

# A Smart Footwear Platform for Gait Augmentation: Application to Musical Feedback for Improving Gait in Parkinson's Disease

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## Abstract

Parkinson's disease (PD) is a progressive neurodegenerative disorder with a rapidly increasing prevalence. Gait disturbances such as reduced stride length and freezing of gait (FoG) are characteristic symptoms that affect quality of life. Because these symptoms fluctuate throughout the day and FoG often occurs transiently, continuous gait monitoring and immediate intervention are required in daily life. Moreover, the progressive reduction of movement amplitude highlights the importance of sustained gait training.

While rhythmic auditory stimulation has been shown to be effective in alleviating gait disturbances in PD, its effects vary across individuals, and monotonous auditory cues often fail to maintain motivation, limiting long-term use in everyday settings. Incorporating musicality into auditory feedback may therefore enhance engagement and adherence by fostering active involvement in movement.

In this study, we propose a musical feedback system built on a smart footwear platform with a foot-mounted gait analysis motion sensor (ORPHE CORE 3.0) and a software development kit that enables flexible handling of gait data. We developed two applications: an interactive auditory cue system that triggers drum sounds synchronized with steps for alleviating FoG, and a musical biofeedback system in which musical layers progressively accumulate as stride length improves, fostering both gait improvement and intrinsic motivation.

Pilot studies with only two individuals with PD demonstrated reduced FoG duration during walking and turning, improvements in gait parameters, and high enjoyment ratings. While preliminary, these findings suggest that linking gait to musical expression has the potential to provide not only movement support but also an engaging experience that enhances motivation. This paper proposes a smart footwear platform that bridges rehabilitation and musical expression, offering new possibilities for healthcare-oriented applications within the NIME community.

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## Keywords

Music for Healthcare, Motion Sensor, Freezing of Gait, Gait Analysis and Rehabilitation

## 1 Introduction

Parkinson's disease (PD) is a progressive neurodegenerative disorder characterized by motor symptoms such as bradykinesia, muscle rigidity, resting tremor, and postural instability [1]. The number of people with PD (PwPD) globally exceeded 8.5 million in 2019 and is projected to reach 25 million by 2050 [2, 3], making it a critical public health issue [4]. Among the various symptoms, gait disturbances—manifesting as reduced stride length, gait cycle instability, and freezing of gait (FoG)—are significant clinical challenges directly linked to an increased risk of falls [5] and a decline in activities of daily living and independence [6]. These gait disturbances are thought to be closely related to the breakdown of internal motor timing generation and update mechanisms within the basal ganglia-cortical network [7]. FoG—typically described as the feet being "glued to the floor"—frequently occurs at gait initiation, during turning, or in narrow spaces [8, 9], and affects roughly 50–80% of PwPD as the disease progresses, reducing both safety and social participation [10]. Pharmacological (L-dopa) and surgical (DBS) treatments are effective for many motor symptoms but show limited or unstable responses for gait disturbances; moreover, L-dopa carries the risk of motor complications [11] and DBS efficacy may wane over time [12]. Because PD symptoms fluctuate and FoG occurs transiently, routine monitoring and immediate intervention are needed [13], yet rehabilitation adherence drops sharply without expert supervision [16] and FoG benefits diminish once training is interrupted [17], underscoring the need for continuous intervention in daily life [14, 15]. Given this background, the importance of non-pharmacological rehabilitation strategies—such as gait training and exercise therapy using visual, auditory, and somatosensory cues—has been repeatedly emphasized [18, 19]. Among these, approaches using rhythmic auditory stimulation (RAS) have been shown to improve gait parameters such as walking speed and stride length [20, 21, 22], and have been reported to exert beneficial effects on functional outcomes such as balance, mobility, activities of daily living, and quality of life [22]. Subsequent studies and meta-analyses have similarly reported improvements in functional indicators such as the 6-minute walk distance [23] and the Timed Up and Go test [15]. There is a wide variety of auditory cues; not only rhythmic stimulation by a metronome but also handclaps or verbal cueing by therapists or caregivers can function as external cues embedded in interpersonal interactions, potentially increasing attention and motivation [24]. Furthermore, in recent years, it has been reported that providing RAS via wearable devices and digital applications supports the improvement of daily walking and home-based rehabilitation [25, 26]. Music-based movement therapy also provides a richer sensorimotor experience by utilizing musical elements such as melody and harmony in addition to rhythmic structure [27]. On the other hand, it has been pointed out that its effectiveness varies among individuals, requiring personalization [27, 28], and that maintaining motivation with sterile sound stimulation is difficult, making continuous use in daily life challenging [29]. To monitor gait over the long term while blending into daily life and to provide training support for alleviating FoG and maintaining function, utilizing musicality as a means of

increasing involvement in physical movement and motivation is considered a key factor [19].

While the effectiveness of auditory and musical interventions is thus demonstrated, challenges remain regarding their implementation in actual clinical settings and daily life. In recent years, several research-grade measurement instruments and wearable devices for digitizing gait have emerged [23, 29–34], improving the precision and convenience of gait analysis. However, many of these primarily focus on the measurement and recording of gait parameters, and their application to real-time musical feedback or personalized interactive interventions remains limited. In particular, platforms equipped with a Software Development Kit (SDK) that allow for the flexible design and verification of mappings to sound and music—essential for personalization and trial-and-error—are scarce. Environments that enable the simultaneous exploration of clinical support and musical interaction have not sufficiently proliferated. Consequently, there is a need for a development infrastructure that allows researchers and clinicians to customize musical feedback according to condition and preferences of PwPD and to rapidly verify its effectiveness.

In this study, we aimed to construct a musical feedback system to support the alleviation of FoG and the enjoyable and effective continuation of gait training for PwPD, based on a smart footwear platform equipped with a foot-mounted wearable motion sensor (ORPHE CORE 3.0) and an SDK (ORPHE-CORE.js) capable of handling gait data universally. ORPHE CORE 3.0 incorporates acceleration and angular velocity sensors and features edge processing capabilities to perform gait analysis within the device. Gait parameters such as stride length, cadence, strike angle, and toe-off angle are calculated in real time and transmitted with low latency via Bluetooth Low Energy. ORPHE-CORE.js is a JavaScript SDK utilizing the Web Bluetooth API, allowing applications running on a browser to connect directly to the sensor and acquire gait data. This configuration enables cross-platform development usable on diverse devices such as PCs, smartphones, and tablets without requiring the installation of dedicated apps. Furthermore, developers can focus on designing musical mappings using gait events and parameters without having to handle complex BLE communication or low-level signal processing. We utilized this platform to implement two applications with distinct approaches. First, ORPHE DRUMNER is a reactive auditory cue system that plays drum sounds in immediate response to steps. Through a direct "one step = one sound" mapping, the user's own physical movement is returned instantly as acoustic feedback, enhancing the sense of agency and likely promoting smooth movement execution. Second, ORPHE BloomBeat is a musical biofeedback system where music is generated and evolves according to gait quality (stride length). Through a "Bloom" process where musical tracks are added stepwise based on gait status, it provides an experience where gait improvement culminates in musical richness, supporting the continuity of gait training and the maintenance of motivation. Pilot studies with two individuals with PD showed that ORPHE DRUMNER reduced FoG duration during a turning task (from 42.0 s to 2.3 s) and task time (from 53.3 s to 18.0 s), while ORPHE BloomBeat elicited a gradual stride-length increase over a 2-minute walk together with

high enjoyment (91/100) and low anxiety (9/100). Although preliminary, these results suggest that linking gait to musical expression can support both immediate intervention for FoG and long-term motivation for training.

This paper proposes a platform that bridges the boundary between rehabilitation and musical expression, based on physical augmentation by smart footwear, and presents preliminary evidence for its potential in healthcare applications within NIME. The development foundation utilizing web technology and an open-source SDK provides an environment where researchers, clinicians, and musicians can collaborate to create new musical interventions, offering practical and creative contributions to the NIME community exploring the relationship between physical movement and music.

## 2 Related Work

To clarify the positioning of this study, we provide an overview of related research from three perspectives: the history of footwear interfaces in the NIME community, their application to rehabilitation, and the challenges regarding clinical implementation.

### 2.1 Footwear Interfaces and Gait Sonification in NIME

As an interface for converting physical movement into sound or music, "shoes" have been a significant theme in the NIME community since its inception. Paradiso et al.'s *Expressive Footwear* [29] stands as a pioneering example, utilizing a wide variety of sensors embedded in shoes to elevate dancers' foot movements into expressive musical control. This work demonstrated to the community that shoes are not merely tools for walking but can become body-augmenting musical instruments.

Since then, footwear interfaces with more specialized functions have been proposed. Papetti et al.'s *Rhythm'n'Shoes* [30] implemented low-latency wireless communication and audio-tactile feedback, highlighting the importance of tight timing in foot-tapping performances. D'Adamo et al.'s *SoniWeight Shoes* [31] demonstrated that a prototype shoe that modulates and provides real-time feedback of footstep sounds can alter users' perception of body weight. They further showed that the magnitude of this effect varies with interoceptive traits such as physical activity level and eating attitudes, highlighting the importance of personalization. Kondapalli and Sung's *Daft Datum* [32] explored intuitive music generation through foot gestures. Furthermore, Nymoen et al.'s *Funky Sole Music* [33] proposed a method for adaptively switching musical sections and mapping rules themselves based on gait pattern recognition. This is significant as an attempt to embed the meaning of walking in musical structure, going beyond simple parameter mapping. Humphrey et al.'s *The Navi Activity Monitor* [34] also proposed a method for generating tempo curves from walking rhythm to humanize computer music, showing high relevance to this study regarding the synchronization of physical rhythm and musical time.

### 2.2 Interactive Sonification for Rehabilitation

The scope of such interfaces has expanded beyond artistic expression into healthcare and rehabilitation. In PD rehabilitation specifically, RAS is widely recognized as effective for gait improvement [22, 35, 36]. Recently, however, interactive sonification—which reacts in real time to the user's movement rather than providing a fixed-tempo metronome—has garnered increasing attention.

Mayo et al. demonstrated that gait training with a real-time positive feedback system based on foot angular velocity led to improved walking ability in PwPD [23, 37]. Ginis et al. [28] used intelligent verbal prompts and cues automatically triggered when gait deviated from baseline, while Cochen et al. [26] employed auditory cues designed to entrain and synchronize the gait cycle; both achieved improvements in walking. Such individualized auditory interventions are increasingly shown to be effective, although broader validation is still required [38].

Wall et al. [39] highlighted the importance of personalized sonification designs tailored to individual walking characteristics. Within the NIME community, Gold et al.'s *P(l)aying Attention* [40] proposed a system combining motion analysis of chronic pain patients with musical feedback to guide patient attention and agency. These studies suggest that musical feedback functions as a powerful medium for eliciting active engagement, going beyond merely serving as a guide for movement.

### 2.3 Bridging the Gap: Towards an Open Clinical Platform

However, many existing studies rely on *ad-hoc* prototypes developed specifically for experiments. There remains a lack of a common platform that integrates these findings with sonification techniques to unlock broader possibilities for use in daily life and actual clinical settings.

The uniqueness of this study lies in bridging this gap between implementation and dissemination by combining commercially available smart footwear (ORPHE CORE) with an SDK based on web standard technology (Web Bluetooth API). By providing widely accessible hardware and an open development environment, we propose a foundation for new applications that blur the boundary between rehabilitation and musical expression. This enables the rich knowledge of musical interaction accumulated by the NIME community to be scaled to clinical sites and daily life without requiring specialized equipment.

## 3 Smart Footwear Platform

The smart footwear platform proposed in this study comprises inertial sensor devices, dedicated shoes and attachments enabling various mounting configurations, an edge analysis algorithm, and an SDK.

### 3.1 Hardware Design

#### 3.1.1 Sensor Module: ORPHE CORE 3.0

The core device of this platform is the ORPHE CORE 3.0, a foot-mounted wearable sensor developed by ORPHE Inc. (Figure 1a).

Encased in a compact housing (45 mm × 29 mm × 14 mm), it incorporates a 6-axis motion sensor (accelerometer and gyroscope, 200 Hz sampling rate), an ARM Cortex-M4 processor, and 128 MB of flash memory. It is powered by a 300 mAh lithium-polymer battery, providing approximately 8 hours of continuous operation. With IPX7-equivalent water resistance, it offers high durability suitable for daily life and outdoor exercise. An RGB LED is included for device status indication and user feedback. Low-latency data communication is achieved via Bluetooth Low Energy (BLE).

### 3.1.2 Mounting Configurations

The platform offers multiple mounting configurations to enhance user convenience.

First, EASYRUN SHIBUYA 3.0 (Figure 1b) is a dedicated shoe designed to fully embed the ORPHE CORE 3.0 within its midsole. This design ensures stable sensor fixation, supporting high measurement accuracy for gait analysis, while maintaining the appearance and feel of a standard shoe. Additionally, the midsole features a translucent side panel, allowing the LED of the ORPHE CORE 3.0 to be visible, thereby supporting visual expression via light.

Second, a SHOELACE MOUNT (Figure 1c) attachment is provided for compatibility with standard shoes. This allows users to retrofit the sensor onto the shoelaces of their preferred footwear, ensuring high accessibility independent of specific shoe models.



**Figure 1 : Hardware configuration of the smart footwear platform.** (a) ORPHE CORE 3.0: Small 6-axis motion sensor device. (b) EASYRUN SHIBUYA 3.0: Dedicated shoes capable of embedding the device inside the midsole. (c) SHOELACE MOUNT: Attachment capable of fixing the device to existing shoelaces.

## 3.2 Gait Analysis Algorithm

The ORPHE CORE 3.0 implements a proprietary algorithm that analyzes accelerometer and gyroscope data in real-time to calculate gait parameters.

Based on Zero-Velocity Update [41], a technique derived from inertial navigation, the algorithm detects the momentary zero-velocity state during foot contact to correct sensor integration errors, enabling high-precision position and orientation estimation. Gait events such as heel strike, foot flat, and toe-off are detected using standard time-domain features of acceleration and angular velocity signals, including peaks, zero-crossings, and inflection points [42].

Key gait parameters calculated include stride length, stride duration, strike angle, and toe-off angle. The measurement accuracy of this algorithm has been verified against optical 3D motion analysis systems, confirming a high correlation sufficient for clinical use [43]. These gait parameters are processed on the edge device and then provided to host applications in an event-driven manner via the SDK.

## 3.3 Software Development Kits

At the core of the smart footwear platform lies a suite of open-source Software Development Kits (SDKs) published on Orphe-OSS (<https://github.com/Orphe-OSS>). These SDKs are designed for both web-based and local environments, allowing developers to select the optimal development environment for their needs.

ORPHE-CORE.py is provided for advanced data analysis and external integration in local environments, while ORPHE-CORE.js is intended for high accessibility via web browsers. This study used ORPHE-CORE.js to prioritize ease of setup in clinical and daily-life environments and versatility across a diverse range of devices.

This library leverages the Web Bluetooth API, enabling direct connection to the sensor via major browsers without requiring dedicated application installation. It operates across diverse environments, ranging from PCs to smartphones and tablets, facilitating easy cross-platform deployment. Functionally, tasks such as sensor time synchronization and the acquisition of edge-analyzed gait data are handled via intuitive APIs (methods) provided by the SDK. This allows developers to rapidly build interactive systems using web technologies without needing deep expertise in complex BLE packet processing or signal processing. Furthermore, the SDK supports the acquisition of raw acceleration and angular velocity data for real-time visualization and logging, offering extensibility for detailed motion analysis. To demonstrate the simplicity of the SDK, the following JavaScript snippet shows how to connect to the sensor and receive real-time gait events:

```
const ble = new Orphe(0);
async function connect() {
  ble.setup(); // Initialize BLE connection
  await ble.begin('STEP_ANALYSIS'); // Start gait analysis
}
ble.getStride = function(stride) {
  console.log(`Stride: ${stride.y} m`); // Step callback
};
```

## 4 Application Scenarios

We developed two applications that address two distinct temporal scales of gait intervention required in PD rehabilitation. ORPHE DRunner provides immediate, step-by-step reactive feedback aimed at suppressing acute episodes such as FoG, sustaining motor execution through instantaneous auditory cues. In contrast, ORPHE BloomBeat provides session-level generative feedback targeting long-term gait improvement, maintaining intrinsic motivation throughout the training session via cumulative musical rewards linked to gait quality. This complementary design—combining a reactive layer for immediate symptom management with a generative layer for sustained behavioral change—reflects the clinical reality that PwPD require both acute intervention and habitual training to maintain gait function.

### 4.1 ORPHE DRunner (step-triggered drum sound system)

#### 4.1.1 Concept

ORPHE DRunner is a portmanteau combining "Drum" and "Runner." The core idea is to convert the daily movement of walking or running into a drum performance by triggering drum sounds at each step. We adopted drum sounds because rhythmic, groove-inducing stimuli engage motor and reward networks of the brain in parallel [44], potentially fostering motor engagement and intrinsic motivation as walking is recast into music-making. By experiencing one's own physical movement directly generating music, the system transforms mere locomotion into a creative and enjoyable act.

#### 4.1.2 System Configuration and Features

This application consists of the wearable motion sensor ORPHE CORE 3.0 and an application on a web browser (Next.js / TypeScript). Gait parameters analyzed in real time inside the sensor (such as stride length, strike angle, and toe-off angle) are transmitted to the application via the SDK (ORPHE-CORE.js).

- **Mapping:** A one-to-one mapping of "one step = one sound" is adopted. At the moment the user makes a foot landing, drum sounds such as kick, snare, and hi-hat are played by a low-latency acoustic synthesis engine using Tone.js on the browser side.
- **Customizability:** Drum timbres can be selected from multiple kits (Jarrah Prism, Fat 808, etc.), allowing for the customization of auditory feedback to user preferences.
- **Accessibility:** Due to the web-based configuration, it can be used immediately with only a smartphone or tablet and smart shoes.

#### 4.1.3 Application for People with Parkinson's Disease

In this study, the concept of ORPHE DRunner was applied to the suppression of FoG and support for continuing gait, which are gait disturbances characteristic of PwPD. This system functions as a step-triggered drum sound system that assists their intrinsic

rhythm generation by detecting steps in real time and immediately presenting corresponding drum sounds.

In contrast to conventional RAS using a metronome, where PwPD need to match their movements to an external rhythm presented at a fixed tempo, ORPHE DRunner triggers sounds directly from the user's own movement, which we expected to support continued walking even when rhythm changes during turning. Furthermore, immediate auditory feedback of one's own movement is expected to enhance the sense of autonomy and control, promoting smoother movement execution.

Among the available drum kits, we used a kick (bass drum) as the step-triggered cue in this experiment, since bass-drum sounds at lower frequencies elicit stronger groove ratings and stronger urges to move [45].

### 4.2 ORPHE BloomBeat (Musical biofeedback)

#### 4.2.1 Concept

ORPHE BloomBeat is a music generation system that makes gait more enjoyable by directly reflecting movement in the evolution of music—adjusting playback speed to gait rhythm and adding tracks based on gait status. At its core is the "Bloom" process, in which sustained or improved movement culminates in greater musical density, supporting users' intrinsic motivation. This layered track-addition design is grounded in recent evidence that the pleasurable urge to move to music increases with the number of concurrent rhythmic layers, with richer instrumental combinations yielding stronger movement-inducing responses [46].

#### 4.2.2 System Configuration and Features

This application consists of three layers: the ORPHE CORE 3.0 sensor, a custom bridge application (Electron) incorporating the SDK (ORPHE-CORE.js), and a music generation environment (Ableton Live / Max for Live) (Figure 2).

- **Data relay (Bridge Application):** When a step is detected, the bridge app connected to the sensor via BLE receives gait parameters such as stride length in real time via the SDK. The data is converted into OSC messages and sent to Ableton Live.
- **Advanced music generation:** By integrating Ableton Live and Max for Live, feedback at professional acoustic quality is realized. Music generation is based on MIDI files (provided by Roland Corporation).
- **Dynamic change of songs:** Close coupling of exercise and music is realized through automatic tracking of BPM according to gait tempo and dynamic activation (On/Off) of tracks based on gait status.

#### 4.2.3 Application for People with Parkinson's Disease

We customized ORPHE BloomBeat as a PD gait-training biofeedback system that links stride-length improvement to the "musical bloom" state, targeting both functional improvement and motivation maintenance. The system operates through the following phases:

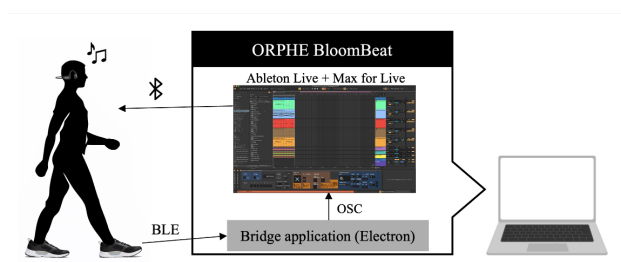
### 1. Calibration period (Initial 30 seconds):

The initial 30 seconds after starting serve as a baseline measurement period. During this time, no music is played (baseline). The median stride length and median cadence are calculated from the gait data during this period. The calculated parameters (music tempo and initial threshold for stride length) are reflected at the start of the next phase.

### 2. Interactive feedback period (30 seconds to 120 seconds):

After the baseline measurement, intervention begins with music playback at the calculated tempo. The stride length of the right foot is measured in real time as the object of evaluation, and feedback is provided through the following three methods:

- **positive/negative feedback:** At each step, if the measured stride length of the right foot exceeds the current threshold, a positive feedback sound is immediately presented, and if it is below, a negative feedback sound is presented. This allows one to intuitively correct the quality of walking for each step through hearing.
- **Adaptive song composition:** At the start of each musical bar, the system checks whether 3 of the most recent 5 steps exceeded the threshold. If so, the music advances through four cumulative stages—Stage 0: drum only; Stage 1: bass and electric piano; Stage 2: lead melody (synth or guitar); Stage 3: fine percussion—so that gait improvement is rewarded with musical richness, fostering a sense of achievement and immersion.
- **Dynamic difficulty adjustment:** As a setting to further enhance training effects, the threshold for stride length is gradually raised (by 4 cm) every 10 seconds. Users can enjoy the challenge of slightly pushing their own limits along with the development of the music.



**Figure 2: System configuration of ORPHE BloomBeat.** Gait data acquired from ORPHE CORE 3.0 is sent to a bridge application via the SDK (ORPHE-CORE.js). The bridge application converts the data into OSC messages and sends them to Max for Live inside Ableton Live. Ableton Live triggers MIDI data, controls effects, and dynamically activates tracks based on the received gait parameters (stride length, tempo, etc.), realizing real-time music generation and feedback.

## 5 Evaluation

In this study, to verify the effectiveness of the proposed platform, we conducted case studies using two different applications (ORPHE DRunner, ORPHE BloomBeat).

### 5.1 Experiment 1: ORPHE DRunner

**Objective:** To verify the immediate effect of interactive auditory feedback using ORPHE DRunner on gait function, particularly FoG, in PwPD.

#### 5.1.1 Methodology

A woman in her 50s, diagnosed with PD six months earlier, participated in this study. As preparation, the participant wore smart shoes (EASRUN SHIBUYA 3.0) with built-in ORPHE CORE 3.0 sensors, and a motion sensor (data logger for research & development, ORPHE Inc.) for gait analysis data collection was separately attached to the dorsal part of the foot using a dedicated mounting part. In addition, wireless bone conduction earphones (Shokz OpenRun Pro 2, Shokz Technology Inc.) connected to a laptop PC were worn.

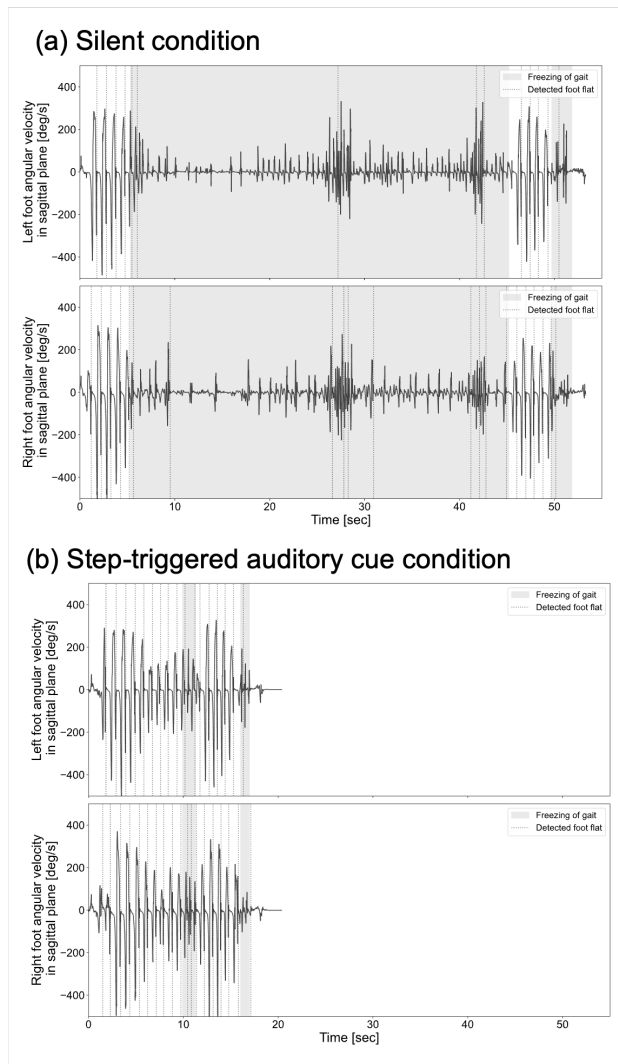
For the exercise task, a TUG540 task, which is an extension of the Timed Up and Go test with an additional turning movement, was adopted. This task consists of a series of movements from standing up from a chair, walking straight up to a cone 3m ahead, turning 540 degrees clockwise around the cone, walking 3m again, and sitting back in the chair. The 540-degree turn imposes a higher load than a typical 180-degree turn, intentionally creating a situation in which FoG characteristic of PD is likely to occur. Under this high-difficulty condition, the influence of step-triggered auditory cues on the facilitation of walking was verified. The participant was instructed to walk at "a comfortable speed at which they usually walk."

The experiment was conducted sequentially under the following two conditions. First, walking without sound stimulation (silent condition) was performed, and then a step-triggered auditory cue condition was performed using ORPHE DRunner. The time required to complete TUG540 and the duration of FoG were quantified by an expert (M.S.) based on video recordings.

#### 5.1.2 Results

The time required to complete TUG540 was 53.3 seconds in the silent condition, whereas it was 18.0 seconds in the step-triggered auditory cue condition. Step-triggered auditory cues thus tended to shorten the completion time of this complex walking task involving turning.

The total duration of FoG during walking was 42.0 seconds in the silent condition compared to 2.3 seconds in the step-triggered auditory cue condition, quantitatively demonstrating that step-triggered auditory cues suppressed FoG, particularly during turning movements (Figure 3). The video of the experiment can be accessed in Appendix 1.



**Figure 3: Time course of angular velocity in the sagittal plane of the foot during the TUG540 task.** In the silent condition (a), freezing of gait occurs during turning, but in the step-triggered auditory cue condition (b), smooth walking is maintained.

## 5.2 Experiment 2: ORPHE BloomBeat

**Objective:** To verify the immediate effect of generative music biofeedback according to the quality of walking (stride length) on PwPD's gait parameters.

### 5.2.1 Methodology

A woman in her 60s, diagnosed with PD 15 months earlier, participated in this study. The participant was prepared in the same way as in Experiment 1 (see Section 5.1.1).

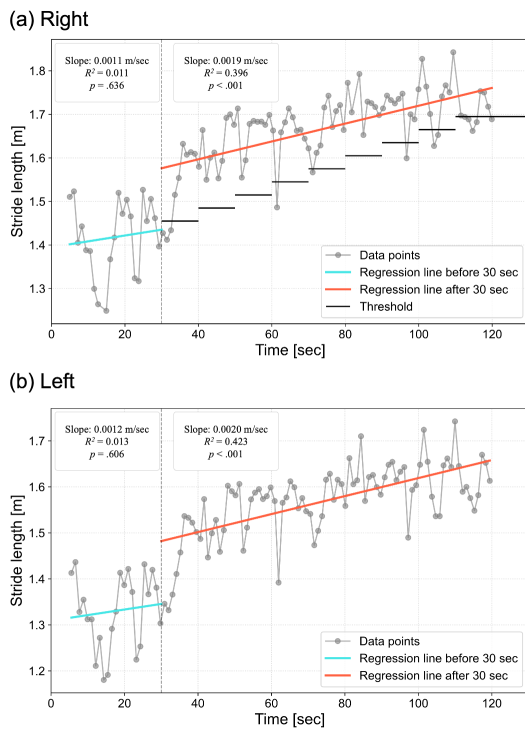
The task was a 2-minute continuous walk on a 30 m indoor loop. The participant was instructed to walk at a comfortable everyday pace for the first 30 seconds (no sound) and was told that music and feedback sounds would begin thereafter. Before starting, she was familiarized with the positive feedback sound (large stride), the negative feedback

sound (small stride), and the background music, and was instructed to consciously take larger steps when she heard the negative sound. The trial had two phases: a 30-second baseline (no sound) and a 90-second interactive phase (30–120 s) during which ORPHE BloomBeat played music that changed dynamically with the participant's gait. Based on data from the measurement motion sensor (200Hz), gait parameters for each step were calculated using gait analysis software (ORPHE ANALYTICS). The initial three steps immediately after the start and the last 7 steps before the end were excluded, and linear regression analysis was performed separately for the initial 30 seconds and thereafter. In addition, immediately after the end of the exercise task, a questionnaire regarding subjective evaluation was conducted using a paper-based Visual Analog Scale (VAS, 0–100). The participant marked a position corresponding to their state on a 100mm straight line and answered the following three items:

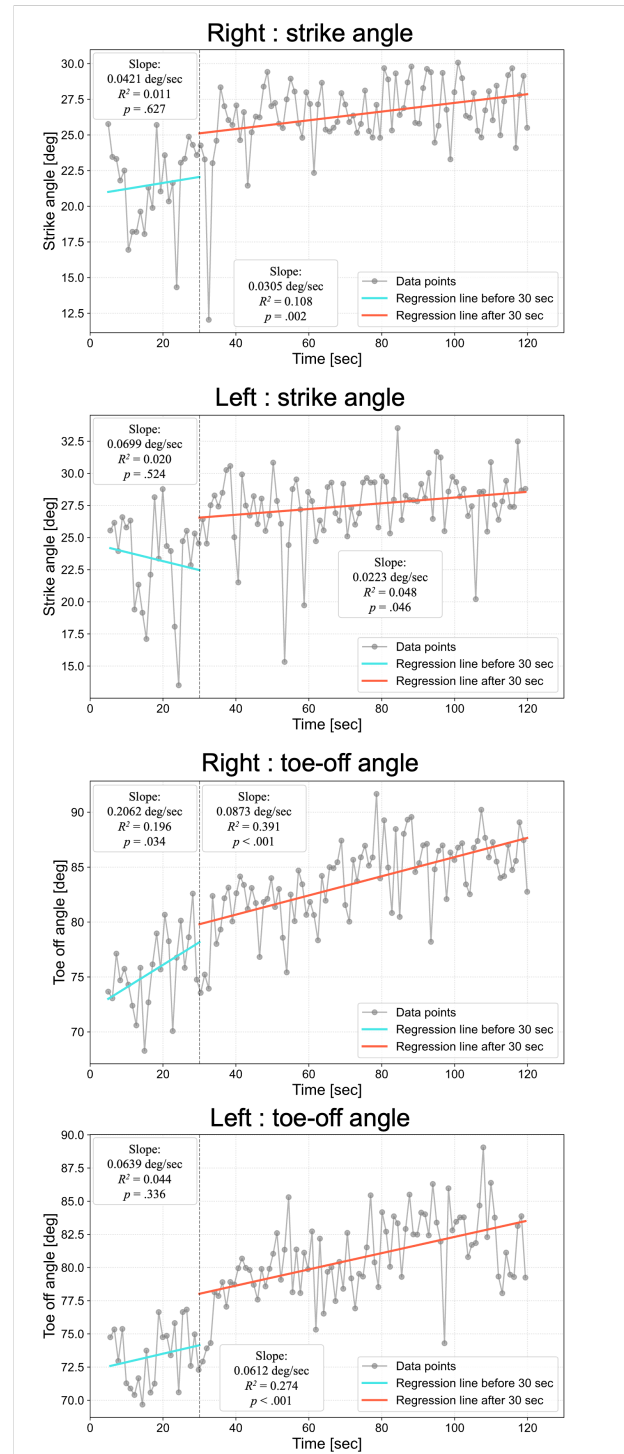
1. Enjoyment: "Was it enjoyable during walking?" (0: Not enjoyable at all – 100: Very enjoyable)
2. Anxiety: "Did you feel anxiety during walking?" (0: Did not feel anxiety during walking – 100: Felt anxiety during walking)
3. Confidence: "Could you walk with confidence during walking?" (0: Could not walk with confidence at all – 100: Could walk with high confidence)

### 5.2.2 Results

The median of stride length for the first 30 seconds was 85.9 cm, the median of cadence was 112 steps/min, and the music was played at 112 BPM. Music tracks were added stepwise, and eventually 7 tracks were played. After 30 seconds, when music playback began, a statistically significant positive trend in stride length was observed (Figure 4). Linear regression analysis confirmed a significant increase in stride length during the interactive phase (left foot: slope = 0.0020 m/sec,  $R^2 = 0.423$ ,  $p < .001$ , 95% CI [0.0015, 0.0025]; right foot: slope = 0.0019 m/sec,  $R^2 = 0.396$ ,  $p < .001$ , 95% CI [0.0014, 0.0024]). In contrast, no significant trend was observed in the baseline phase (left:  $R^2 = 0.013$ ,  $p = .606$ ; right:  $R^2 = 0.011$ ,  $p = .636$ ). Significant positive trends were also observed in angular parameters during the interactive phase (Figure 5), indicating motion-amplitude expansion: toe-off angles increased (left: 0.0612 deg/s,  $R^2 = 0.274$ ,  $p < .001$ ; right: 0.0873 deg/s,  $R^2 = 0.391$ ,  $p < .001$ ), reflecting larger push-off, and strike angles also rose modestly (left: 0.0223 deg/s,  $p = .046$ ; right: 0.0305 deg/s,  $p = .002$ ). No such trends appeared in the baseline phase. The experimental sound files can be accessed in Appendix 2. Subjective evaluation showed high enjoyment (VAS 91/100), low anxiety (9/100), and moderate confidence (48/100). The participant commented that the negative sound made her aware of her weakness at walking curves, that the music was enjoyable and helped her feel the rhythm, and that the experience resembled her habit of walking while singing outside.



**Figure 4: Changes in Stride Length during ORPHE BloomBeat intervention.** Gray dots indicate the stride length of each step, the cyan line indicates the regression line for the initial 30 seconds (baseline), and the orange line indicates the regression line after 30 seconds. The black horizontal lines in the right foot panel indicate the step-wise thresholds used for real-time positive/negative feedback, which were set to increase by 4 cm every 10 seconds based on the right foot's baseline stride length.



**Figure 5: Changes in strike angle and toe-off angle during ORPHE BloomBeat intervention.** Gray dots indicate the data of each step, the cyan line indicates the regression line for the initial 30 seconds (baseline), and the orange line indicates the regression line after 30 seconds (interactive). In the interactive phase, significant positive trends were observed in both toe-off and strike angles, indicating an expansion of the motion amplitude.

## 6 Discussion

### 6.1 Feasibility of Implementing Auditory and Musical Biofeedback using Smart Footwear

The smart footwear platform used in this study has a significant advantage in its ability to rapidly implement advanced musical biofeedback based on SDKs grounded in web standard technology and OSC. In addition to being lightweight and easy-to-handle hardware, gait analysis, which normally requires expertise, is automated by algorithms inside the device and provided as analyzed gait parameters, which greatly lowers the technical hurdles for development. Furthermore, the handling of sensor data is organized as methods by the SDK, which has extremely good compatibility with interactive programming utilizing generative AI in recent years. This allowed developers to focus on constructing mapping logic that tightly couples physical movement with musical expression, without dealing with the implementation of complex signal processing.

As shown by the examples of low-latency acoustic synthesis using Tone.js in ORPHE DRumner and the advanced integration with Ableton Live in ORPHE BloomBeat, the ability to flexibly scale implementation effort according to project complexity is a core value of this platform. The combination of a well-structured SDK and modern AI-assisted development workflows accelerates the construction of systems that bridge healthcare and musical expression.

### 6.2 Contribution to Improvement of Gait Function and Maintenance of Motivation in Parkinson's Disease

The results of Experiments 1 and 2 suggest that the proposed system contributes to the improvement of gait disturbances in PwPD and the reduction of psychological barriers to exercise. Step-triggered sound presentation by ORPHE DRumner strengthened the sense of agency, where the user's physical movement directly generates sound, and was shown to be effective in suppressing the occurrence of FoG, particularly during turning movements, and allowing for the smooth continuation of walking.

In addition, in ORPHE BloomBeat, the quality of walking (stride length) functioned as reward-based feedback directly linked to musical richness, and a tendency for stride length to gradually expand compared to the baseline was confirmed. What is noteworthy is that high enjoyment and low anxiety were reported in subjective evaluations. This indicates that music, by serving not merely as a guide for training but as a celebratory expression that affirms the extension of one's own physical abilities, can strongly sustain intrinsic motivation in rehabilitation. The simultaneous emergence of functional improvement and positive psychological change is a key strength of music-mediated healthcare interfaces. The moderate confidence score (48/100) likely reflects the participant's reported difficulty during curved walking, suggesting that the biofeedback meaningfully surfaced moments of gait instability rather than indicating a system failure.

Although these were limited to preliminary case reports, future larger-scale clinical research is needed to verify the maintenance and improvement of gait function through long-term intervention. An important strength of this platform is that such music-based feedback intervention systems can be rapidly updated, fine-tuned on site, and flexibly adapted to the diverse needs of clinical research.

### 6.3 Contribution to the NIME Community and Future Prospects

This study contributes to the NIME community by presenting a tight integration of musical expression with walking—and, by extension, with healthcare—as a platform that anyone can implement and experience. By realizing practical gait measurement and interactive auditory intervention on an open foundation built from consumer devices and web standard technology, it extends NIME knowledge, previously confined to specialized experimental environments, into continuous physical expression and care practices in daily life.

As a future prospect, we are considering the implementation of wearable device operation without a graphical user interface (GUI) toward the social implementation of gait support through gait monitoring and auditory feedback in daily life. GUI-less operation, where intervention starts just by putting on shoes and walking and minimizes cognitive load such as smartphone or PC screen operation, is an essential element for improving usability and adherence in the elderly and PwPD.

In addition, to reduce the burden of charging and data management, which are challenges in continuous data collection, development of a dock system equipped with non-contact power supply and automatic data extraction functions is also underway. A system that completes charging and data synchronization to the cloud simultaneously with the action of storing shoes after returning home is expected to serve as a foundation for supporting long-term behavioral change by integrating health management from a conscious task into a part of daily life.

Combining the physical extension afforded by smart footwear with music has the potential to reframe movement-based care from "training" into "creation" and to enrich healthcare as a multi-layered embodied experience. Health management and promotion are then achieved naturally, through musical experiences that accompany daily physical movements. This study is a concrete proposal from the NIME community toward the construction of such future healthcare systems.

## 7 Conclusion

In this study, by integrating foot-mounted wearable sensors (ORPHE CORE 3.0) and an SDK based on web standard technology (ORPHE-CORE.js), we proposed a smart footwear platform that bridges Parkinson's disease rehabilitation and musical expression. This platform realizes gait sonification, which previously tended to depend on specialized equipment and closed environments, using only commercially available smart shoes and a web browser, dramatically improving accessibility in clinical sites and daily life.

Through the two applications implemented, the effectiveness and diversity of expression of this platform were demonstrated. Step-triggered auditory feedback in ORPHE DRumner produced immediate improvements in FoG, a symptom difficult to address with pharmacological therapy alone. Musical biofeedback in ORPHE BloomBeat provided an experience in which improvements in gait quality led to greater musical richness, promoting an expansion of stride length along with high enjoyment. These results suggest the possibility of fostering intrinsic motivation in rehabilitation by redefining walking not merely as a means of transportation but as an "act of expression."

In the NIME community, shoes have long been explored as a powerful interface for body expression; this study extends that expressive power into healthcare, providing a concrete and scalable foundation for transforming functional recovery into a creative bodily experience. Through this open platform, we hope that researchers, clinicians, and artists will collaborate to make personalized musical intervention a familiar part of daily life.

## 8 Ethical Standards

### 8.1 Ethical Review and Informed Consent

This study was conducted with the approval of the Ethics Committee of Reiwa Health Sciences University (Approval No.: 24-016). Prior to the experiment, the purpose, content, risks, and data handling of the study were thoroughly explained to all participants both verbally and in a written explanation document, and written informed consent was obtained.

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### 8.3 Conflicts of Interest

Yuki Uno is an employee of ORPHE Inc., the developer of the smart footwear platform used in this study. Yuya Kikukawa is the CEO of ORPHE Inc. The other co-authors have no conflicts of interest to disclose relevant to this study.

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### Appendix

The video file of the Experiment 1 (ORPHE DRummer) and the sound file of Experiment 2 (ORPHE BloomBeat) are available on Zenodo at <https://doi.org/10.5281/zenodo.20069107>.