

# Manubrio: Investigating Musical Instrument Embodiment Through a Feedback-Based New Interface for Musical Expression

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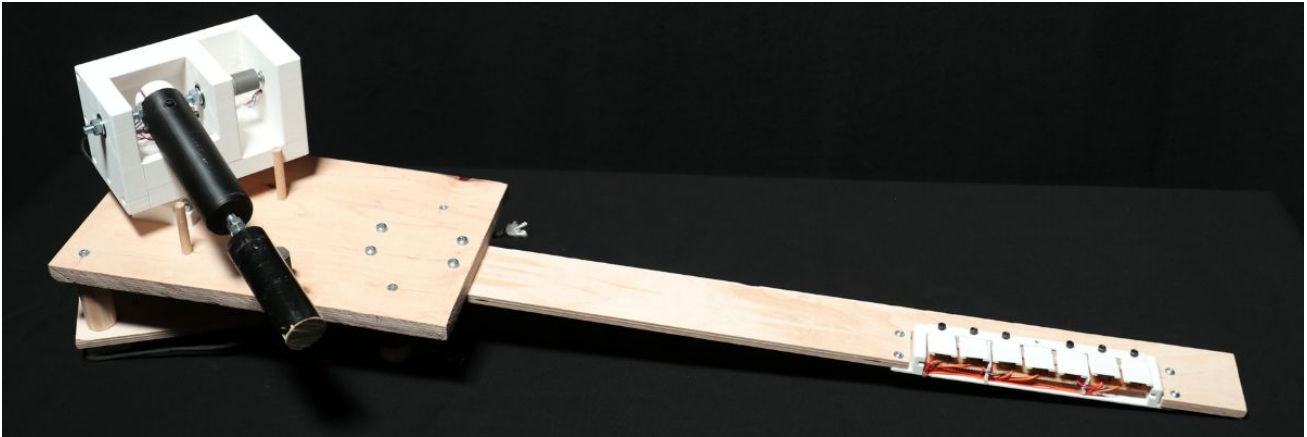


Figure 1: *Manubrio*

## Abstract

This paper presents *Manubrio*, a digital musical instrument designed to investigate embodied musical interaction. The instrument explores how continuous bodily engagement and feedback-based sound generation can support the incorporation of a digital interface into the performer's bodily awareness. *Manubrio* approaches feedback as a performative resource that requires sustained physical regulation and attentive listening. The instrument was developed through an integrated hardware–software design process that prioritizes sensorimotor feedback cues and minimizes indirection between gesture and sound. A qualitative user study with four musicians examines how embodied interaction arises, focusing on incorporation, immersion, and the emergence of transparency between body, instrument, and sound. The findings suggest that *Manubrio* can support music practices for embodied interaction to emerge, while also revealing the sensitivity and fragility of such interactions. This work contributes a novel musical interface and synthesis approach and explores how a new musical instrument can serve as a research artefact for investigating embodiment in musical interaction.

## Keywords

NIME, Digital Musical Interface, Embodied Interaction, Karplus-Strong Synthesis, Frequency Modulation, Gesture–Sound Coupling, Enactive Interaction

## 1 Introduction

Embodiment has become a central concept in contemporary research on musical interaction, emphasizing the role of the body as an active mediator between intention, action, and sound. From perspectives of embodied cognition, musical meaning and expressive control emerge through continuous sensorimotor coupling, where perception and action are tightly interwoven rather than sequential or symbolic [20, 21]. Within this framework, musical instruments are not neutral transmission devices, but potential extensions of the performer's body, capable of being incorporated into bodily schemas through practice and engagement [24, 25].

The New Interfaces for Musical Expression (NIME) community has played a key role in advancing this view by exploring how physical interfaces, mapping strategies, and sound synthesis techniques shape embodied musical interaction. A diverse array of digital musical instruments has been developed that emphasize gesture, movement, and physicality as primary expressive resources. Nevertheless, many of these systems continue to depend on discrete control mechanisms, visually guided interactions, or parameter mappings that partially decouple bodily effort from sonic outcomes. Moreover, they often produce an imbalanced relationship between musician and instrument, either rendering the performer's body overly dominant while marginalizing the instrument, or conversely, subordinating the performer's role to the instrument. Consequently, the exploration of sound negotiation through continuous bodily engagement, sensorimotor awareness, and sustained physical action, while maintaining a balanced interaction between instrument and musician, remains an open area of investigation.



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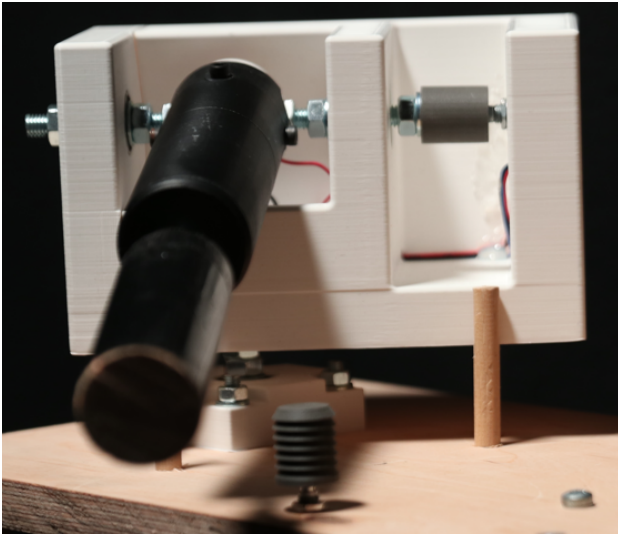


Figure 2: 3DOF handlebar.

This paper approaches this space from a complementary perspective, seeking to support a more balanced and dynamic interplay in which musical meaning emerges through bodily negotiation rather than through abstracted control mappings alone.

We present *Manubrio*<sup>1</sup> (figure 1), a digital musical instrument prototype conceived as a vehicle for investigating how embodied interaction emerges in musical performance. *Manubrio* combines a portable, three-degree-of-freedom (3DOF) handlebar interface (figure 2) with a modified Karplus–Strong synthesis engine that allows controlled positive feedback. Arm movements directly shape feedback gain, spectral damping, and delay-based frequency modulation in a feedback-dependent synthesis system. The resulting sound depends on prior system states and gestures are determinative of change rather than of absolute sonic states. The feedback mechanism is intentionally unstable, such that small gestural variations can produce large sonic effects. This instability demands performer precision and sustained engagement by design. Hardware and software were designed together to minimise indirection and encourage the development of embodied skill through sustained interaction, prioritising sensorimotor feedback cues and tight gesture–sound coupling over visual mediation.

The contribution of this work is threefold. First, it introduces a novel interface and synthesis approach that reframes feedback and instability as expressive dimensions. Second, it situates the instrument within embodied music cognition by explicitly designing for incorporation, transparency, and bodily engagement. Third, it explores how a new musical instrument can function as a research artifact, using a qualitative user study to examine how embodied interaction emerges.

## 2 Related Works

Research on embodied music interaction emphasizes the body as a central mediator of musical meaning and control, rather than a peripheral input mechanism. Foundational work in embodied music cognition by Leman [20, 21] and subsequent developments by Nijs, Lesaffre, and Leman [24, 25] frame musical instruments as potential extensions of the performer’s body, incorporated

<sup>1</sup>A short demonstration anonymized video is available at <https://archive.org/details/s/maubrio-showcase-anon>

through practice and characterized by varying degrees of transparency and presence.

Within the NIME community, embodiment has been approached both as a design objective and as an evaluative construct. Guidi and McPherson propose quantitative methods for assessing aspects of embodiment in digital musical instruments [11], while other approaches emphasize experiential, soma-based, and phenomenological perspectives on interaction [13, 15]. Gesture-sound coupling and mapping strategies have been widely studied, highlighting how clarity, ambiguity, and consistency shape expressive potential and learning [9, 12, 14].

A parallel line of work investigates the relationship between physical gesture and sound generation through spatial, energetic, or model-based mappings, as explored by Babio [1], Giomi and Leonard [8], and Tomás et al. [33]. These systems demonstrate how movement qualities can be rendered perceptually legible through sound.

From a synthesis perspective, the Karplus–Strong algorithm and its extensions form a well-established foundation for plucked-string modeling [16, 17], while frequency modulation and delay-based techniques provide powerful tools for spectral shaping and temporal modulation [5, 18]. In most implementations, feedback is constrained to ensure stability and predictable decay.

A dedicated strand of NIME research treats acoustic feedback not as an undesirable artifact but as a primary sonic and expressive resource. Eldridge and Kiefer’s self-resonating feedback cello demonstrates how feedback thresholds and gestural regulation can be integrated into live improvisation [7]. Magnusson, Kiefer, and Ulfarsson offer a critical reflection on feedback-based practice that addresses control, instability, and performer agency [23]. *Manubrio* situates itself at the intersection of these strands by treating feedback and instability as controllable, embodied resources. By combining an enactive interface that demands physical engagement with a feedback-based synthesis engine, the instrument offers one perspective within this growing NIME tradition of continuous, feedback-based bodily engagement, specifically foregrounding the negotiation of controlled instability through whole-arm sensorimotor sensing alongside real-time auditory feedback.

## 3 Instrument and Implementation

*Manubrio* is a digital instrument built around a handlebar with two rotational and one linear (piston) axes of movement (figure 2). This allows controlling different parameters of a Karplus–Strong software synthesizer, enabling positive feedback for sound shaping. The physical interface and the synthesis engine were developed together, focusing on coupling gestural interaction with the produced sound. This creates a tool for sonic exploration that bridges the performer’s musical ideas with a sonic reality.

The design aims to actively involve the musician’s body while minimising unnecessary mechanical constraints, leaving the upper body free to move expressively beyond the minimum gestures required for sound production. The handlebar does, however, constrain hand placement to three defined axes of movement, and these affordances directly shape the gestural vocabulary of the instrument. The oscillating feedback is shaped by precise arm movements, establishing a responsive interface that connects the musician with the produced sound.

### 3.1 Hardware

*Manubrio* comprises two primary hardware elements: a custom handlebar interface and a keyboard, together with an embedded microcontroller responsible for sensor acquisition and sound synthesis. The handlebar provides three continuous degrees of freedom, two rotational and one linear, enabling whole-arm interaction with the instrument.

Angular position along the two orthogonal rotational axes is captured using rotary potentiometers mechanically coupled to the handlebar shafts. Linear displacement is measured through an optical sensing mechanism housed within a hollow tube, where an LED and a light-dependent resistor (LDR) detect the position of a sliding piston by measuring variations in reflected light intensity. The mechanical design of the handlebar is shown in figure 3.

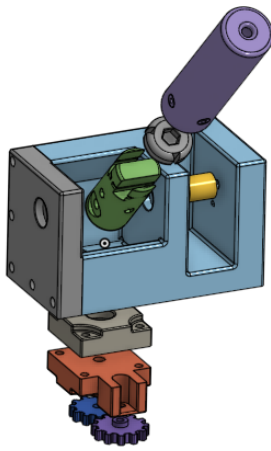


Figure 3: Handlebar mechanical design.

The keyboard (figure 4) is intentionally simple and conventional, serving only as a pitch-selection mechanism. It is limited to seven keys, with five mapped to a minor pentatonic scale and two used for octave shifting. This reduced design aims to lower cognitive load [22] and to direct the performer’s attention toward interaction with the handlebar rather than the construction of complex melodic structures.

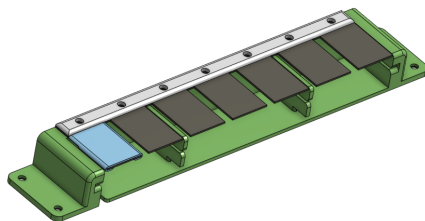


Figure 4: Keyboard design.

The instrument is designed as a modular system that supports straightforward assembly and maintenance [26]. All components are mounted on a compact wooden structure whose overall form approximates that of a guitar, with the handlebar positioned on the body and the keyboard aligned along a neck-like extension.

Sensor data and control inputs are routed to a Bela board, which hosts the software synthesiser.

### 3.2 Software

The software has been developed in Pure Data. It is divided into two main parts, the Karplus-Strong oscillator engine, and the FM modulation engine. The signal is generated by the Karplus-Strong oscillator, then fed to the FM modulation engine, and finally fed to the DAC output.

The underlying software synthesiser of *Manubrio* is an active, responsive system, rather than a passive sound generator. It delivers fine control of its parameters to the performer, who is responsible of every sonic detail.

**3.2.1 Karplus-Strong-Based Oscillator.** The sound engine is based on a modified Karplus-Strong algorithm [17], in which a short noise excitation is injected into a delay line whose length determines the fundamental frequency, selected via the keyboard. Unlike conventional implementations, where the feedback gain is constrained below unity to ensure stability, *Manubrio* allows gain values both below and above 1. This enables a continuum between classic plucked-string behavior and sustained oscillation [28].

Feedback gain and spectral damping are controlled continuously via the two potentiometers, directly shaping the system’s dynamic behavior. To prevent unbounded amplitude growth, the signal is clipped and high-pass filtered before being reinjected into the delay line. The processed signal is simultaneously routed to the oscillator output with gain compensation.

**3.2.2 Delay-Based Frequency and Pitch Modulation.** The output of the Karplus-Strong oscillator is further processed using delay-based frequency modulation, implemented by modulating the playback time of a delay line with a sinusoidal oscillator [32]. The modulation frequency is set as a fixed ratio of the fundamental frequency, ensuring consistent spectral relationships across pitches.

Modulation depth is controlled by the linear piston movement, with greater displacement producing stronger frequency modulation. Increasing depth raises the FM index, introducing additional sidebands and contributing to a progressively richer and more abrasive timbral character [5, 28].

To maintain a stable perceived pitch, the delay line is offset by an amount proportional to the modulation depth, centering the modulation around the original delay time. While this prevents long-term pitch drift, dynamic changes in modulation depth introduce transient pitch deviations analogous to Doppler effects in time-varying delay systems [32]. These transitions generate coloration, as well as temporally non-stationary spectra [18, 30].

## 4 Designing for Embodied Interaction

The relationship between musician and instrument plays a fundamental role in shaping musical performance, particularly when considered through the lens of embodiment. Within embodied cognition, expressive performance emerges from the musician’s physical attunement to sound, where perception and action form a continuous loop rather than a sequence of discrete operations [20]. For such attunement to occur, the instrument must recede from focal awareness and become incorporated into the performer’s bodily schema, functioning as a natural extension of the body [24, 25].

*Manubrio* is framed not as a neutral control interface but as an instrument designed to investigate how embodied interaction emerges. Considerations of movement, physical effort, and spatial interaction were not treated as evaluative criteria applied after

the fact, but actively informed both hardware and software design decisions. This led to prioritising sensorimotor feedback cues and a tight gesture–sound coupling that minimizes indirection between physical action and sonic outcome.

A central aspect of this interaction is the control of positive feedback, which requires continuous physical regulation. Small variations in arm position can move the system between stable oscillation, saturation, or silence, encouraging the performer to develop a bodily awareness of spatial position and system sensitivity. Sound is not simply triggered but must be physically sustained through ongoing movement.

Because the mapping is deliberately tight, physical actions are immediately reflected in sound. Small variations in position or movement directly affect timbre and system behavior, encouraging active listening and continuous adjustment. Gestures unfold as trajectories in three-dimensional space rather than as discrete control events.

Interaction with *Manubrio* is structured as an enactive loop rather than a visually mediated control task. The performer's proprioceptive sense of arm position and effort provides an ongoing internal reference, while sound simultaneously serves as immediate perceptual feedback on the system's state. Action and listening become inseparable, establishing a continuous sensorimotor dialogue in which movement shapes sound and sound guides subsequent movement, an instance of enaction in the sense of Varela, Thompson, and Rosch [35].

*Manubrio* is designed to offer a previously unknown performance experience, functioning as a "blank interaction canvas" while actively encouraging embodiment through precise physical and sonic coupling. By avoiding familiar gestural conventions and providing unfamiliar sonic behavior, the instrument invites the performer to develop new action–sound relationships [9, 20], supporting the gradual incorporation of the instrument as a transparent extension of the body [25].

Interaction with *Manubrio* is intentionally demanding, requiring sustained engagement to maintain sonic stability. This sensitivity discourages detached or symbolic control, shifting attention toward felt movement and listening. Sound thus functions as immediate perceptual feedback, supporting continuous action–perception loops and allowing control relationships to be internalised as embodied, spatial skill through repeated sensorimotor experience, rather than acquired as a set of explicitly stated rules, potentially enabling flow-like states during performance [24].

## 5 Gestural Framework

*Manubrio* is played in a posture analogous to that of a guitar, typically worn over the left shoulder while standing. The left hand operates a simplified keyboard using a familiar fretting-like gesture, providing stable pitch selection without demanding complex motor coordination.

The right hand controls the handlebar (figure 5). Although the human arm exhibits biomechanical redundancy for this task, effective movement control emerges through coordinated whole-arm action rather than isolated joint manipulation [2]. By constraining interaction to hand position in space, the handlebar encourages motor synergies that simplify action planning while allowing expressive variation [3, 19].

The interface constrains only hand placement, leaving the performer free to move through space. Inspired by the stage mobility of electric guitar performance, this portability allows



Figure 5: The right hand grabs the handlebar controlled by arm movements.

personal movement to coexist with instrumental control, supporting expressive movement beyond the minimum required for sound production and reinforcing embodied interaction during performance [24].

Sound timbre and feedback are shaped continuously through handlebar movement. Near regions of instability, small positional changes can produce significant sonic variation, requiring precision and sustained attention. Through this sensitivity, *Manubrio* establishes an ongoing dialog between gesture and sound.

During performance, control unfolds through a continuous loop of action, sound, listening, and adjustment. Each movement immediately reshapes the feedback, which is perceptually evaluated and used to guide subsequent micro-corrections. This dynamic aligns with Leman's coupled mechanisms, in which low-level sensorimotor loops support fine-grained stabilization, while higher-level action–perception loops organize broader gestural strategies and expressive form [21]. Coherent embodied metaphors explained in the following section allow performers to anticipate sonic outcomes from movement trajectories, facilitating rapid prediction, refinement, and expressive shaping in real time.

## 5.1 Main Gestures

Interaction with *Manubrio* is organized around three recurrent gestural archetypes that structure the relationship between movement and sound.

A first gesture can be described as *pulling*. Raising the hand position rotates the handlebar along one axis, increasing the feedback gain of the Karplus–Strong oscillator. As the gain crosses unity, the system enters self-oscillation. This action is often experienced as physically holding and drawing the feedback into a desired state, requiring careful regulation to maintain sonic balance.

A second gesture, referred to as *opening*, involves moving the hand away from the body along the handlebar’s second rotational axis. This motion reduces spectral damping, resulting in a brighter timbre. Performers frequently report this gesture as an embodied metaphor (see Section 6 for full study details): opening the body produces an opening of the sound, reinforcing the coherence between spatial movement and sonic outcome.

The third gesture, termed *pumping*, is realized through the linear sliding of the handlebar piston, which controls delay-based frequency and pitch modulation. This movement can be perceived as stretching and compressing the sound. Larger outward piston displacements require broader motion and simultaneously increase spectral richness. As with the opening gesture, expanding the body spatially corresponds to a more open and intense sonic character, strengthening the consistency of gesture–sound coupling.

Tight and coherent gesture–sound coupling is further evident in so-called “closed” gestures, where low filter cutoff values combined with marginal feedback gain produce delicate, fragile sonic states. These interactions require subtle and restrained movements, yielding mellow timbres that can easily collapse into silence if over-damped. Conversely, wide, rapid, or irregular movements result in unstable or chaotic sonic behavior. Gestures that trace circular or closed trajectories in space tend to generate periodically evolving timbres that mirror the cyclical nature of the motion.

Together, these gestures establish an expressive gestural vocabulary grounded in metaphors. Rather than functioning as abstract controls, they promote an embodied understanding of sound through physically legible actions.

## 5.2 Gesture–Sound Mapping Characteristics

As described above, *Manubrio* is designed around a tight gesture–sound coupling. In order to support embodiment, this coupling is also coherent: performers and listeners are able to infer motion from sound and sound from motion [10].

Following the mapping strategies discussed by Gurevich et al. [12], the mappings in *Manubrio* can be analytically grouped into three categories:

- **Clarity:** Individually, each handlebar axis exhibits a clear and consistent mapping, with stable cause–effect relationships. Such clarity supports transparency, facilitates learning, and enables reliable control of timbre and feedback behavior.
- **Ambiguity:** When mappings are considered in combination, a degree of ambiguity emerges. For example, interaction between feedback gain and low-pass filtering can suppress oscillation even when gain exceeds unity, depending on spectral damping. Additionally, a given handlebar position does not specify a single sonic outcome;

instead, it shapes the evolution of an already active system. The resulting sound depends on prior states and movements, making gestures determinative of change rather than of absolute sonic states. While this reduces strict one-to-one coherence, it encourages exploration, sensitivity, and attentive listening [12].

- **Intentional instability:** Drawing on Di Scipio’s framing of instability as a performative resource [29], certain mappings are deliberately sensitive and demand continuous regulation. This is particularly evident when controlling feedback gain near unity, where minimal positional changes can cause the sound to oscillate, saturate, or vanish. Expressive control thus emerges through sustained negotiation rather than discrete command.

## 5.3 Energy–Motion Models

From the perspective of energy–motion models [34], musical meaning arises from the perception of dynamic forces and trajectories rather than from static sonic states. Sound is understood as the audible trace of motion and transformation, allowing listeners to infer underlying gestures and tensions [31, 34]. While developed in the context of acousmatic composition, this framework is particularly applicable to *Manubrio*, where sound is directly shaped by continuous action.

The instrument’s feedback-based synthesis translates physical energy, expressed through gesture direction and speed, into evolving sonic energy, making motion perceptually legible. Across the three interaction axes, sustained gestures support continuous energy flows and stable yet tense sonic states, while gradual increases in movement introduce accumulative energy that leads to spectral densification and saturation. Abrupt or impulsive gestures inject bursts of energy that destabilize the system, producing transient pitch shifts, noise components, or sudden silences. Cyclic gestures generate periodic sonic morphologies that reinforce the perception of motion.

Rather than prescribing specific outcomes, these behaviors emerge through the performer’s physical negotiation of an active system. In this sense, *Manubrio* functions as an embodied energy–motion interface, where musical form is enacted through the continuous modulation of bodily energy and its sonic consequences.

## 6 User Study

In order to explore the capacity of *Manubrio* to support embodied interaction, a small-scale, exploratory user study was conducted using a qualitative thematic analysis approach [4]. The purpose of the study was not to validate embodiment in a formal sense, but to investigate whether musicians could begin to develop an embodied relationship with the instrument, as intended by its design, or whether the instrument remained experientially present as an obstacle between musician and music.

As a consequence of this focus, the study also serves as an exploratory examination of the playability and musical potential of the instrument. Rather than providing statistical validation, the study seeks to generate experiential and reflective insights into interaction qualities, in line with approaches to soma-based and experience-centered design [15].



**Figure 6: A participant performing the first experiment task.**

Participants were recruited through personal networks within local music and sound-art communities. Inclusion criteria required active experience performing or practising a musical instrument. No prior experience with NIMEs was required; variation in NIME familiarity was considered desirable for exploring a range of perspectives on embodied interaction with novel interfaces.

Four musicians participated in the study, each with a different musical background and level of technical expertise. Collectively, they had experience with instruments such as guitar, electric bass, drums, keyboards, trumpet, percussion, and voice, and varying degrees of familiarity with sound design and electronic music production. Most participants had little prior experience with New Interfaces for Musical Expression, while one participant reported extensive experience in this area. All participants took part in the same experimental procedure, conducted individually (figure 6).

A detailed description of the experimental protocol and interview questions is provided in the appendix A.

## 6.1 Methodology

The qualitative data were analyzed using a theoretically informed thematic analysis following Braun and Clarke’s framework [4]. This approach was chosen to identify recurring patterns in participants’ subjective accounts while remaining sensitive to embodiment-related concepts.

The analysis followed the standard phases outlined by Braun and Clarke. First, all interviews were transcribed and repeatedly read to achieve familiarity with the data, while initial notes were taken. Next, a set of initial codes was generated, including, for example, *intuitive design*, *initial discomfort*, and *focus on sound*. These codes were then organized into candidate themes, which were iteratively reviewed, refined, merged, or discarded. Finally, the themes were clearly defined and named, forming the basis for the interpretation presented in the following sections.

## 6.2 Thematic Analysis

Five themes were identified across the dataset. The most prominent and consistently recurring theme concerned the *incorporation process*, describing how participants gradually integrated the instrument into their bodily action and perception.

**6.2.1 The Incorporation Process.** All participants described a progressive process through which the instrument became more

familiar and playable. This process followed a similar trajectory across sessions.

Initially, participants reported discomfort and unfamiliarity. Encountering an unknown physical object required bodily adaptation, and different postures or playing positions were explored to find more comfortable configurations.

“In the beginning, when I was standing, I had a hard time reaching, but I felt better out there sitting.”

“At first there was a certain level of discomfort with the instrument. After sort of getting over that, the sound was interesting enough and the playability was good enough that I was able to actually get into playing the instrument.”

A sub-theme of this process was *unfamiliarity*. Participants repeatedly described the instrument as unknown and framed their interaction in terms of discovery.

“I could describe it as discovery, it’s a new instrument.”

“It was different than instruments that I played.”

Once initial discomfort diminished, participants entered a phase of exploration. During this stage, they developed sonic and gestural frameworks independently, discovering both the range of sounds the instrument could produce and the movements it afforded.

“I listened to what sounds could be extracted from the instrument.”

“[...] this sort of weird movement, like, okay, I’m moving my hand like this.”

Subsequently, participants began to couple these frameworks by learning relationships between gestures and sonic outcomes. This *coupling* emerged as a key sub-theme of the incorporation process.

“It wasn’t just about grasping or understanding the range of motion of the instrument, but also how that fit in with my movements and how I could or wanted to produce sound. That harmony between the sounds and the movement that could be achieved.”

Through the composition tasks (appendix A), participants also reported coupling sound with emotion. Rather than focusing on bodily movement or interface mechanics, they selected sounds that matched expressive intentions.

“I started with the feelings and tried to match the sounds.”

“[...] knowing what (sonic) possibilities I had, I tried to find among those possibilities one that evoked in me a certain feeling or a certain energy.”

All participants reached this stage. One participant with extensive prior experience in NIMEs further described a reduction in awareness of both the instrument and their own body.

“I didn’t really pay a lot of note to it (my body).”

“It’s almost as if your consciousness sort of occupies that space of the instrument in a way that I’m less conscious of my body.”

“[...] a point where you’re able to forget that (your body movements), and you’re just like, I’m moving the sound. I’m not thinking about my hand, but the sound is moving.”

**6.2.2 Felt Movement and Spatial Awareness.** A closely related theme concerned proprioception and felt movement awareness. Participants repeatedly emphasized reliance on felt position and movement to orient themselves within the instrument’s interaction space, particularly during blindfolded tasks (figure 7).

“I had to find the movements where my body was.”

“Especially when I couldn’t see anything, it was more about being aware of what movements my body was making.”



**Figure 7: A participant performing one of the blind-folded experiment tasks.**

**6.2.3 Immersion.** Participants reported experiences of immersion, characterised by sustained focus and a reduced awareness of the passage of time during interaction. Three of the four participants described moments of becoming absorbed in the sonic and gestural process.

“I was getting lost into it in a good way.”

This state shares characteristics with Csikszentmihalyi’s concept of flow [6], in which skilled engagement produces an effortless merging of action and awareness. The demanding but learnable precision required by *Manubrio* appears to have provided conditions conducive to such states.

**6.2.4 Ease of Use.** Ease of use emerged as a facilitating theme. Three of the four participants described the instrument as intuitive and quickly understandable, supporting sustained engagement.

“I feel that the instrument’s design is intuitive.”

While participants found the instrument’s basic mapping quickly legible, fine-grained control, particularly near the feedback threshold, remained a persistent challenge, suggesting a distinction between initial accessibility and deeper mastery.

**6.2.5 Obstacles.** All four participants identified at least one obstacle that temporarily disrupted interaction. The most commonly reported difficulty (three participants) was the precision required to regulate feedback near the self-oscillation threshold.

“I struggled with the positions to stop feedback.”

Two participants also noted ergonomic discomfort in certain postures, particularly when standing. These breakdowns increased awareness of the instrument as an external object, disrupting transparency.

## 6.3 Results Discussion

The identified themes collectively suggest that *Manubrio* supported the emergence of embodied interaction over the course of the experiment. The *incorporation process* reflects a gradual increase in instrument transparency, particularly evident in one participant who reported reduced awareness of both body and interface. In phenomenological terms, this can be understood as a perceptual illusion of non-mediation, where the instrument recedes from focal awareness during action [24, 27].

Felt movement and spatial cues played a central role in this process, shaping how participants oriented themselves and regulated sound. Reliance on felt movement, especially under blindfolded conditions, reinforced the coupling between gesture and sound and supported bodily internalization of the interaction.

Experiences of immersion further contributed to embodiment. States of focused engagement and the loss of self-awareness resemble aspects of flow [6], which may facilitate the formation of stable bodily and perceptual schemas associated with a merging of musician and instrument [24].

At the same time, reported obstacles highlight the fragility of embodied interaction. Ergonomic constraints and the demanding precision required to control feedback occasionally disrupted transparency, reminding performers of the instrument as an external object. These breakdowns underline the importance of balancing sensitivity and accessibility in embodiment-oriented design.

Overall, the results suggest that tight and coherent gesture–sound coupling can support the development of embodied interaction. While the findings are exploratory, they indicate that embodiment-based design strategies may enhance the incorporation potential of new musical instruments. Further studies with larger participant groups and comparative conditions are needed to evaluate these effects more systematically, as well as to examine the role of instrument portability and full-body movement, which remained beyond the scope of this study.

## 7 Conclusions

This paper presented *Manubrio*, a digital musical instrument conceived as an embodiment-oriented instrument rather than a conventional controller. By combining a feedback-based Karplus–Strong synthesis engine with a portable, three-degree-of-freedom handlebar interface, the instrument foregrounds continuous bodily negotiation as a primary musical resource. Sound is not triggered or parameterized in isolation, but emerges from sustained physical engagement and spatial interaction.

Across design analysis and a qualitative user study, participants described a gradual incorporation process. The sensitivity of feedback control encouraged close listening, continuous adjustment, and the development of embodied skill rather than symbolic control. However, the demanding precision and ergonomic limitations reduced the instrument’s embodiment potential.

These findings do not constitute a formal validation of embodiment, but they suggest that *Manubrio* supports conditions under which embodied interaction may emerge. Deterministic yet sensitive mappings, intentional instability around self-oscillation, and immediate sonic responsiveness fostered tight action–perception loops, allowing control to be learned as felt, spatial knowledge rather than explicit instruction.

This work contributes to NIME in three ways: by reframing positive feedback in Karplus–Strong synthesis as a performable

dimension; by presenting a portable interface providing mutual responsiveness and demanding bodily engagement; and by demonstrating how a musical instrument can function as a research artifact for investigating embodied interaction.

More broadly, *Manubrio* highlights how feedback, instability, and physical effort can be embraced as expressive resources in musical interface design. By treating sound as the audible trace of continuous movement and energy, the instrument challenges interaction models based on discrete control and symbolic manipulation, suggesting that new insights into musical embodiment may arise through the lived experience of playing responsive, unstable systems.

## 8 Future Work

*Manubrio* is at an early stage of development and offers multiple directions for improvement. On the hardware side, a systematic ergonomic analysis is needed to reduce physical interference between performer and instrument. The interface could be expanded by replacing the keyboard with an alternative note-selection mechanism that better supports a wider pitch range and polyphony. The handlebar itself could be redesigned to integrate finger-operated buttons for note triggering, excitation of the Karplus–Strong oscillator, and additional parameter control (figure 8). A further refinement would be the addition of a restoring force to the piston (e.g., elastic elements), enhancing the physical sensation of stretching and compressing sound.

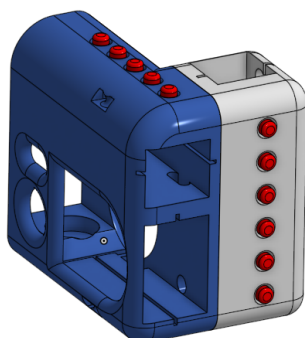


Figure 8: Concept design of the future expanded handlebar.

On the software side, the current hard-clipping saturation could be replaced with a more refined model, and the one-pole low-pass filter with a more flexible filtering system. Mapping strategies could also be revised to reduce excessive precision demands and improve stability and reliability during performance.

Finally, future studies should include a larger participant pool, incorporate quantitative measures alongside qualitative analysis, and introduce control conditions to more rigorously evaluate the instrument's embodiment potential.

## 9 Ethical Standards

Before starting the experiment, participants were provided with a detailed consent form outlining the purpose of the study, the procedures they would be asked to complete, potential risks and discomforts, anticipated benefits, and any incentives for participation. The form also addressed the recording of audio and video for research purposes, optional consent for photography for publication and promotional use, and measures to ensure privacy,

confidentiality, and data security. Participation was entirely voluntary, and the experimental procedures were conducted only after participants provided written informed consent.

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## A Experimental Protocol

The experiments were conducted in a small, quiet meeting room with an informal atmosphere at Aalto University. Participants used headphones to monitor the instrument output and to listen to audio samples during specific tasks. Seating was available, allowing participants to perform either standing or seated. A fixed camera recorded the interaction between the participant and the instrument, and a microphone was used to record all interviews.

Each participant took part in an individual session following the same experimental protocol, structured as follows:

- (1) *Manubrio* was introduced to the participant, including a brief explanation of the interface components and their mappings to the synthesis engine.
- (2) The participant was given up to 10 minutes of free exploration to become familiar with the instrument.
- (3) The participant was asked to compose a short improvised musical piece within a maximum of 10 minutes. The following expressive guidelines were provided: the piece should begin softly, become aggressive, and end melancholically. These abstract instructions were intended to divert attention away from technical control and toward expressive interaction, supporting instrument transparency. During this task, the experimenter left the room to avoid external influence. The resulting performance was then presented to the experimenter and recorded.
- (4) The participant listened to a series of pre-recorded audio samples generated using *Manubrio*. After a single listening, the participant attempted to recreate each sound by playing the instrument. Samples were presented in random order and focused on handlebar interaction. All samples began on the same pitch; most consisted of a single sustained note, while a small number included very simple melodic structures (up to three notes). This simplification was intended to minimize keyboard involvement and encourage engagement with the handlebar.
- (5) The participant was blindfolded using an eye mask, removing visual cues. They were then asked to repeat the free exploration task to adapt to the new interaction conditions.

- (6) While blindfolded, the participant repeated the sound-matching task, again attempting to reproduce the presented audio samples.
- (7) With the eye mask removed, the participant composed a second short improvised piece. This time, the expressive guidelines were: the piece should begin dizzy, become sad, and end annoyingly. As before, the participant performed alone, and the resulting piece was recorded.
- (8) Finally, the participant took part in a semi-structured interview consisting of open-ended questions. Participants were encouraged to elaborate freely and introduce additional comments if desired. All participants were asked the following questions:
  - Can you describe the performance or playing experience from an inner point of view?
  - Can you describe the transformation of a musical idea from its conception to its sonic realization?
  - Can you describe how your focus of attention changed throughout the experiment?
  - How did your experience differ when performing blindfolded?
  - How did your body experience the tasks?
  - Did you struggle with anything?

The experimental protocol was designed to progressively familiarize participants with the instrument, encourage exploration of its gestural and sonic space, and promote reliance on non-visual cues. Through repeated interaction, sound-matching, and improvisation tasks, participants were supported in developing a gestural language and deeper engagement with the instrument. The concluding interviews aimed to assess whether embodied interaction emerged during the session and how embodiment potential evolved over time.