Body, Bend: Resolving the soft-rigid paradox using 3D printing innovation

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Abstract

Wearable musical instruments face a material challenge: piezoelectric percussion sensors require rigid, stable mounting, while garments demand softness and flexibility, and must be body-conforming. This tension is particularly acute for piezoelectric sensors used in percussion applications, where consistent signal response depends on stable sensor placement. In this paper we present a novel fabrication method using 3D-printed, flexible TPU substrates that we developed to embed piezo sensors in wearable garments. This approach enabled us to create a sensing infrastructure that is not only stable and reliable for sensor response, but is uniquely lightweight, wearable, aesthetically resolved, and fully integrated into a wearable fabric system. Developed through a collaboration between an instrument designer and an electronic musician with deep African influences, this infrastructure enabled a complete wearable percussion instrument that musically and aesthetically supported the artist's practice. By resolving the soft-rigid paradox through 3D printing that is widely accessible and cost-effective and presenting a material-led response to the notion of the 'unfinished instrument' that is completed through use, this work demonstrates how fabrication innovation can move technology from foreground constraint to background infrastructure, empowering artists and designers to prioritise musical, aesthetic, and visual factors.

Keywords

wearable technology, 3D printing, African percussion tradition, musical instrument design

1 Introduction

Across musical traditions from flamenco palmas to East African ngoma, the body serves as its own percussive instrument. Yet wearable technologies often introduce friction: sensors require stable mounting, electronics demand power and connectivity, and yet garments must remain comfortable, flexible, and aesthetically aligned with performance practice. This creates a fundamental *soft–rigid paradox* for body percussion instruments.

Piezoelectric sensors excel at capturing percussive strikes but require rigid, stable mounting to function reliably. Attaching them directly to skin or fabric produces inconsistent signals as sensors shift during movement, and while rigid housings solve sensing problems they create less wearable instruments that constrain the body. Previous approaches, such as taping sensors to

Figure 1: The finished instrument worn by Nyokabi Kariũki, from front (top) and back (bottom).

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skin, sewing into fabric, or using semi-rigid enclosures, represent compromises between technical performance, comfort, and aesthetics.

This paper presents a fabrication technique that resolves this paradox through 3D-printed flexible TPU (thermoplastic polyurethane) substrates. Emerging from collaboration between instrument designer Astrid Bin and composer Nyokabi Kariũki (whose practice explores the "sounding African body" rooted in East African rhythmic traditions), this work transforms body percussion sensing from technical obstacle to reliable infrastructure. Building on earlier work between Kariũki and Alex Hofmann into wearable body percussion in which piezo sensors were taped to her body, we report here on the development of a performance entitled 'Body, Bend', a performance driven by a complete wearable DMI where a TPU substrate integrated sensors into a leather garment while preserving flexibility and aesthetic integrity.

We contribute the following:

(1) A reproducible 3D printing fabrication method costing $0.30 per substrate,
(2) The "unfinished" instrument philosophy exposing flexible data streams for artistic mapping, and
(3) Practice-based reflections demonstrating how accessible technologies can centre artistic practice over technical negotiation.

2 Background

2.1 Context of African traditions

Across many African traditions, the notion of *music* has no analytic separation into 'song' vs. 'instrument' vs. 'dance'. Rather, music is an integrated activity where bodies, voices and tools coproduce rhythm and meaning. In Bantu East Africa, the Kiswahili/Bantu term *ngoma* can mean a specific drum, a drumming ensemble, or an entire event where song, dance and drumming are inseparable. Similarly, among the Samia people, music is understood as a collage of song, dance and instrumental performance, with no single cover term. The analytic separation of rhythmic dance as 'body percussion' emerges from ethnographic and music-education framings of African music, largely by Europeans, in the early and mid 20th century. Naranjo points out that for the communities under study, "the link between music and movement in a tribal context was inseparable" [14].

In what follows, we use the term 'body percussion' to refer to musical dance that produces sound directly with the body. We do so with some hesitation, since the category itself reflects a colonialist analytic separation of movement from music in African traditions that is inherently reductive. Nevertheless, 'body percussion' is a useful shorthand here for practices that are not just 'traditional' but continue to evolve in relation and resistance to social and political forces. For example, gumboot dance originated in South African mines in the late 19th and early 20th centuries, where migrant African miners working in deplorable conditions used slaps on their rubber boots as a means of communication in situations where speech between workers was forbidden and could be punished. A basic body-percussion vocabulary, tightly constrained by the uniform and the environment, became a substitute communication system when direct speech was illegal or dangerous. Over time, this practice evolved into gumboot dance, a symbol of resistance and solidarity [13].

A key motivation for Kariũki in this project was to explore the 'sounding African body'. As gumboot dance demonstrates, body-as-instrument is not just aesthetic and rooted in long histories, but can encode experience and reflect identity. This resonates with her influences as an electronic artist, from African body-based musics to Halim El-Dabh's early tape works in Cairo, often described as among the first electronic compositions [15]. Kariũki seeks to engage these traditions within her own electronic composition and performance practice.

2.2 Theoretical positioning

Digital musical instruments (DMIs) decouple gesture from sound, yet materiality remains non-neutral [11], inscribing specific interaction scripts and aesthetics into the design [8]. Digital lutherie [10] treats this fabrication as a craft where physical properties—how an instrument is worn and felt—are inseparable from musical affordance. For wearables, this necessitates moving beyond rigid forms toward soft, compliant materials that move with the body [16].

This creates a 'soft-rigid paradox': sensors like piezos require stability, while garments require flexibility [3]. We resolve this using 3D-printed TPU substrates to move technical constraints into the background infrastructure. Conceptually, we adopt the 'unfinished' instrument philosophy, and align with Bowers and Haas's view of the DMI as a collection of affordances that only becomes an instrument through use [2]. This stable infrastructure allows the technology to become transparent, enabling the 'completion' of the instrument to occur through the performer's embodied practice and the cultural specificities of the sounding body.

2.3 Wearable Instruments

Wearable musical instruments have become an important strand within DMI research, extending sensing and actuation directly onto the performer's body. Many systems use the body as a site for gestural control rather than as a percussive surface: hand-based instruments such as the Mi.Mu Gloves [1] and Xyborg [5] use inertial sensors, flex sensors and buttons to capture finger movements and arm gestures, which are then mapped to sound parameters in software. Other work in 'body lutherie' explores how garments and harnesses shape vocal or bodily performance, focusing on how sensors and actuators are integrated into costumes and stage presence rather than into discrete handheld devices [7]. Across these examples, wearability is typically framed in terms of ergonomic fit and movement freedom, while the materials that carry the sensors are often treated as a largely neutral substrate.

A parallel line of research in wearable sensing and smart textiles foregrounds the specific challenges of putting sensors onto and into garments. Textile-based strain and pressure sensors built from conductive yarns, coated fabrics or printed conductive inks promise soft and unobtrusive measurement, but suffer from issues such as hysteresis, non-linearity and drift under repeated deformation [4, 9]. Within this context, 3D printing has emerged as a promising fabrication method for wearable interfaces, allowing local tuning of stiffness and form while remaining compatible with textile substrates.

Our project builds on these strands by treating the wearable not only as a site for gesture capture, but as a percussive instrument in its own right. Rather than stitching sensors directly into fabric or mounting them in rigid boxes strapped to the body, we use flexible 3D-printed TPU forms as both the structural layer and the interface to sensing. This approach aims to reconcile the

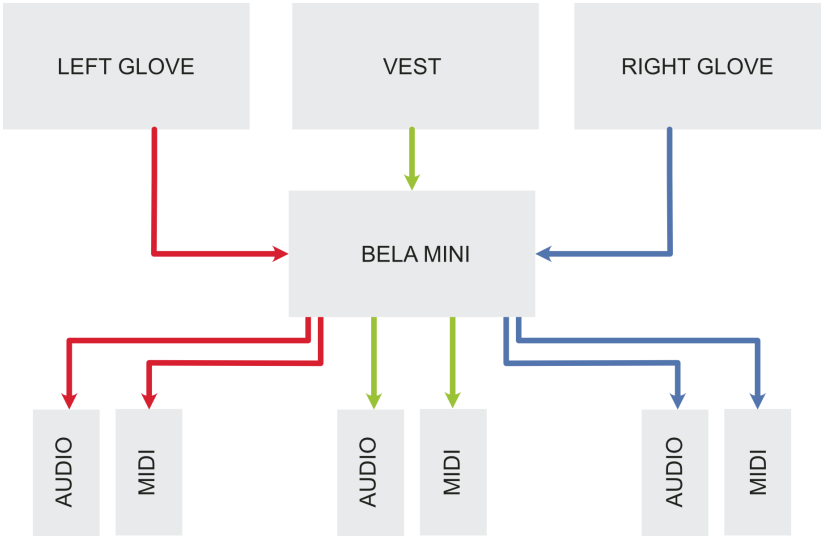

Figure 2: Diagram of signal processing.

need for stable, repeatable sensor behaviour with the requirement that the garment moves with the performer's body, turning the material properties of the printed TPU, such as its softness, deformability and contact with the skin, into central musical resources rather than secondary engineering details.

2.4 Unfinished and open instruments

While many DMIs are presented as complete, self-contained instruments, a parallel strand of work treats them as deliberately unfinished systems. In this view, the designer does not fix a single, closed mapping from gesture to sound, but instead exposes a space of possibilities that performers, composers and even audiences can configure over time. This resonates with broader discussions of cultural artefacts as "permanently unfinished" [6], whose functional identity emerges through ongoing interaction rather than being fully specified at design time.

One way this stance is operationalised in DMI design is by exposing control streams instead of prescribing fixed behaviours. Mapping frameworks [12] formalise this separation by treating instruments as producers and consumers of generic control signals, with connections between them created, edited and re-routed in a separate mapping layer. Rather than baking mappings into firmware or enclosures, instruments in this paradigm offer stable, legible streams of data that can be dynamically linked to synthesis parameters, spatialisation or score structures. This shifts part of the instrument's authorship into the mapping environment, where performers and composers complete the instrument by constructing their own signal networks.

Our project adopts this open-instrument stance in the context of a wearable percussive garment. The hardware and sensing behaviour of the garment are finished: the locations of impact zones, the piezo and contact microphone circuitry, and the extraction of onset and velocity are fixed. But their musical meaning is left deliberately underdetermined. We discuss how this open-instrument approach influenced the design of this instrument's sonic capabilities further in Section 3.4.

3 Implementation

This instrument was developed through a collaboration between Astrid Bin, an instrument designer, and composer/performer Nyokabi Kariũki. It builds on 2024 work between Kariũki and Hofmann, wherein they explored piezoelectric sensing for body percussion using sensors taped directly to her skin for proof-of-concept experiments. The goal for this iteration was to transform this from a technical experiment into a complete performance instrument where aesthetics, wearability, and fabrication quality matched the technical functionality.

The wearable instrument includes a vest with an integrated vest sensor array and gloves with palm-mounted sensors. These connect to an integrated Bela Mini system mounted on the back, a multichannel audio device that processes the piezo signals in real time and communicates with the musician's setup. These discrete data streams can in turn be mapped in any way by the artist within her electronic setup according to her compositional and performance needs (see Figure 2).

3.1 Design process and concept

The design process began with design sketches and material testing to identify suitable materials that balanced signal response with aesthetic and tactile qualities (Figure 3). Bin selected leather as the primary material for its range of colours, weights and densities, and its particularly good signal response. Kariũki had significant input into colour choices and aesthetic direction, in order to ensure that the instrument aligned with her performance practice and stage presence. This collaborative approach meant that technical decisions were always evaluated against artistic and wearability requirements, rather than optimising solely for sensing performance.

3.2 TPU Substrate Design and Fabrication

The core innovation of this work is the use of 3D-printed flexible TPU as a substrate for embedding piezoelectric sensors within soft garments. TPU offers the mechanical properties needed to hold sensors in stable positions while remaining flexible, lightweight, and body-conforming.

We created TPU substrates with embossed depressions to hold each sensor in place (see Figure 4). However, through testing we discovered that this was unnecessarily complex. The final design instead features substrates with the backs entirely cut out behind each sensor position, with sensors secured using tape.

This approach proved simpler to fabricate and assemble while maintaining sensor stability.

A critical fabrication innovation was the use of 3D printing brims. Brims are typically used for bed adhesion and discarded after printing, this ultra-thin surrounding layer instead served as a strong but pliable sewing interface, allowing the substrate to be easily machine-stitched into the garment without adding bulk or stiffness.

3.2.1 Vest Substrate. The vest presented different design challenges. The larger sensing area required a substrate that exceeded the print bed dimensions of 20cm x 20cm. To address this, we designed the vest substrate as two mirrored pieces that could be assembled. Each piece holds 5 sensors (4 x 35mm, 1 x 15mm), positioned to capture strikes across the chest and upper torso (see Figure 5, top).

3.2.2 Glove Substrates. The glove substrates were designed to be thin, to maintain hand flexibility and tactile sensitivity. Each substrate holds 3 piezo sensors (1 x 35mm and 2 x 15mm), positioned to capture strikes across the whole palm. The substrates were designed to fit the palm anatomy, following its natural contours. See Figure 5, bottom).

The vest substrate's interaction with body topology emerged as an important characteristic of the instrument. Sensors positioned over the sternum sit close against the body, while sensors higher on the chest over the clavicles have more distance from the skin. This anatomical variation creates distinct sonic responses: strikes on the sternum produce one character of sound, while strikes higher up exhibit a transient response due to the looser coupling between sensor and body. Rather than treating this as a problem to solve, we recognised it as part of the instrument's character, and a way in which the topology of the performer's body becomes part of the instrument's sonic identity.

The cost of producing these substrates on a consumer-grade 3D printer is approximately $0.30 per piece, making the technique highly accessible as long as machinery is available. TPU can be printed on standard FDM printers without additional hardware. Due to its flexibility, we found it helpful to slightly loosen the filament clamp to avoid over-constraining the filament.

3.3 Garment Construction

3.3.1 Vest. The vest was constructed from leather, with the sensing surface a double layer of very thin suede with the substrate

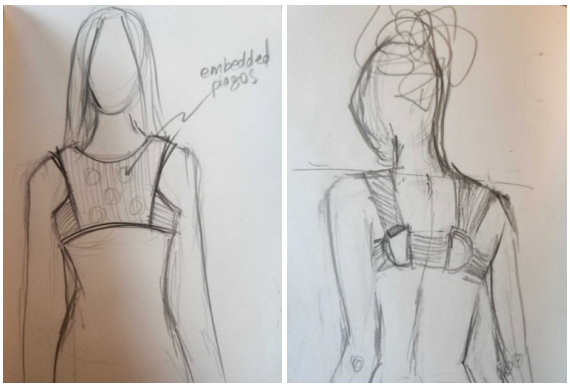

Figure 3: Initial design sketches for the vest, front (top) and back (bottom).

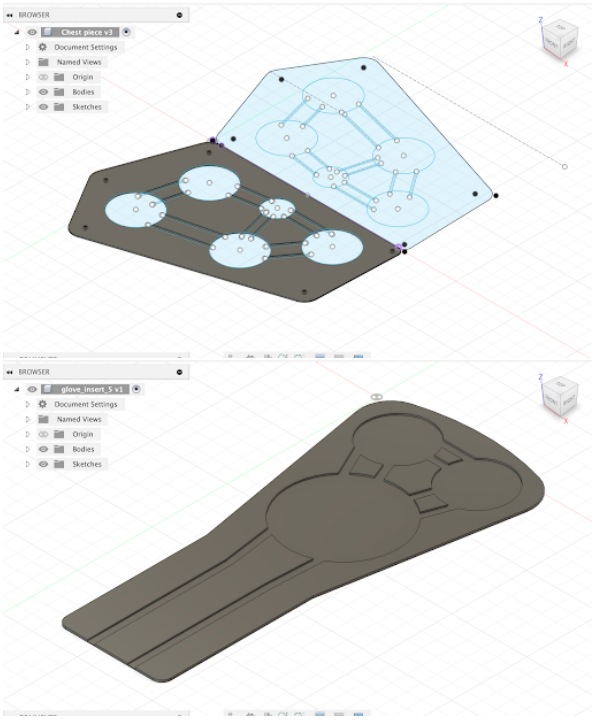

Figure 4: 3D models of the vest substrate (top) and glove substrate (bottom).

sewn into the garment interior. The two-piece substrate was centred on the chest and sewn in place using the printed brims as sewing interfaces.

A key design feature was accessibility: the front panel of the vest could be lifted when the garment is unworn, to access the sensors for testing, adjustments, and maintenance. This practical consideration ensured the instrument could be debugged and refined without disassembling the garment.

All fasteners, clips, and attachment hardware for the vest were also 3D printed in PETG, creating a design where additive manufacturing served as the primary fabrication method throughout. The back of the vest is made up of a series of elastic straps that attach to a central plate, upon which the Bela system and all input/output jacks are located, and the slides at the shoulders and sides, as well as the back buckles, are also 3D printed. This meant that instead of the design being led by the available hardware, we could simply print what we needed according to our technical and aesthetic needs.

3.3.2 Gloves. The glove substrates were integrated differently than the vest. Each palm substrate was sandwiched between two pieces of leather that covered the palm. These leather pieces loop around the middle two fingers and are held in place by elastic overlays, providing compression to keep the sensor assemblage stable against the hand while allowing the glove to flex naturally during movement.

The glove design had to balance sensor stability with hand mobility. The elastic compression system ensures consistent sensor contact with the palm without restricting finger movement or making the gloves uncomfortable for extended wear.

3.3.3 Cable management. We paid special attention to how the cables were integrated into this garment, to ensure that they were not only functional but also aesthetically integrated.

Figure 5: Substrates with sensors. Vest substrate (top), glove substrate (bottom).

Paracord was chosen for its lightweight durability and its ability to visually align the instrument with the artist's nature-based metaphors. We developed a braiding technique that made the cables resemble vines. Every part of the cabling was resolved in colour and material: not only was all cable braided to be entirely integrated, but we also wove sheaths for the audio adapters connecting to the Bela Mini, and sewed the audio jacks to the back plate using colour-integrated embroidery floss (see Figure 6). In this way the aesthetics of this instrument are entirely driven by the artistic concept and values of the artist, rather than being shaped by the component parts of its technology.

3.4 Electronics and Signal Processing

Each of the three groups of sensors (vest, left glove, right glove) are connected in three independent, parallel networks. This is to ensure robustness as well as to amplify the signal generated by each strike. The signal from each network is connected to a Bela Mini embedded audio processing system with a Multichannel Expander mounted on the back. The system architecture organises signals into three independent channels: chest (combining both substrate pieces), left hand, and right hand. This three-channel approach gives the artist clear spatial zones for mapping and composition.

The Bela Mini system processes and analyses the raw piezo signals in real time using custom software written in C++. After processing and analysis it outputs 3 channels of processed audio, as well as three channels of MIDI velocity data (6 channels in total). This pairing of MIDI and audio data provides flexibility in how the artist maps the instrument's data to sound. The audio channels can be used directly or processed further, while the MIDI velocity streams can trigger samples, control synthesis parameters, or drive other musical processes. Kariūki maps these data streams to her compositional system (typically a DAW such as Ableton Live) in whatever way is relevant, using all of them or only a subset. This allows her to design the instrument's sonic response for each piece she composes.

This architecture exemplifies our design philosophy of providing flexible infrastructure rather than predetermined musical

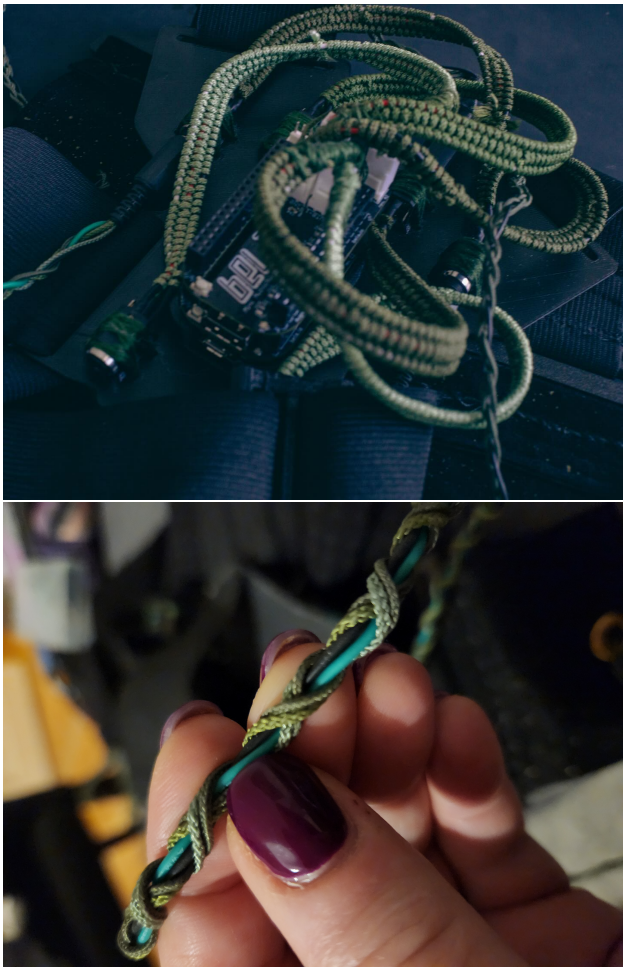

Figure 6: Detail of integrated cables.
Top: Audio connectors woven with paracord.
Bottom: Braiding technique for cables connecting the gloves to the system.

responses. The instrument captures expressive gestural data, but Kariũki retains full creative control over how and when that data becomes sound.

4 Outcomes and Discussion

Body, Bend was performed in 2025, notably at Sonic Territories and Stroom den Haag (Figure 7)[1]. It proved robust, needing only occasional servicing. A revised version is currently in development to improve stability further.

4.1 Substrate Design Evolution

The development of the TPU substrate involved significant iteration. Our initial assumption was that sensors needed to sit within moulded depressions in the substrate to maintain stable positioning. However, testing revealed this approach to be unnecessarily complex and difficult to assemble. The final design, for which the substrate material behind each sensor was cut away and the sensors were secured with adhesive tape, proved simpler to fabricate while maintaining sensor stability. This discovery demonstrates the value of rapid prototyping and testing over theoretical design optimisation.

The use of printing brims as sewing interfaces emerged as an unexpected but critical innovation. This technique repurposes a 3D printing feature that's typically purely structural and later discarded, and transforms it into a functional garment interface. The ultra-thin border provides sufficient material for secure stitching without compromising the substrate's flexibility or adding bulk to the garment. This approach may have applications beyond this specific instrument, offering a general strategy for integrating 3D-printed components into textile construction.

[1]Sonic Territories performance: https://youtu.be/R1ZOAal1fxw?si=9auChPoGdBVw8f1-

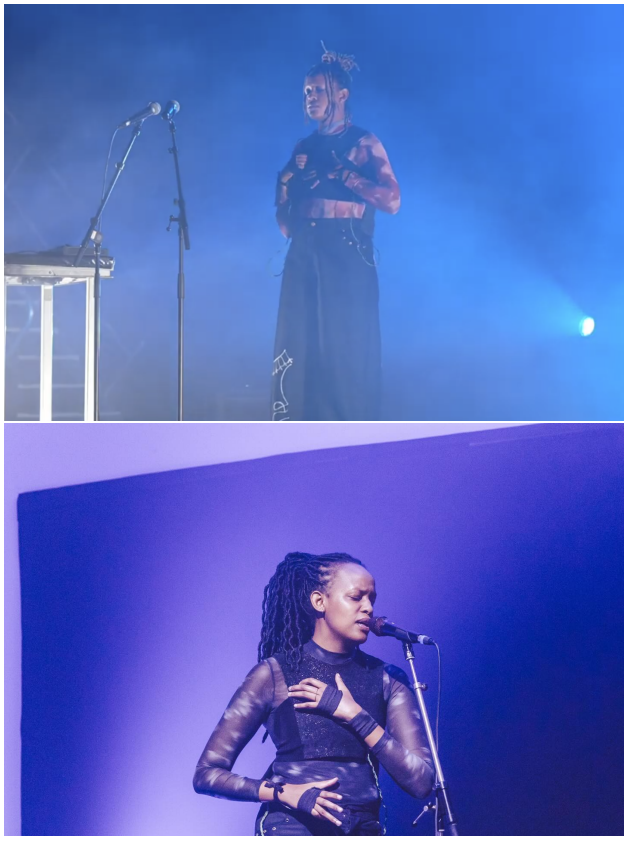

Figure 7: Kariũki performing Body, Bend.
Top: Sonic Territories Festival in Vienna, October 2025
Bottom: Stroom den Haag in The Hague, December 2025

4.1.1 Body as Instrument: Topology and sonic character. The interaction between the vest substrate and body topology revealed an important characteristic of body-worn instruments. Sensors positioned over the sternum sit close against the body due to the relatively flat bone structure, producing consistent, immediate response to strikes. In contrast, sensors positioned higher on the chest over the clavicles have greater distance from the skin, creating a looser mechanical coupling. This results in a transient response with different sonic character when these areas are struck.

Rather than viewing this variation as a flaw requiring correction, we recognize it as an intrinsic feature of the instrument. The body's anatomical topology, which will be unique to each performer, becomes part of the instrument's sonic identity. This challenges assumptions in sensor design that prioritize uniformity and consistency across all sensing locations. For body-worn instruments, the body itself contributes to the instrument's character: its curves, bones, and soft tissues shape how sensors respond, and therefore how the instrument sounds.

This finding has implications for how we conceptualize wearable instruments. Rather than attempting to create neutral sensing surfaces that erase bodily variation, designers might instead embrace body topology as a sonic resource, mapping different body regions to distinct musical functions based on their mechanical and acoustic properties.

4.2 The Unfinished Instrument

A significant insight from this collaboration is what we term the 'unfinished instrument' design approach. Rather than determining the instrument's sonic output in advance or designing for some pre-determined 'need', we created a system that provides rich data streams (three channels each of audio and MIDI velocity), which the artist in turn maps to musical processes within her chosen setup, according to her specific compositional needs. The instrument captures gestural and percussive information, but the transformation of that data into sound remains under the artist's control and can be changed, remade, or updated at any time.

This design philosophy recognises that musicians complete the instrument by using it, and may complete it over and over in new ways. We maintain that musical instruments should offer interesting performative affordances while leaving room for artistic interpretation. This has always been the case: a violin provides certain physical constraints and sonic possibilities, but players develop their own techniques, sounds, and vocabularies within that framework. Similarly, this wearable provides stable, expressive sensing infrastructure that supports an expanding set of musical explorations rather than pre-determining its scope.

This approach contrasts with instrument designs that embed specific synthesis algorithms or predetermined sound mappings. While such designs may produce impressive demonstrations, they risk constraining artistic practice to the designer's imagination. By providing flexible data streams that the artist can route and map freely, we enable ongoing creative development. Kariũki continues to discover new compositional possibilities as

she works with the instrument, and the design supports rather than limits her exploration.

4.3 From Technical Management to Artistic Freedom

Kariũki's experience with the earlier iteration where sensors were taped to her hands illustrates a persistent challenge in wearable instrument design: technology that demands constant attention. The performer's focus divided between musical expression and technical management, compromising both stage presence and creative exploration.

The TPU substrate approach resolves this by making technology functionally invisible. Sensors maintain stable positions without adjustment; electronics integrate seamlessly into the garment. Kariũki can rehearse with confidence, explore subtle variations in touch and dynamics, and develop sophisticated techniques without worrying about sensor failure.

This shift also enables aesthetic freedom. Material selection, colour, form, and finish respond to artistic and cultural considerations rather than technical constraints. Kariũki's input on leather, colour, and finish shaped the instrument to align with her performance practice and cultural context. For practice-based instrument research, this aesthetic integration represents a significant advance: instruments can carry cultural meaning and visual identity alongside functional performance.

4.4 Practice-Based Research Implications

This project demonstrates a methodological approach that centres artistic practice alongside technical innovation. Rather than validating the instrument through controlled studies, we position Kariũki's creative engagement and reflections as primary evidence of success. Her ongoing compositional work and upcoming performances represent validation through use – the ultimate test for any musical instrument.

This acknowledges that musical instruments exist within networks of artistic practice, cultural meaning, embodied skill, and aesthetic expression. Some qualities, such as feel, creative potential, cultural fit, resist quantification but remain essential. The collaboration between designer and musician demonstrates this: technical decisions served artistic and aesthetic goals, producing an instrument that functions technically while operating successfully within Kariũki's cultural and artistic context.

5 Conclusion

This work contributes a fabrication technique that resolves long-standing challenges in wearable instrument design. The 3D-printed TPU substrate provides stable sensor mounting within soft, body-conforming garments, shifting electronic sensing from technical obstacle to reliable infrastructure. At $0.30 per substrate using consumer-grade equipment, this demonstrates accessible technologies can enable practice-based instrument development.

By resolving the soft-rigid paradox through 3D-printed TPU substrates, this project demonstrates how fabrication innovation can shift technology from a 'foreground constraint' to 'background infrastructure'. This transition allows the technology to become transparent, and the performer's focus remains on musical expression rather than technical negotiation. The 'unfinished' instrument philosophy, implemented here via flexible data streams, ensures that this infrastructure remains an open site for artistic agency. This approach allows the instrument to be 'completed' through compositional mapping that is rooted in the artist's cultural practice. Ultimately, the Body, Bend instrument offers a model for wearable DMIs that are technically reliable, culturally grounded, and aesthetically integrated into performance practice.

Through technologist–artist collaboration grounded in Kenyan body percussion traditions, this project demonstrates technical innovation and cultural specificity can productively inform each other. The result is a reliable instrument that carries aesthetic and cultural meaning, supporting artistic practice that honours its roots while exploring new technological possibilities.

6 Ethical Standards

This research was funded in part by the Austrian Science Fund (FWF) [10.55776/AR743]. No human subject or animal research was carried out in the context of this research, and this work presents no conflicts of interest.

Acknowledgments

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