demonstrating enhanced melody recognition for cochlear implant users through vibrotactile stimulation [4]. Fu and Riecke provided EEG based evidence of neural entrainment during audio-tactile integration, confirming that synchronized stimuli across modalities may optimize auditory temporal resolution [5],[6]. Beyond auditory enhancement, the integration of somatosensory stimuli has shown considerable impact on balance and postural control. Some studies reported that somatosensory rehabilitation techniques led to improved postural stability in children with hearing loss and vestibular dysfunction [4]. Similarly, Choi observed that vibrotactile feedback improved balance performance in elderly participants, reinforcing the relevance of tactile cues in proprioceptive and vestibular compensation [4].

Several additional studies strengthen the theoretical foundation of this study. Fletcher demonstrated that electro-haptic stimulation could significantly improve spatial hearing and localization for cochlear implant users, highlighting the effectiveness of wearable multisensory plasticity in cochlear implant users and emphasizing the importance of incorporating visual and tactile cues into rehabilitation strategies [6]. Furthermore, he investigated the long term impact of subconscious vibrotactile stimulation in patients with bilateral vestibulopathy and found substantial improvements in mobility and balance that persisted over two years [6].

These findings are reinforced by foundational neuroscience research. Gick and Derrick demonstrated that aero-tactile stimulation could directly modulate speech perception in normal hearing individuals, supporting the presence of early multisensory integration mechanisms in speech processing [7]. Deneber also showed modulation of auditory evoked potentials after cochlear implantation, indicating neuroplastic adaptation that could facilitate tactile-auditory synergy [8].

Taken together, these studies provide a robust foundation for the development of multisensory therapeutic tools, such as the proposed vibrotactile wristband, aimed at improving both speech-in-noise comprehension and balance in cochlear implant and hearing aid users. They support the hypothesis that synchronized tactile feedback can stimulate neuroplastic reorganization in auditory and postural control pathways. [17-20]

B. Prototype Description

The proposed vibrotactile wristband prototype is currently in the early design stage and aims to transform acoustic information into synchronized tactile feedback to support multisensory rehabilitation. The system is conceived as a compart, wearable device capable of translating speech rhythm or spectral cues into tactile stimulation on the wrist.

The prototype will operate as a closed-loop audio-tactile system. An onboard digital microphone will capture incoming sounds (speech or environmental noise, which will then be processed by a microcontroller unit (Arduino Nano or Raspberry Pi Pico W). The signal will undergo either temporal envelope extraction or spectral band mapping, depending on the test condition, to generate vibration control patterns. These processed signals will drive miniature vibrotactile actuators (coin vibration motors) embedded within the wristband, delivering rhythmic pulses synchronized with the acoustic input. The resulting tactile feedback will allow users to perceive temporal speech structure through vibration pattern aligned to syllabic rhythm. Power will be supplied by a rechargeable Li-ion battery, ensuring portability and daily usability. A Bluetooth module will enable wireless configuration, parameter adjustment and real-time data transmission for experimental monitoring. To maintain temporal precision between auditory and tactile events, a real-time clock module will be implemented within the signal processing loop. [Fig. 1]

From an ergonomic standpoint, the wristband will be made of hypoallergenic silicone and include an adjustable strap to ensure comfort during long wear. All vibrotactile outputs will remain safe tactile thresholds to prevent sensory fatigue or discomfort. The prototype's physical design will prioritize low weight (<100 g) and user autonomy during daily listening sessions.

Schematic representation of the system (Fig.1):

Audio Input (Microphone) → Signal Processing (MCU) → Envelope Extraction/ frequency band mapping → Vibration Control Signal → Vibrotactile Actuators → User Feedback.

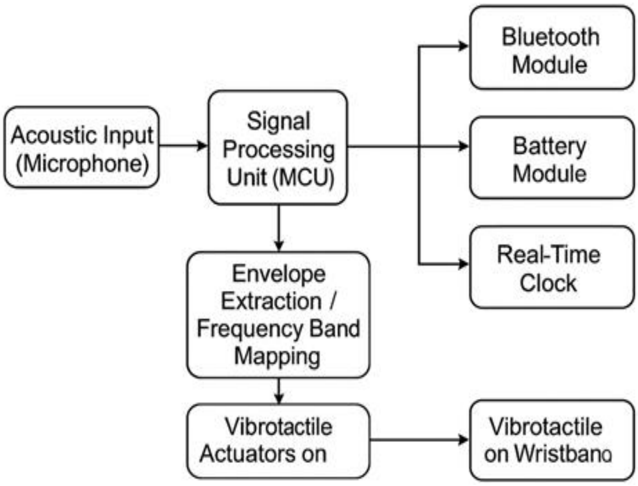

Fig. 1. Functional diagram of the vibrotactile wristband prototype

Table 1. Prototype Elements for Multisensory Stimulation

Component	Description	Role
Audio Input	Digital Microphone	Captures the acoustic signal
Microcontroller Unit (MCU)	Arduino Nano/ Raspberry Pi Pico W	Processes input
Vibrotactile Actuators	Coin vibration motors	Synchronized tactile feedback
Power Supply	Rechargeable Li-ion battery	Powers the system
Bluetooth Module	Wireless module	Allows remote configuration
Real time Clock/Sync System	Timing module	Maintains temporal accuracy of signals
Enclosure and Wristband	Wearable housing with adjustable strap	Ensures portability

C. Participants

The study is designed as pilot investigation including twenty participants (12 females, 8 males) aged 15-70 years. All participants will present unilateral or bilateral sensoneural hearing loss and will be fitted with either cochlear implant or hearing aids. Individuals will be recruited from the clinical database of a private audiological clinic. Inclusion criteria include at least six months of auditory device use and stable audiometric thresholds. Exclusion criteria involve severe neurological, vestibular or musculoskeletal disorders that could affect postural control.

D. Experimental Protocol

- Pre-test: speech-in-noise tonal and vocal audiometry using bisyllabic words (65 dB SPL + 60 dB noise); postural analysis on Kistler platform in eyes open/closed conditions.
- Intervention: subjects will wear the wristband daily for seven days during 30 minutes passive listening sessions (audiobooks and conversation recordings).
- Post-test: repetition of audiometry and posturography.

E. Data Analysis

As the study is currently at an early planning stage, data analysis methods are outlined here for the future implementation. Pre- and post- intervention scores for word recognition in noise and postural sway parameters will be compared within subjects using paired-sample t-tests. Effect sizes will be reported to quantify the magnitude of observed changes. EEG data will be processed using MATLAB and EEGLAB to extract spectral power and phase locking values in theta (4-7 Hz) and beta (13-30 Hz) frequency bands. A repeated-measures ANOVA will be conducted to assess potential changes in neural entrainment before and after vibrotactile exposure. These analyses aim to provide objective confirmation of multisensory integration effects once empirical data become available.

The innovation in this study lies not only in the integration of vibrotactile stimulation with auditory input, but also in its ergonomic, user-friendly format suitable for real-world use. By combining two core rehabilitation goals (speech comprehension and postural control) the wristband provides a dual solution that may enhance patient outcomes and reduce reliance on fragmented therapeutic protocols. Insights from the pilot study will help refine both the technical design of the device and the therapeutic strategies employed in clinical audiology.

III. Results and Discussion

As the practical phase is in progress, this section outlines anticipated outcomes based on existing studies. The dual function of the wristband aims to bridge the gap between conventional rehabilitation approaches that treat hearing and balance separately.

A. Expected Speech and Postural Results

Previous studies showed speech-in-noise improvements of up to 15%. We expect comparable effects, which will be quantified through bisyllabic word recognition tests before and after exposure. Likewise, postural data are expected to show reductions in sway path length and velocity, consistent with Choi, who observed comparable balance enhancements following vibrotactile feedback in older adults. [1],[4], [5],[11].

Balance improvements are expected in sway path metrics, especially under eyes-closed conditions [10]. This would confirm that supplemental vibrotactile stimulation can improve proprioceptive feedback and posture control.

B. Integration and Usability

User feedback will be collected to assess wearability, comfort, and daily use. Limitations include potential tactile habituation, individual variability in sensitivity, and difficulty isolating variables in a complex clinical environment. The innovation in this study lies not only in the integration of vibrotactile stimulation with auditory input, but also in its ergonomic, user-friendly format suitable for real-world use. By combining two core rehabilitation goals (speech comprehension and postural control) the wristband provides a dual solution that may enhance patient outcomes and reduce reliance on fragmented therapeutic protocols.

The study aligns with current efforts to integrate wearable technology into hearing rehabilitation, combining engineering design with clinical feedback from audiology practice.

C. Expected EEG Findings

Since the project is currently in its initial phase and EEG data collection has not yet begun, the following results are theoretically anticipated. Based on previous literature, vibrotactile stimulation synchronized with speech rhythm is expected to enhance neural entrainment in auditory cortical areas, reflected by increased theta-band phase-locking values and improved temporal coherence between auditory and tactile signals. Once data collection is completed, statistical comparisons will be performed to confirm whether these patterns are observed empirically.

D. Comparative Analysis of Multisensory Technologies

A comparative review of multisensory approaches in audiological rehabilitation was integrated to contextualize the novelty of this research. Electro-haptic stimulation has demonstrated efficacy in enhancing spatial hearing, while mechanical stimulation devices are often simpler but less adaptable. In contrast, the proposed wristband combines rhythmic vibrotactile cues with ergonomic design and EEG monitoring, offering real-time feedback and multisensory synchronization. Table 2 presents a summarized comparison.

Table 2. Comparison of Multisensory Stimulation Approaches

Technology	Advantages	Limitations
Electro-haptic systems	High precision; spatial localization aid	Energy- intensive; complex integration
Mechanical stimulation	Low-cost; easy to implement	Limited encoding flexibility
Vibrotactile wristband	Rhythmic, intuitive; wearable; EEG linked	Requires calibration; user-dependent

This comparison reinforces the potential of the proposed solution to deliver an accessible and integrative alternative with broad clinical applicability. By combining technological flexibility with user centered design, the wristband addresses both clinical and functional expectations. Further comparative studies are needed to quantify long term benefits across different patient profiles.

E. Implementation Challenges and Limitations

Potential barriers to long-term implementation include user habituation to tactile input, inter-individual differences in sensitivity thresholds, and variability in daily use compliance. The device's usability may also be affected by comorbid conditions or dexterity limitations. Future versions of the system will include personalized calibration algorithms and optional remote monitoring through Bluetooth modules.

IV. Conclusions

This study outlines an interdisciplinary approach to audiological and vestibular rehabilitation by combining vibrotactile stimulation with auditory input in a wearable format. The wristband prototype was designed to address two key challenges (enhancing speech comprehension in noisy environments and improving postural stability) through synchronized multisensory feedback. Drawing on existing literature, the concept shows promising therapeutic potential, and the study will further validate its impact through pilot studies targeting both auditory and motor performance outcomes. The compact design supports daily use and encourages user autonomy, especially in patients using cochlear implants or hearing aids.

Looking forward, we plan to optimize signal processing algorithms, refine the system's adaptability to individual sensory profiles, and investigate its applicability in pediatric rehabilitation contexts. To enhance clinical supervision and individualized treatment planning, real-time monitoring will be implemented via digital tracking and cloud-based feedback systems. We believe this approach can streamline current rehabilitation procedures by combining two therapies, auditory and balance, into a single, user-friendly system.

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