HaptiDrum

"The Air Drum You Can Feel."

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ABSTRACT

HaptiDrum is a revolutionary wearable air-drumming system that transforms the virtual drumming experience through advanced haptic feedback technology. It leverages XIAO ESP32-S3 and XIAO nRF52840 microcontrollers, along with BNO085 IMUs, to achieve high-frequency, accurate motion tracking and deliver precise 3D localization of hand and foot movements. The core innovation lies in its dual-mode haptic feedback system, combining Linear Resonant Actuator (LRA) motors and Electrical Muscle Stimulation (EMS) to create a realistic drumming sensation. The system includes four wireless peripheral units—two for simulating hand-held drumsticks and two for foot-based hi-hat and kick drum control. The hand modules are mounted on the forearms and deliver tactile feedback that aligns with hand impact motions, while the foot modules are worn near the ankles or shoes to provide vibration feedback during foot gestures. This design ensures that feedback feels both natural and anatomically intuitive. All peripherals communicate via Bluetooth Low Energy with a mobile application that handles visualization and device configuration. The system architecture is fully scalable, supporting the addition of new peripherals and instruments without altering the core logic. By removing the need for physical drums or sticks, HaptiDrum offers musicians a portable, expressive, and immersive drumming experience that seamlessly connects air gestures with musical expression.

Keywords

Interaction devices, Haptic devices, User interface programming, Ubiquitous and mobile computing systems and tools

1. INTRODUCTION

The evolution of digital music interfaces has long attempted to bridge the gap between the expressiveness of acoustic instruments and the portability of new technology. While air drumming is a natural gestural language for rhythm expression, from casual music enthusiasts tapping along with their favorite songs to professional drummers practicing without a kit, it has always been deprived of the critical tactile feedback that makes physical drumming so immersive and intuitive. Not only is the absence of haptic response a detractor from immersive experience, but it also impedes the development of proper technique and timing that drummers rely on.

HaptiDrum transcends this intrinsic restriction by introducing a wearable system that augments air drumming with sophisticated haptic feedback through the utilization of Electrical Muscle Stimulation (EMS). By combining high-frequency inertial tracking and wireless communication, our system delivers a portable drumming experience that preserves the expressiveness of acoustic drums without the need for physical instruments.

The intersection of growing demand for available musical creation interfaces with advances in wearable technology and haptic interfaces presents us with a unique opportunity to reimagine interaction with drum instruments. We present in this paper the design and implementation of HaptiDrum, detailing our approach to motion tracking, haptic feedback rendering, system architecture, and integration challenges surmounted in creating a responsive, extensible, and truly portable drumming experience.

2. RELATED WORK

Research in haptic-enhanced musical interfaces has explored various methods for enriching musical expression through tactile feedback. These systems often leverage wearable hardware to provide rhythmic cues, simulate instrument response, or assist in musical training.

The DigiDrum system [1] combined physical drum hardware with virtual sound synthesis, using vibrotactile feedback to replicate the sensation of different drum surfaces. This approach emphasized the augmentation of physical instruments rather than free-space interaction.

The Haptic Drum Kit [2] employed limb-mounted vibrotactile actuators to guide users in rhythm learning tasks. By delivering tactile pulses synchronized with beats, the system demonstrated that rhythmic coordination could be supported without auditory cues, highlighting the pedagogical potential of haptic-only feedback.

In broader contexts, commercial haptic suits such as Teslasuit[1] and TactSuit[2] have focused on full-body feedback for immersive applications, including gaming and VR. While these systems can deliver complex haptic patterns, their emphasis is on environmental immersion rather than precise, gesture-driven control, and they often lack portability or musical specificity.

Research into wearable vibrotactile displays has also explored expressive and communicative applications, such as mid-air gestural instruments and wearable audio-tactile garments. These studies reinforce the role of haptics not only as a feedback modality but as a means of embodied expression in digital performance contexts.

Additionally, electrical muscle stimulation (EMS) [4] has been explored as an alternative or complementary feedback modality. EMS systems provide deeper proprioceptive sensations by activating muscle groups directly, enabling users to feel force or movement rather than surface vibration. Prior work has investigated EMS for gaming, rehabilitation, and task guidance, but its application to rhythmic or musical interaction remains relatively underexplored.

Together, these studies establish the technical and conceptual groundwork for wearable haptic systems in expressive performance scenarios, especially in rhythm-focused or free-form interaction environments.

[1] https://teslasuit.io/
[2] https://www.bhaptics.com/en/tactsuit/

3. TECHNICAL DETAILS

3.1 Overview

Figure 1: Peripheral Devices

HaptiDrum is a wearable air-drumming system that allows users to simulate the experience of drumming without physical drums or sticks, while receiving real-time haptic feedback. The system is designed to be worn on the forearms and feet and is capable of detecting strike gestures, localizing hand position in three-dimensional space, and delivering tactile or electrical feedback corresponding to virtual drum hits. It consists of four wireless peripheral units (Fig. 1), two for hands and two for feet. Each unit is equipped with a microcontroller, an inertial measurement unit (IMU) sensor, Bluetooth communication module, haptic actuators including linear resonant actuators (LRA) or electrical muscle stimulation (EMS), and a compact power source.

The device enables an expressive and immersive playing experience through a combination of high-frequency motion tracking and real-time haptic feedback delivery, and a mobile application for visualization, configuration, and audio playback.

Users can freely move their limbs in the air to strike different types of virtual drums such as snare, tom, cymbal, and bass. The system responds with corresponding haptic feedback while the mobile application renders both sound and visual cues.

3.2 Theory of Operation

HaptiDrum operates through four coordinated wearable modules—two mounted on the forearms and two on the lower legs—that detect user motion and deliver corresponding haptic feedback in real time. Each module integrates a BNO085 inertial measurement unit.

Motion processing occurs directly on the embedded microcontroller. The firmware monitors linear acceleration and angular velocity data to detect sharp, directional movements indicative of drum strikes—such as a downward swing of the forearm or a rapid foot tap. When motion exceeds predefined thresholds, a strike event is registered.

Upon detection, the module activates its onboard haptic output. Vibration feedback is generated by a DRV2605L driver that drives a linear resonant actuator (LRA) positioned near the point of motion, such as the wrist or ankle. For modules mounted on the forearms, electrical muscle stimulation (EMS) is also employed. A biphasic current pulse is delivered via a Howland current pump circuit to target extensor muscles, simulating the muscular sensation of impact.

All four modules communicate wirelessly with a central mobile application using Bluetooth Low Energy (BLE). While the core motion detection and feedback logic run locally on each module, the mobile application handles drum sound playback, user configuration, and system visualization.

Each module is powered by a rechargeable lithium polymer battery and includes onboard power regulation circuitry. The combination of distributed sensing, local feedback, and centralized coordination enables a low-latency, self-contained drumming experience without the need for physical instruments or external tracking systems.

3.3 Implementation Details

3.3.1 Hardware Design and Implementation

The hardware architecture of the HaptiDrum system was designed to support high-resolution inertial sensing, low-latency haptic actuation, and wireless peripheral communication in a compact wearable format. The system consists of several modular components integrated into a forearm and foot mounted form factor. This section details the selection and integration of each hardware module.

Hand Modules: Seeed XIAO ESP32-S3

The hand-mounted modules are powered by the Seeed XIAO ESP32-S3 microcontroller, which serves as the core controller for sensor acquisition, signal processing, and haptic output. This chip was selected for its compact footprint (21 * 17.5 mm), dual-core LX7 processor, and integrated support for Bluetooth Low Energy (BLE) 5.0. The ESP32-S3 communicates with the BNO085 IMU via I²C to acquire high-frequency 9-axis inertial data, and also interfaces with the DRV2605L haptic driver over the same bus to generate localized vibration feedback. Electrical muscle stimulation (EMS) output is controlled through GPIO-triggered analog switches, targeting the extensor muscles in the forearm to simulate realistic percussive impact.

Foot Modules: Seeed XIAO nRF52840

The foot-mounted modules are built around the Seeed XIAO nRF52840 microcontroller, chosen for its low-power characteristics and reliable BLE 5.0 communication. Unlike the hand modules, the foot modules utilize the onboard 6-axis IMU integrated in the nRF52840 platform for basic motion detection. The microcontroller drives the DRV2605L haptic driver to generate vibration feedback corresponding to foot strike gestures. Since EMS functionality is not required in the foot modules, the nRF52840 provides a more efficient balance of resources and power consumption suited to this configuration.

Inertial Measurement Unit: BNO085

The system employs a BNO085 9-axis IMU capable of capturing 3-axis acceleration, 3-axis angular velocity, and 3-axis orientation (quaternion), delivering fused accelerometer, gyroscope, and magnetometer data at rates at least 200 Hz. This high-frequency tracking supports responsive gesture recognition for rapid arm and leg movements during virtual drumming.

Electrical Muscle Stimulation (EMS) Circuit

The EMS module is implemented using a Howland current pump topology with a rail-to-rail operational amplifier and matched precision resistors to ensure consistent and symmetric biphasic current delivery. The system is designed to generate a pulsed electrical signal at approximately 100 Hz to stimulate muscle contraction and reinforce rhythmic timing through muscle recruitment. The ESP32-S3 microcontroller generates a 100 Hz PWM signal that controls the timing and duration of the biphasic pulses, with the output current programmable in the range of 0 to 10 mA.

To ensure user safety, the output stage includes Schottky diode clamping and a series shunt resistor for current monitoring and limiting. Additional thermal and duty-cycle safeguards are implemented to prevent overheating and muscle fatigue during extended use. A refractory interval is enforced between successive activations to reduce the risk of overstimulation.

The EMS circuit is triggered by the ESP32-S3 only upon validated strike gestures, ensuring precise temporal alignment between gesture recognition and feedback delivery. Electrodes are placed on the dorsal side of the forearm, targeting the wrist extensor muscle. This location was selected to simulate the physical sensation of impact when striking a drum, producing naturalistic muscle contraction that enhances the immersive quality of the air-drumming experience.

Vibrotactile Feedback Module: DRV2605L with LRA

Tactile haptic feedback is delivered using DRV2605L haptic motor drivers paired with Linear Resonant Actuators (LRAs). The driver IC supports a rich library of pre-configured haptic effects and dynamic control of vibration amplitude.

Printed Circuit Board Design

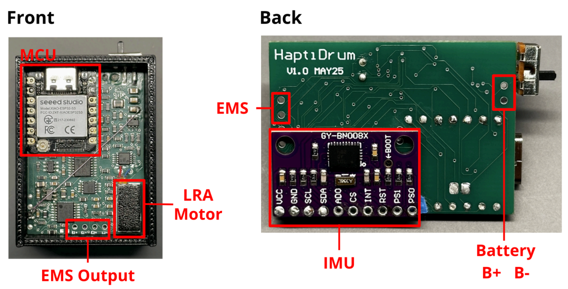

Figure 2: PCB Design

A custom dual-layer PCB measuring 30 mm by 42 mm integrates the ESP32-S3 microcontroller, BNO085 IMU, DRV2605L haptic driver, EMS switching components, and power management circuitry (Fig. 2). The board features a double-sided layout to optimize space utilization and minimize the device footprint. Integrated low-dropout (LDO) voltage regulators ensure stable operation of sensitive components, while surface-mount LEDs and status indicators provide visual feedback during operation. The entire board is housed within a lightweight, 3D-printed ABS enclosure.

Power System

Each unit is powered by a 3.7v 820 mAh Li-Po battery, supporting at least 3 hours of continuous operation. Safety features include over-discharge protection, short-circuit prevention, and charge-balancing. Charging is achieved via a USB-C connector, and battery voltage is monitored by a voltage monitor circuit to report real-time status to the mobile app.

3.3.2 Software

The software system behind HaptiDrum consists of two major components: the firmware running on each wearable unit using the Arduino framework for ESP32-S3, and the iOS mobile application written in Swift, designed using Figma as the prototyping tool. Together, these components enable real-time motion capture, gesture recognition, haptic actuation, and user interaction through a responsive UI.

Embedded Firmware Design

The embedded firmware of the HaptiDrum system is implemented on two distinct microcontroller platforms: an ESP32-S3 for the hand unit and an nRF52840 for the foot unit. Despite differences in hardware architecture, both firmware implementations share a unified structure for motion sensing, Bluetooth Low Energy (BLE) communication, and command-based control. This section describes the shared system architecture and highlights the functional differences between platforms.

Shared System Architecture. Both units operate as BLE peripherals, advertising unique device names (e.g., HaptiDrum_Hand_L, HaptiDrum_Foot_R). Upon connection with a host device, each unit transmits inertial data at 50 Hz in JSON format. The data packets contain orientation information derived from onboard IMUs and, when available, linear acceleration components. For example: {"pitch": -3.2, "roll": 1.4, "yaw": 178.5, "ax": -0.01, "ay": 9.80, "az": 0.12}

Each device accepts BLE write commands via a designated characteristic. Supported commands include: 1."RESET": Reinitializes the IMU and resets the orientation baseline;
2. "FIND": Triggers a long vibration to assist in locating the device; 3. "CONNECT": Emits three short vibration pulses to indicate successful pairing; 4. "PLAY": Triggers haptic feedback on both platforms, with platform-specific behavior (see below).

All commands are handled in real time via BLE characteristic write callbacks.

Hand Unit (ESP32-S3 with External IMU and EMS). The hand unit uses an external BNO085 IMU over I²C, enabling full 9-axis motion tracking. The firmware extracts pitch, roll, and yaw from the rotation vector, and reads 3-axis linear acceleration (ax, ay, az) from the IMU's linear acceleration channel. These six parameters are continuously streamed to the host.

Upon receiving the "PLAY" command, the hand unit performs two simultaneous feedback actions: 1. Vibration feedback using the DRV2605 actuator driver; 2. Electrical Muscle Stimulation (EMS) via a custom control function: ems(frequency, duty, voltage, durationMs);

The EMS output is generated using a digital-to-analog converter (MCP4725) to control voltage amplitude, and PWM signals from GPIO pins to define pulse frequency and duty cycle. This allows precise modulation of stimulation intensity and duration, delivering deep tactile cues synchronized with virtual drum hits.

Safety constraints are enforced: EMS can only be triggered after BLE connection and IMU initialization, and each EMS event has a fixed duration limit to prevent overstimulation.

Foot Unit (nRF52840 with Internal IMU). The foot unit is based on the nRF52840 platform and utilizes its integrated 6-axis IMU (accelerometer + gyroscope). Due to hardware limitations, it does not provide yaw or az values. The transmitted data includes only: {"pitch": 2.7, "roll": -1.9, "ax": 0.15, "ay": 9.60}, which is sufficient for our use on feet.

The foot firmware mirrors the BLE interface of the hand unit and supports the same commands: "RESET", "FIND", and "CONNECT". Additionally, it responds to "PLAY" by issuing a short vibration via the DRV2605, but does not include EMS functionality. This streamlined design reduces power consumption and complexity for lower-limb tracking, where haptic feedback is limited to surface-level vibration.

iOS Mobile App

The iOS application for HaptiDrum is composed of several modules responsible for Bluetooth communication, peripheral management, command transmission, and virtual drumming interaction. The interface follows a two-level structure: a device management screen for scanning and connection, and a performance screen for real-time motion detection and sound feedback.

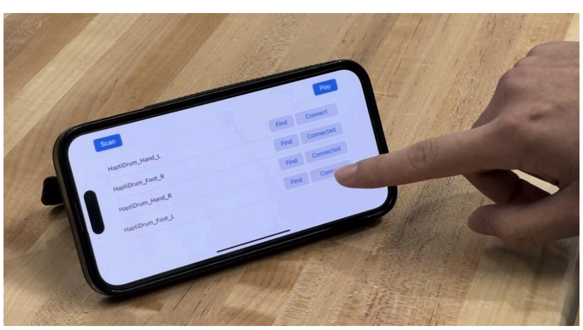

Figure 3: Devices Pairing App Interface

BLE Device Management and Control. Bluetooth communication is encapsulated within a centralized management module, which handles peripheral scanning, connection establishment, characteristic discovery, and command writing. Devices are filtered based on their advertised names, and only peripherals whose names begin with "HaptiDrum" are recognized and processed.

The user interface displays a list of all discovered peripherals and allows the following actions: 1. Triggering a “find” command, causing the device to vibrate for physical identification; 2. Sending a “connect” command to establish a BLE connection; 3. Displaying connection status and transitioning to the interaction interface upon successful connection.

Scanning is initiated via a user control element and supports dynamic updates of the peripheral list.

Figure 4: Drumming Page

Virtual Drumming Interaction Flow. The drumming interface presents multiple virtual drum elements, each mapped to a wearable device attached to a different part of the user’s body. Users may either tap on a drum image to manually trigger its associated sound or perform physical gestures to activate a real hit event via sensor data.

The system continuously listens for BLE notifications from connected devices. Incoming data is encoded in JSON format and includes orientation and acceleration parameters. Upon reception, the application parses the data and compares the orientation to a previously calibrated baseline to determine whether a hit gesture has occurred.

An “initialization” control is provided to collect one second of yaw, pitch, and roll values for each device. These averages are stored as the personalized baseline orientation for that session, improving gesture recognition robustness across varied postures and wear conditions.

A separate “reset” control can be used to issue a "RESET" command to all connected devices, remotely reinitializing their IMU states and refreshing BLE communication.

Hit Detection and Feedback Mechanism. Hit detection is based on deviation thresholds: when a device moves outside a predefined rest zone and was previously stationary, a hit is detected. Upon detection, the system performs the following sequence: Sends a "PLAY" command to the corresponding device to trigger hardware-level feedback; Plays the associated drum sound locally; Temporarily switches the drum image to a “hit” visual state, then restores it after a short delay.

This processing pipeline creates a closed-loop interaction flow, combining synchronized BLE command transmission with local audiovisual feedback. The result is a responsive and immersive user experience for interactive drumming.

4. EVALUATION AND RESULTS

The HaptiDrum system was comprehensively tested to assess its performance in different areas, such as the quality of haptic feedback, system responsiveness, and general user experience. Overall performance of the system demonstrated solid performance with the gesture recognition and motion tracking algorithms successfully detecting strike gestures on different playing styles and intensities. The dual haptic feedback system was most successful, with the EMS feedback providing distinct and obvious muscle stimulation that users all reported as realistic simulation of physical drum impact sensations. The electrical muscle stimulation to forearm extensor muscles yielded realistic responses that were intuitive and engrossing for users, while the LRA-based vibrotactile feedback with palm and wrist-mounted actuators provided immediate tactile feedback of strikes. The Bluetooth Low Energy connection delivered stable connections throughout test sessions, battery performance meeting design expectations of approximately 3 hours' continuous operation, and the modular design achieved scalability due to all four peripheral devices being able to communicate well with the central mobile application. However, significant latency issues were discovered to be the primary constraint, whereby the system occasionally experienced delays in haptic feedback delivery and gesture detection, leading to timing inconsistencies that disrupted smooth, continuous drumming. Such delay problems critically impacted users' performance in terms of delivering rapidly unfolding drumming patterns and continuous fast sequences, since the delay in feedback disrupted the natural rhythm and timing employed by drummers when developing skills and playing music. In spite of this limitation, users enjoyed the portability and uniqueness of the system, indicating that it effectively eliminated the constraint of using physical drum kits while maintaining expressive control through its dexterity in a lightweight, fingerless design during long playing sessions.

5. DISCUSSION

5.1 Limitations

Our HaptiDrum system successfully demonstrates the viability of haptic-aided air drumming, with good responsiveness and few latency issues. Combining LRA motors and EMS provides robust tactile feedback users report significantly enhances their experience with virtual drumming compared with visual or audio systems alone. The wireless modular architecture performed well, enabling untroubled communication among multiple peripherals while maintaining portability essential to real-world usage.

While the HaptiDrum system successfully demonstrates the viability of haptic-aided air drumming, several limitations were identified during evaluation. The most critical issue encountered was latency in gesture recognition and haptic feedback delivery. These delays occasionally disrupted the precise timing required for continuous or rapid drumming sequences, affecting performance during fast-paced patterns. Although the wireless modular architecture enabled stable multi-device communication, minor inconsistencies in Bluetooth throughput contributed to timing jitter across peripherals.

From a hardware standpoint, the use of breakout boards and single-layer PCB layouts increases the system’s physical footprint and limits mechanical durability. Additionally, the thermal management of EMS components during extended sessions requires improvement to avoid heat buildup. On the software side, the absence of auto-calibration for EMS parameters means manual tuning is still necessary to accommodate individual users, which may limit ease of deployment across a wide audience.

5.2 Future Works

Future development will focus on both hardware and software enhancements to address current limitations and extend the system's functionality. On the hardware side, a move toward fully integrated, double-sided PCB layouts and removal of breakout modules will significantly reduce the form factor and improve overall performance. Enhanced thermal management strategies will be implemented to support prolonged play without overheating. Standardizing the microcontroller model across all peripherals will also simplify manufacturing and maintenance.

Software efforts will prioritize latency reduction by optimizing Bluetooth communication protocols and exploring the use of edge computing to enable more localized processing of gesture recognition and actuator control. The system will also expand the range of supported drum gestures and introduce auto-calibration algorithms for EMS intensity scaling based on user feedback and impedance measurements.

Multi-Zone Hit Detection with a Single Device. In addition to device-specific mapping, the system supports triggering multiple virtual drums using a single wearable device. This is achieved by dividing the gesture space into distinct detection zones based on pitch and roll angles. For example, tilting the hand forward and striking triggers a snare drum, while a sideways swing may correspond to a hi-hat or cymbal. These directional zones are defined relative to the user's calibrated baseline orientation. Each zone is associated with a different virtual drum, allowing users to perform expressive drumming sequences using only one hand. This approach significantly expands the interactive capability without requiring additional hardware, and supports more compact or mobile usage scenarios. Zone boundaries and thresholds can be tuned per user to improve accuracy and responsiveness.

Beyond the scope of air drumming, HaptiDrum's underlying architecture and feedback strategies have potential applications in virtual reality (VR), rehabilitation, and assistive musical technologies. By combining accurate motion sensing with multimodal haptic output, the system can be adapted for VR controllers, surgical simulators, or musical interfaces tailored to users with physical disabilities.

5.3 Regulations

In alignment with the safety recommendations outlined in the FDA's Guidance Document for Powered Muscle Stimulator 510(k)s [4], the EMS system is designed to comply with key output safety thresholds. Specifically, the output current is capped at 10 mA, and the electrode design maintains a current density of 0.012 W/cm², which is significantly below the FDA-advised maximum of 0.25 W/cm². This conservative threshold greatly reduces the risk of thermal injury during use.

These safeguards are reinforced with additional measures, including pulse timing control and enforced refractory periods, ensuring that electrical stimulation remains within safe physiological bounds while still delivering convincing haptic feedback suitable for recreational scenarios.

Furthermore, the EMS subsystem incorporates real-time current monitoring and duty cycle limitations to prevent overstimulation and muscle fatigue. While HaptiDrum is not a medical device, adherence to FDA safety guidance ensures that its electrical stimulation features conform to established best practices for non-clinical use.

6. CONCLUSION

HaptiDrum can demonstrate the feasibility of providing an immersive, travel-sized air-drumming experience using a blend of advanced haptic feedback technologies with precise motion tracking. The unique blend of Electrical Muscle Stimulation and Linear Resonant Actuator feedback creates a naturalistic simulation of real drumming that users perceive as fun and realistic.

The main contributions of the project are a wireless, scalable peripheral architecture with no physical drum needs, but still retaining expressiveness in the music, and the success of the dual haptic feedback solution that integrates EMS muscle-level impact simulation to significantly enhance the virtual drumming experience. BNO085 IMU sensor plus MediaPipe vision tracking presents robust gesture detection over broad spaces of user motion and playstyles.

However, the test highlights critical latency constraints that are currently inherent in the system, preventing it from maintaining complex drumming patterns with rapid, continuous impacts. Such timing delays are the main obstacle to widespread adoption and indicate the need for highly optimized communication protocols and increased processing pipelines.

Future growth should be directed towards latency minimization with edge computing deployment, real-time optimization of the Bluetooth communication stack, and hardware acceleration of gesture recognition algorithms. In addition, further development of the musicality of the system by adding support for additional instruments and automatic calibration to suit individual users would enhance its versatility and usability.

Effective implementation of safety-compliant EMS circuitry and modular hardware design opens up possibilities for expanding applications into domains other than drumming, for example, virtual reality interfaces, rehabilitation systems, and assistive musical technologies for physically disabled musicians. The project demonstrates that haptic-augmented air instruments can bridge the gap between digital convenience and acoustic expressiveness, offering new possibilities for portable, interactive musical interfaces.

Despite continued issues with latency, HaptiDrum represents a significant improvement in wearable music technology and provides a solid foundation for continued development of haptic-enabled air instruments. The success of the system in delivering realistic haptic feedback in handheld form validates the underlying concept and provides valuable lessons for continued development in immersive digital musical interfaces.

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