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Better Neutral: A Wearable Sound-Based Biofeedback System for Enhancing Pelvic Alignment in Pilates

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Abstract

INTRODUCTION: This paper introduces *Better Neutral*, a low-cost wearable IoT system designed to enhance Pilates practice through sound-based biofeedback. The system aims to address the challenge of maintaining proper pelvic alignment—particularly during supine exercises where visual monitoring is limited—by providing intuitive auditory cues instead of visual or continuous corrective feedback.

OBJECTIVES: The main objective of this research is to develop and evaluate an embodied interaction system that promotes somatic awareness and self-correction through subtle, non-intrusive auditory feedback. The goal is to support practitioners in recognizing and adjusting pelvic alignment independently during Pilates sessions.

METHODS: The device employs a linear potentiometer to detect pelvic tilt and converts pressure variations into minimalist sound patterns. A user-specific calibration framework with adaptive thresholds ensures stable, individualized responses using commodity sensors. Grounded in soma design principles and informed by techniques derived from social network analysis, the system's feedback design emphasizes interpretive engagement rather than prescriptive correction.

RESULTS: A preliminary study with four participants across eight Pilates sessions generated 19,200 seconds of sensor data and qualitative reflections. Findings indicate improved pelvic control, heightened somatic awareness, and perceived support for autonomous practice. Participants recognized the auditory cues as both informative and non-distracting.

CONCLUSION: This paper demonstrates how evocative sound feedback can foster embodied self-correction and engagement without overwhelming the user. This approach shows promise not only for Pilates practice but also for broader applications in posture training, rehabilitation, and preventive care.

Keywords: Wearable IoT, Auditory biofeedback, Pilates, Pelvic alignment, Posture monitoring, Neutral Position, Somatic Interactions.

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1. Introduction

Pilates is a widely adopted exercise method that emphasizes core strength, postural alignment, and synchronized breath control, making it particularly effective for rehabilitation and injury prevention [20]. A central principle in Pilates is achieving and maintaining a neutral pelvic position, which promotes biomechanical efficiency and reduces the risk of strain during movement. However, in unsupervised or solo practice, maintaining correct pelvic alignment becomes challenging due to the absence of immediate feedback. To address this gap, *Better Neutral* was developed as a novel wearable biofeedback system that detects pelvic contact pressure and provides

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real-time auditory cues to guide users toward optimal alignment. Unlike many existing systems that rely on visual displays or haptic signals, *Better Neutral* employs tonal buzzer feedback as a low-cost, non-visual interface. This approach is particularly suitable for exercises performed in a supine position, where visual confirmation is impractical.

Pelvic floor disorders (PFDs), such as urinary incontinence and pelvic pain, are prevalent among women and have been linked to muscular weakness and postural imbalance [16], [19], [10]. Addressing these dysfunctions requires enhanced awareness and control of the pelvic region. Educational and therapeutic frameworks in physiotherapy emphasize understanding pelvic anatomy and incorporating targeted exercises, such as those promoted through Pilates-based rehabilitation programs [8], [24].

Better Neutral contributes to this broader field of pelvic health and human-centered Internet of Things (IoT) design by integrating edge-sensing with embodied interaction (see Fig. 1). Through its minimal hardware footprint and intuitive tonal feedback, the system provides a portable and scalable solution for posture training, movement learning, and remote rehabilitation in Pilates-based pelvic exercises.

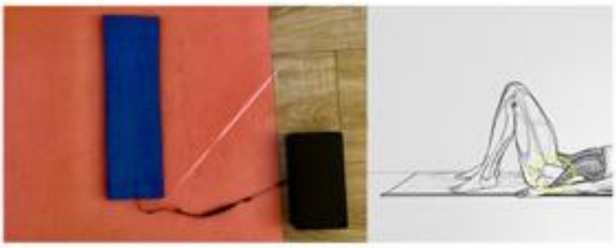

Figure 1. Prototype of the Device(left), When user place it from the lowest part of pelvic(coccyx).

2. Related Literature Review and Necessity of a Pelvic Movement Check System

2.1. Literature Review

This Core-strengthening exercises have been shown to improve pain and functional capacity in individuals with chronic low back pain, particularly when combined with lumbar flexibility and gluteus maximus training [13]. Pelvic stability is therefore critical in rehabilitation. Pilates interventions similarly promote musculoskeletal health and psychological well-being; for instance, a 12-week program improved pain, hip strength, back flexibility, sleep quality, and stress in participants with dysmenorrhea [20].

Existing wearable posture-monitoring systems often rely on visual or haptic feedback. Zhang et al. [27] developed an IMU-based device that provided vibrotactile alerts for misalignment, while Dinh-Le et al. [9] observed that wearable systems typically require smartphone or dashboard interfaces, which can disrupt movement. SitPose [12] achieved high accuracy in sitting-posture detection using ensemble learning and depth sensors, but portability remains limited due to reliance on external hardware and controlled environments.

From a cognitive-science perspective, human information-processing capacity is fundamentally limited. Working-memory research indicates that only about three to four items of information can be held simultaneously [6], [17], and applied sport psychology suggests that athletes retain only one or two instructions effectively during practice [4], [3]. When feedback becomes too detailed or frequent, learners experience cognitive overload, reducing both performance and retention [22]. This indicates that posture-monitoring systems should avoid overwhelming users with complex visual dashboards or multi-parameter feedback during active movement.

Moreover, visual feedback systems risk distracting practitioners. Studies in sport contexts show that moving or complex visuals can pull attention away from task goals; for example, moving advertisements behind a soccer goal systematically disrupted players' gaze behavior and reduced penalty-kick accuracy [25]. Similarly, high-gain visual feedback during motor tasks has been shown to increase gaze shifts and degrade steadiness, particularly in older adults [2]. These findings suggest that visual displays may compete with proprioceptive focus, drawing attentional resources away from body awareness during practice.

In contrast, *Better Neutral* leverages a pressure-sensing array to provide real-time auditory feedback during Pilates practice. Unlike prior visual or haptic systems, it enables mobile, minimally intrusive monitoring through tonal mapping ("do–re–mi") corresponding to light, neutral, and heavy pressures. This design is especially suitable for supine exercises, where visual cues are inaccessible. From a somatic-design perspective, *Better Neutral* emphasizes embodied awareness, enabling users to perceive and adjust subtle postural shifts through auditory feedback rather than visual cues. By foregrounding first-person bodily experience, the system encourages practitioners to develop a deeper, self-guided understanding of pelvic alignment [11], [21]. This soma-based interaction supports posture training, movement learning, and rehabilitation, highlighting how minimal, non-distracting sensory feedback can enhance self-correction and bodily engagement.

2.2. Pelvic Movement: Importance and Common Errors

Although pelvic alignment is critical, poor alignment and insufficient core activation during exercise remain major contributing factors to ineffective practice and potential injury. Traditional observation methods, such as mirrors or instructor guidance, are often limited in supine positions, leaving practitioners unable to verify or self-correct neutral alignment.

Better Neutral addresses this gap by detecting pelvic pressure distribution via a linear FSR sensor and translating it into auditory cues. The space between the pelvis and the floor (yellow area in left image, see Fig. 2) indicates variable pressure zones depending on position, while the red point in the image (right) marks the coccyx as the reference location. To enable practitioners to verify and internalize neutral alignment corrections without reliance on visual monitoring, Better Neutral introduces the following features:

- Sound-based feedback, in place of visual or haptic cues.
- Targeted support for pelvic alignment, rather than general spinal posture.
- Demonstrated effectiveness in supine positions, where conventional observation methods are constrained.

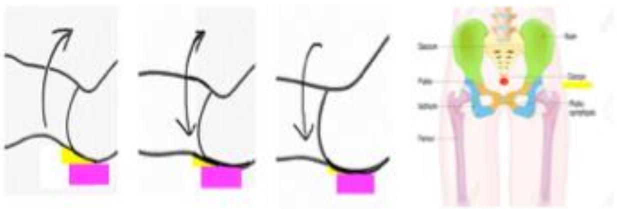

Figure 2. The device detects pelvic movement during breathing, corresponding to pelvic elevation, neutral alignment, and pelvic lowering (left). Device placement relative to the coccyx is indicated by the red mark (right).

From a somatic perspective, *Better Neutral* emphasizes embodied awareness, allowing users to attune to subtle postural shifts through auditory feedback rather than external observation [11], [21]. The system's key advantages include portability, minimal hardware requirements, and an intuitive mapping between pressure changes and tonal cues. Therefore, a wearable pelvic movement checker that provides intuitive, real-time feedback is not only justified but urgently needed in the intersection of Pilates, pelvic health, and IoT-driven rehabilitation.

3. System System Design and Methodology

3.1. User experience with Sensor Mapping Logic

The user begins by lying on a mat to establish a stable position for device placement. Once positioned, the device is activated and records pelvic movements during Pilates exercises. Data are processed in real time, and auditory feedback is generated according to the measured pressure. The session concludes after reviewing the feedback, completing a structured exercise cycle (see Fig. 3)

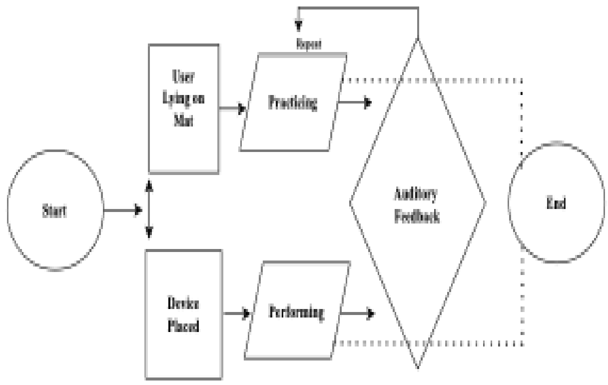

Figure 3. User Experience Diagram.

3.2. Sensor Mapping Logic and Sound Output Log

Pelvic Posture and pressure into Sensor

The system classifies pelvic pressure into three distinct zones: neutral, posterior tilt, and anterior tilt. When pressure is evenly distributed across the sit bones and pelvis, the system identifies a *neutral pelvis*. Excessive pressure concentrated on the pelvis with reduced load on the sit bones indicates a *posterior pelvic tilt,* while reduced pelvic pressure combined with increased sit bone load corresponds to an *anterior pelvic tilt.*

Sensor Mapping Logic

Each tone is played for 200 milliseconds. Within the neutral range, auditory feedback is presented as a simple ascending triad (Do–Mi–Sol) at three-second intervals, reinforcing steady alignment awareness. The system classifies pelvic pressure into three distinct zones, with each assigned a unique auditory cue.

Table 1. Sensor range and Sound out upon Posture

Zone	Data Range	Postural State	Sound

Neutral	300–700	Neutral	C–E–G sequence (130–196 Hz), do–mi-sol
Heavy	>700	Posterior Tilt / High Contact	F (65 Hz), low warning tone
Light	0–299	Inhalation / Minimal Contact	A (440 Hz), short tone

3.3. Arduino Circuit and Code Implementation

Circuit Connections

- Force Pressure Sensor:
  VCC: Connect to Arduino 5V.
  GND: Connect to Arduino GND.
  Analog Output Pin: Connect to Arduino A0.
- Passive Buzzer:
  Positive Pin: Connect to Arduino Digital Pin 9
  Negative Pin: Connect to Arduino GND.

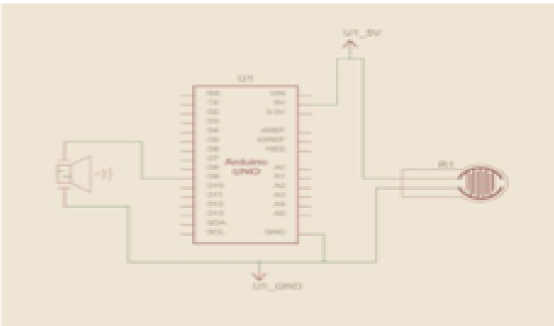

Figure 4. Arduino circuit

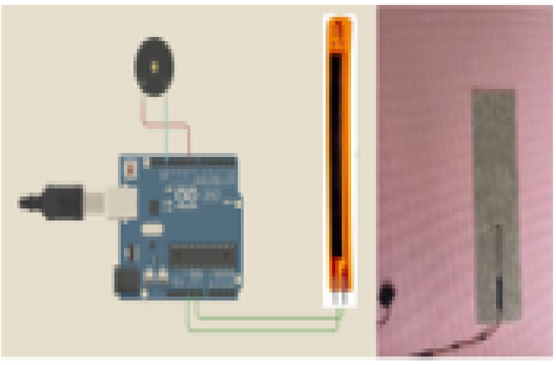

Figure 5. Essential Hardware Configurations: Diagram(left), Part of Prototype(right).

Figure 6. A Prototype device, measured 120 mm x by 55 mm, designed in the form of a flat mat, encased in a polypropylene wrap.

3.4. Code Implementation

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Table 2. Code Implementation

```
const int sensorPin = A0;
const int buzzerPin = 9;

void setup() {
Serial.begin(9600);
pinMode (buzzerPin, OUTPUT);}

void loop() {
int sensorValue = analogRead(sensorPin);
Serial.println(sensorValue);
if (sensorValue < 300) {
tone(buzzerPin, 440);  // Light
delay(200);
noTone(buzzerPin);
} else if (sensorValue >= 300 && sensorValue <= 700) {
int tones[] = {130, 164, 196};  // Neutral tones
for (int i = 0; i < 3; i++) {
tone(buzzerPin, tones[i]);
delay(200);

noTone(buzzerPin);
delay(3000);}
} else {
tone(buzzerPin, 65);  // Heavy

delay(200);
noTone(buzzerPin);}
delay(6000);
}
```

4. Evaluation, Data Analysis and User Surbey

4.1. Experimental Design and Protocol

A preliminary evaluation was conducted in March 2025 at a Pilates studio in Tokyo with four female participants in their 30s, each with Pilates training with minimum of 3 years. Inclusion criteria required prior familiarity with pelvic tilt exercises and the absence of musculoskeletal conditions that could impair safe participation. All participants provided informed consent prior to the study. Each participant completed eight guided sessions over two weeks, performing pelvic tilt exercises in a supine position while FSR data were recorded. Sessions lasted 10 minutes, repeated across eight trials per participant, yielding 2,400 readings each (300 per session, sampled every 2 seconds). Across all four participants, the dataset comprised 19,200 seconds of FSR recordings, providing a consistent basis for pressure distribution analysis. In addition to quantitative sensor data, qualitative feedback was collected through semi-structured post-study interviews to assess perceived usability and subjective impact on pelvic control.

Table 3. Summary of participants, session structure, and recorded data.

Metric	Value
Number of participants (pairs)	2 pairs (4 individuals)
Session duration per pair	20 minutes
Session duration per individual	10 minutes
Session duration per individual	8
Total time per individual	4,800 seconds (10 min × 8)
Total time per pair	9,600 seconds
Readings per session	300 readings
Total readings per participant	2,400 readings per participant
Total recorded duration	19,200 seconds

4.2. Data Processing

Data Collections and Calibration Procedure

All sensor data were collected across the full set of sessions prior to calibration and analysis. SQL was used for data storage and organization, while the calibration computations were performed in Python. These calibration pairs (ADC readings vs. force in Newtons) were stored in a structured SQL table, enabling organized storage and efficient querying. The collected data were exported to Python, where the slope and intercept were estimated.

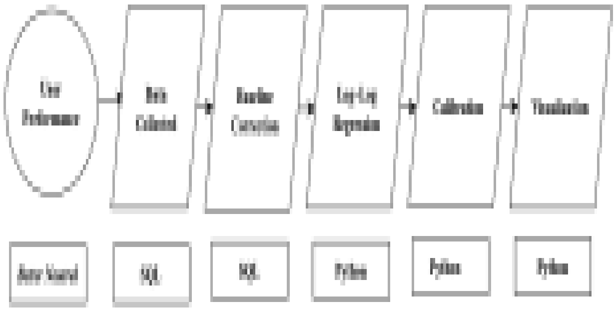


Figure 6. Data Processing Flow.

Calibration was performed individually for each participant, using their corresponding calibration pairs (ADC reading vs. applied force). As expected for force-sensitive resistors, piezoelectric films, or conductive fabrics, the raw sensor output was **nonlinear** with respect to applied force (see Fig. 7).

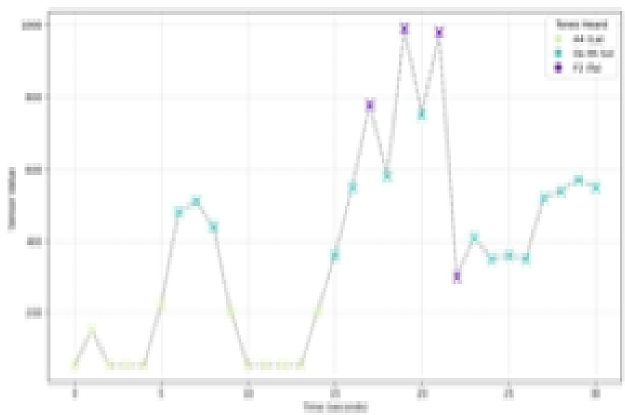


Figure 7. Random Readings Records at one Evaluation.

To account for this nonlinearity, calibration was performed using a log–log regression model to determine the participant-specific parameters α and *K*. Once calibrated, all subsequent analyses and visualizations present **Force (N) vs. Time (s)**. Without calibration, the raw values cannot be directly interpreted in Newtons. Thus, even for the simplest device structure, each participant's data were adjusted using their individualized calibration parameters, and stored for longitudinal tracking of changes throughout Pilates practice.

The calibration pipeline

The **calibration** consisted of the following steps:

Zero-force offset reading

Before any load was applied, an initial baseline reading was recorded:

$$R_0 \qquad (1)$$

Raw ADC readings
During sessions the sensor produced raw ADC values:

$$R_{raw} \qquad (2)$$

Baseline Correction
Raw outputs were baseline-corrected by subtracting the zero-force offset:

$$A_{out} = R_{raw} - R_0 \qquad (3)$$

Inverse exponential response
The relation between corrected ADC output and applied force was modeled as:

$$A_{out} \propto \frac{1}{F^{\alpha}} \qquad (4)$$

Log–log linearization
Applying logarithms converts the relationship to a linear form suitable for regression:

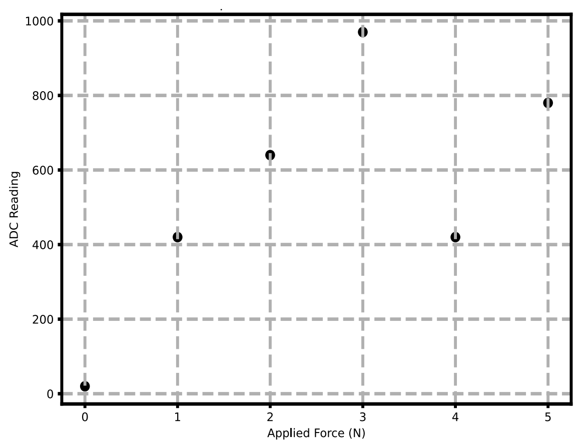
$$log(A_{out}) = -\alpha \cdot log(F) + log(K) \qquad (5)$$

$Where \ \alpha = slope, F = force \ in \ Newtons,$ K = Constant

Final calibration formula
Given a new A_{out} and knowing α and K, it can compute the correspon ding force F :

$$F = \left(\frac{K}{A_{out}}\right)^{\frac{1}{\alpha}} \qquad (6)$$

The above panel of Fig.8 shows the raw nonlinear relationship between applied force and ADC values, while the below panel displays the same data after log–log transformation, revealing a strong linear fit that validates the model(see Fig. 8).



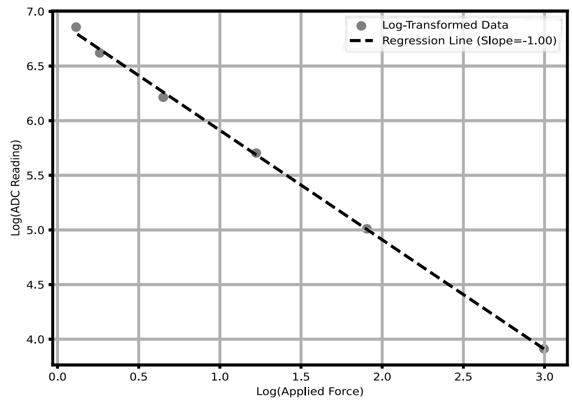


Figure 8. Random sample of FSR Calibration Data: The raw, non-linear relationship between applied force and ADC reading(above). The same data on a log-log scale, revealing a linear relationship with $-\alpha$ value on slope(below).

Data Analysis

Calibrated Data were subsequently collected and processed using a standardized SQL pipeline, with further analysis conducted in Google Colab through Python-based coding routines. These force values were then classified into three posture zones—Light, Neutral, and Heavy—corresponding to the sensor ranges defined earlier (0–299, 300–700, >700). This mapping ensured that all data were analyzed in a consistent, participant normalized framework (see Fig. 9).

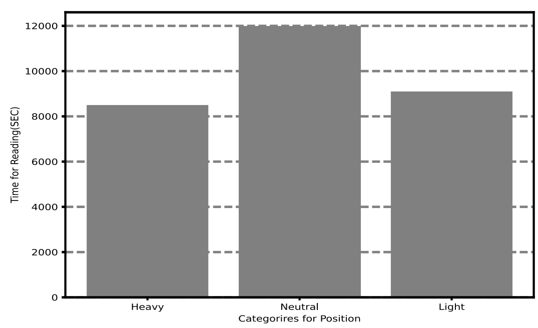


Figure 9. Three Groups of the Data.

Quantitative analysis

Quantitative analysis focused on the stability of sensor outputs across repeated sessions and the distribution of posture classifications. FSR values were mapped to three zones: Neutral, Light, and Heavy. Across participants, the distributions were Neutral (47.5%), Light (40.7%), and Heavy (11.8%). These values provided a quantitative basis for evaluating the consistency of posture maintenance and corrective adjustment.

Quantitative analysis

Quantitative *analysis* involved thematic coding of participant interviews. Three participants reported increased awareness of pelvic control and expressed interest in further use of the system, while one participant remained uncertain about its effect. These insights were triangulated with sensor data to assess both objective and subjective indicators of usability(See Table. 4).

4.3. User Survey with Ethical Consideration

User Survey

The Feedback was collected to evaluate perceived effectiveness and user experience. Three participants reported improved awareness and control of pelvic alignment, while one noted no significant change. Two participants found the auditory feedback corresponded well to movement and enhanced body awareness. Suggestions for refinement included using more harmonious tones and limiting repetitive beeps to a single cue per movement phase to reduce distraction. Overall, participants recognized the potential value of the *Better Neutral* for Pilates practice but emphasized the need for customizable auditory feedback and device design to better suit individual preferences and practice settings.

Table 4. Summary of Post-Intervention User Feedback.

Feedback Category	Participant Responses (n=4)	Notes
Perceived improvement	3 participants reported Improvement 1 participant reported no significant change	Subjective self-assessment
Effectiveness of auditory feedback	2 participants found sounds well-aligned with movement	Helped increase body awareness
Suggestions for auditory system	1 participant requested more harmonious tones 1 participant suggested fewer beeps	One preferred single-tone cue per movement phase
Perceived value of device	All 4 participants acknowledged the device's usefulness	Recognized potential for Pilates practices
Recommendations for improvement	All 4 participants emphasized the need for customizable sound and adaptable size	Each user-specific needs and varied environments

5. Discussion: Usability, Interactional Qualities, and Possibilities

5.1. Usability and Feedback Effectiveness

Usability

The evaluation demonstrated that *Better Neutral* effectively communicated postural states through auditory tones, enabling clear differentiation between light pressure, neutral alignment, and heavy contact. The ascending triad (C–E–G) for the neutral pelvic position was particularly intuitive, reinforcing proprioceptive awareness and supporting self-correction during Pilates exercises where visual feedback is limited. Analysis of 59 sensor readings showed that nearly half (47.5%) corresponded to the neutral pressure zone, suggesting that auditory biofeedback encouraged sustained engagement with the target posture.

Interactional dialogue between body and device

Beyond usability, the findings highlight how minimalist auditory cues can function as an interactional dialogue between body and device. By translating micro-movements into familiar yet open sound patterns, the system achieved an evocative balance: tones were recognizable enough to anchor alignment, yet open to personal interpretation, allowing users to integrate feedback into their own bodily practice. In this sense, *Better Neutral* aligns with soma design principles, deepening users' first-person awareness of pelvic movement and connecting sensation, breath, and posture into an ongoing aesthetic experience.

Limitations

Several limitations must be acknowledged. With only one sensor positioned at the sacral region, the system lacked lateral sensitivity and was unable to capture left–right asymmetries, which are critical for precise alignment. Moreover, the evaluation was conducted as a small-scale pilot with only four participants. Not only does this sample size constrain the generalizability of findings and preclude statistical validation, but the participants also had relatively similar body weights and figures. This homogeneity further limits the breadth of inference, as the system's responsiveness to different body types and load distributions could not be evaluated.
For ethical reasons, specific anthropometric details of participants (e.g., weight, height, or body shape) are not reported in this paper or in presentation materials. Only

anonymized raw sensor data have been stored and analyzed in accordance with approved research protocols.
While the observed trends provide encouraging feasibility evidence, a larger-scale study with greater participant diversity and more rigorous analysis will be required to confirm these effects. Such an extension will necessitate renewed IRB approval and additional resources for participant recruitment.
Future iterations of the system may also integrate adaptive machine learning methods such as Random Forest or Gradient Boosting to capture subtle variations in force-sensor signals, alongside hybrid sensing that combines wearable inputs with vision-based skeletal tracking. These enhancements would extend applicability from controlled Pilates sessions to broader contexts of movement training and sedentary posture monitoring.

5.2. System Limitations Future Development

Future iterations of *Better Neutral* aim to enhance portability, connectivity, and sensing accuracy. To this end, a portable ESP32-based prototype was developed (see Fig. 11). The ESP32 version integrates sensing, processing, feedback, and wireless connectivity in a compact, wearable form:

ESP32 version circuit:

- ESP32 Dev Board Widora AIR V6.0.
- Spectra Symbol 95mm linear force sensor
- Active Buzzer Module 5V: Connected to GPIO25
- 3.7 V Lithium Polymer battery 175 mAh
- Small Breadboard – 80×60 mm

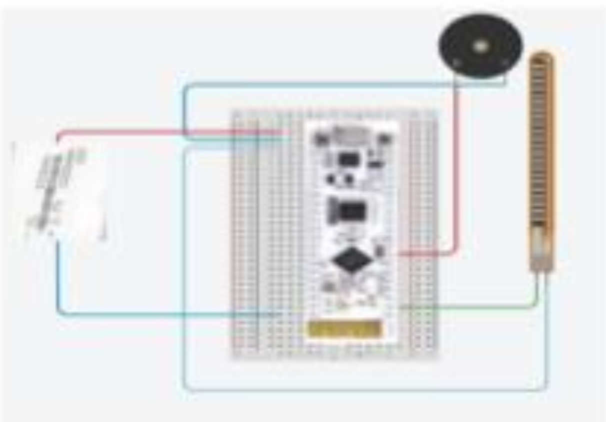


Figure 11. The Essential Hardware: ESP32 Widora Circuit.

This prototype emphasizes portability and wireless connectivity, enabling real-time data streaming and future integration with mobile or cloud applications. Importantly, the ESP32 version has not been formally evaluated; the Arduino-based system remains the primary platform for the pilot study. Planned enhancements also include multi-sensor configurations and mobile app integration to detect lateral asymmetries, track session history, and support adaptive auditory feedback.

6. Conclusion

Better Neutral, a lightweight and low-cost wearable IoT system that delivers real-time auditory feedback to support pelvic alignment in Pilates practice. By mapping pressure data to tonal cues, the device enhances somatic awareness and enables self-correction without reliance on visual input, addressing a key limitation in supine exercises where conventional observation methods are ineffective. Evaluation results showed that users could reliably interpret tonal patterns, with the triadic “neutral” chord particularly effective in reinforcing correct pelvic positioning.
The integration of quantitative sensor data with qualitative feedback underscores the preliminary effectiveness of the system while highlighting opportunities for refinement. As a pilot feasibility study, the work provides initial validation of the system’s design and calibration approach. The small sample size represents a limitation, but it also frames this study as a necessary foundation for future large-scale evaluations once renewed IRB approval and funding are secured.
Participants emphasized the need for customizable auditory design and adaptable form factors, pointing toward the value of tone minimalism and personalization in future iterations. Beyond its technical contribution, *Better Neutral* demonstrates how auditory biofeedback can be framed as an interactional dialogue, achieving an evocative balance between familiarity and openness. In doing so, it aligns with soma design principles, positioning feedback not merely as corrective output but as a means of deepening first-person bodily awareness.
The system’s simplicity and immediacy make it especially relevant for solo training, remote practice, and rehabilitation contexts. As a human-in-the-loop IoT application, *Better Neutral* illustrates how embedded sensing and subtle, embodied feedback can foster both preventive care and meaningful user engagement. Its low-cost, modular architecture and potential for wireless connectivity position it as a promising platform for future research in personalized health technologies, embodied interaction, and IoT-enhanced movement learning.

Acknowledgements.

Ethical Considerations
The study adhered to the principles of the *Declaration of Helsinki* and followed relevant national ethical guidelines for human participant research. The researcher completed accredited ethics training through the Institutional Review Board(IRB) platform at

irb.or.kr, ensuring compliance with IRB standards. All participants provided informed consent prior to participation and were informed of the study purpose, data collection procedures, and their right to withdraw at any stage without penalty. Sensor data were anonymized prior to analysis to protect participant privacy.

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