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Citation for the original published paper (version of record):
Kilic Afsar, O., Luft, Y., Cotton, K. et al (2023). Corseto: A Kinesthetic Garment for Designing, Composing for, and Experiencing an
Intersubjective Haptic Voice. Conference on Human Factors in Computing Systems - Proceedings.
http://dx.doi.org/10.1145/3544548.3581294

Corsetto

A Kinesthetic Garment for Designing, Composing for, and Experiencing an Intersubjective Haptic Voice

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Figure 1: Corsetto garments in use during a live immersive opera performance rehearsal with six audience members.

ABSTRACT

We present a novel intercorporeal experience – an *intersubjective haptic voice*. Through an autobiographical design inquiry, based on singing techniques from the classical opera tradition, we created *Corsetto*, a kinesthetic garment for transferring somatic reminiscents of vocal experience from an expert singer to a listener. We then composed haptic gestures enacted in the Corsetto, emulating upper-body movements of the live singer performing a piece by Morton Feldman named *Three Voices*. The gestures in the Corsetto added a haptics-based 'fourth voice' to the immersive opera performance. Finally, we invited audiences who were asked to wear Corsetto during live performances. Afterwards they engaged in micro-phenomenological interviews. The analysis revealed how the Corsetto managed to bridge inner and outer bodily sensations, creating a feeling of a shared intercorporeal experience, dissolving boundaries between listener, singer and performance. We propose that 'intersubjective haptics' can be a generative medium not only

CHI '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9421-5/23/04.
https://doi.org/10.1145/3544548.3581294

for singing performances, but other possible intersubjective experiences.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI); Interaction design** → Interface design prototyping; • **Haptic devices**;

KEYWORDS

Robotic textiles, shape changing interfaces, haptics, machine learning, voice, somaesthetic interaction design, micro-phenomenology

ACM Reference Format:
Ozgun Kilic Afsar, Yoav Luft, Kelsey Cotton, Ekaterina R. Stepanova, Claudia Núñez-Pacheco, Rebecca Kleinberger, Fehmi Ben Abdesslem, Hiroshi Ishii, and Kristina Höök. 2023. Corsetto: A Kinesthetic Garment for Designing, Composing for, and Experiencing an Intersubjective Haptic Voice. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23), April 23–28, 2023, Hamburg, Germany*. ACM, New York, NY, USA, 23 pages. https://doi.org/10.1145/3544548.3581294

1 INTRODUCTION

Within the Human-Computer Interaction (HCI) community, we have seen the adoption of novel actuated materials and interfaces for experiences pertaining to our tactile apparatus [3, 13, 16, 46, 51, 61, 73]. Much progress has been made in devising experiences involving digital touch for mediating interpersonal interactions [5, 8, 28, 30, 33, 36, 45, 74, 79, 81, 83, 121]. A wide repertory of sensations such as vibration [9, 11, 53, 114, 126, 128], texture [49, 87, 88], pressure [10, 17], weight [31, 82], temperature shifts [29, 69, 73, 89, 90, 98], pain [47, 59], itching [94], tingling [4], and wetness [32] have been enabled. When integrated with other senses, these sensations have been used to mimic pre-existing human-human interaction, such as kissing [105], holding hands [28], or hugging [8]. There are also alternatives aiming to go beyond mimicking by exploring unusual experiences these novel technological materials afford, with an aim to produce new bodily knowledge and new understandings through touch [12, 50, 67, 100]. In both cases, whether mimicking human-human touch or aiming to go beyond those, there are very few phenomenological accounts of what those interactions *feel* like.

Our work originates in bodily-vocal experiences as felt from the inside by a professional singer, but our aim is not solely to mirror her movements while singing. Instead, we seek to understand and communicate the inside perspective of human vocality [120], whilst thriving off the affordances of the on-body haptic materials to add to the aesthetic experience. Driven by this vision, our endeavour connects a wide range of fields from robotic textiles, to pneumatic system design, system architecture, machine learning, musical composition and performance. Through this holistic technological and artistic development, we aim to share insights for the various expertise at the core of such a collaborative project including designers, creative technologists, composers, vocal performers, movement connoisseurs, educators, and audience members.

Our bodily experiences are unique, coloured by our past lived experiences, making it challenging to fully understand the sensations and perceptions of others [19, 20, 35, 39, 42, 102, 131]. In fact, it is often difficult to describe or understand even our own bodily experiences and knowledge as they are habitual, hard to discern and tacit to us. Singing presents an intriguing model of interaction to study as the singing body experience is rooted both in covert internal muscular processes and at the same time the outer expressions generated are heard by both the singer and listeners [120]. The outer expression – the auditive, proprioceptive, motional, aesthetic, and intentional singing – constitute a profound intercorporeal communication. To shed light on how to design and understand this communication between the singing and listening bodies, we employ the lens of *intercorporeality*, a notion introduced by French phenomenological philosopher Merleau-Ponty. Intercorporeality captures how we explore and exploit the affordances of 'the other' through our 'own' bodily experience in the process of social understanding emerging from the entanglement between our bodies [22, 77, 78, 132]. We argue that interactive technologies may let us experience such intercorporealities in novel ways [86].

To show what those possibilities might entail, we embarked on a design journey to create an *intersubjective haptic voice.* When we listen to someone singing, it becomes *a dynamic felt experience* of a *resonance* of sorts between bodies. In particular, when professional vocalists listen to one-another, they resonate or vibe with the muscle movements of the singer. They feel the muscular movements, tensions and engagements of the singer through listening to the sound produced, interpreting what movements will have had to take place in order to create the singing. We saw an opportunity to learn and thrive off the richness of professional vocalists' aesthetic appreciation of listening and their ability to resonate with another singer. We wanted to create mediating technology that would let audience participants share more of such 'resonance' experiences, feeling the movements of the singing body unfolding in synchrony with the sounds heard. Our aim was to express some of the qualities and movements embedded in the singing body – the vocal gestures – translated into haptic gestures worn on the torso of the listening body. The gestures in the haptic wearable we created thereby added a new aesthetic dimension to the experience of the performance. It became a voice of its own, sometimes resonating with sounds produced by the singer, sometimes adding an entirely different voice singing with, or against, the singer. This intersubjective haptic voice fostered a novel form of intersubjectivity between singer and audience: bridging inner and outer experiences in the listening body; traversing the subject-object divide; and adding novel ways of aesthetically experiencing and appreciating the other.

In here, we describe how we designed this intersubjective haptic voice experience through detailing three different stages of the design process. In the first stage, we grounded our design work in a professional opera singer's (Singer K.) knowledge of what corporeal processes are involved in producing 'singing'. Through repeatedly engaging with her first-person experiences, we attempted to share and create meaning through feeling what she feels when singing. This led to designing and building a high-fidelity kinesthetic wearable platform, Corsetto, able to materially emulate and viscerally communicate the nuances of a singing body. The Corsetto platform consists of hardware and software enabling orchestration of movements in a robotic garment using air-driven artificial muscles [52]. As singing is produced by an active subject, intentionally activating muscles and shaping aesthetic expression from the 'inside-out', we instead aimed to express some of the qualities and movements embedded in her singing body –her vocal gestures– into haptic gestures enacted from the 'outside-in' on the listening body. We provide details of our design process in order to let the learnings from devising the garment to provide insights for other designers and creative technologists who wish to explore technologies for intercorporeal, intersubjective experiences.

In the second stage of our project, we configured our system design for a live immersive opera case study based on a haptic variation of American composer Morton Feldman's musical composition *Three Voices* [130]. To provide some context to why this particular piece fascinated us, let us provide a brief account of Feldman's artistic intent. In a homage to two recently passed close friends, Feldman composed the vocal piece *Three Voices.* It is written for three vocal parts, traditionally performed by one single female vocalist. The vocalist first records herself singing two vocal lines, and sings the third voice live alongside the two pre-recordings playing through loudspeakers placed on her sides (Figure 2a-b), hence the three voices. The phenomenological experience of performing the piece becomes one of 'singing with and against one's self'. Musically, Feldman utilises extensive voice crossings[1], closely set intervallic differences between voices and microtonal beatings[2] to create the effect of swirling, physical sound bodies in the air. These 'sound bodies' appealed to us as a design team. We wanted to build on and possibly extend on those sound bodies to achieve even stronger intersubjective bodily experiences of the performance. Singer K composed a shortened haptics-based interpretation harmonising with the original artistic intent behind the *Three Voices* piece. Each gesture of the Corsetto score is triggered by the live singer's vocal performance generating a *Fourth Voice* accompaniment to the other three voices in the piece.

Finally, in the third stage of our project, we staged two immersive opera performances where the audience members wore the Corsetto (see Figure 1). After each performance, we probed audience experiences in micro-phenomenological interviews. As we will detail below, we found that the experience with the Corsetto: (i) at most fundamental level supported somatic materialisation of the voices in the performance; (ii) which in-turn allowed for kinaesthetic sharing of signer's experience or to form a dialogue with an artificial other; (iii) at times this dialogic subject-object divide was overcome in a fused experience of blurred boundaries and connecting inner and outer soma experience, (iv) which suspended time and space and (v) provided a sense of *wearing* the vocal expressions and the whole performance; – harmonising with the artistic intentions of Morten Feldman.

Our contribution forms a unique haptics-based intercorporeal experience crafted around a multimodal robotic corset. To deepen our understanding of this experience, we draw upon Merleau-Ponty's conception of intercorporeality. We conclude by discussing how 'intersubjective haptics' can be a generative medium not only for singing performances, but other possible intersubjective experiences in emerging research across Human-Computer Interaction (HCI) and Human-Robot Interaction (HRI).

2 RELATED WORK

We provide a background to the concept of intercorporeality followed by the state of art in designs for vocal practice and upper-body haptics.

2.1 Kinesthetic Sharing and Intercorporeality

Our bodies are the site of all our experiences, carrying our embodied knowledge [133] and giving rise to our affective experiences and emotions [15]. This way, to achieve intersubjectivity or a shared understanding between people, including primordial empathy, we need to consider the extent to which they can share their bodily and kinesthetic experiences. Specifically, the embodied cognition perspective on social cognition suggests that connection, intersubjectivity, and interaffectivity are achieved through a harmonic alignment of bodily states [118]. When our bodily states and movements are matched, this also blurs the distinction between self and other, as what we see in others, we also feel in ourselves [64, 116].

Intersubjectivity has spurred design ideas based on examining the act of proprioceiving someone else's movement through exploration of various sensory modalities. For instance, Françoise et al. [25] leverage continuous auditory feedback for cultivating kinesthetic awareness to reveal experiences of the other through a second-person inquiry [91]. In bioSync [83], Nishida et al. studied the kinesthetic blending of muscle contraction and joint stiffness [84] through paired wearable devices for enhancing understanding of Parkinson's patients' physical challenges in daily life. Several systems aim to elicit kinesthetic sharing by encouraging movement or breathing synchronisation between participants [44, 104, 113]. Researchers argue that kinesthetic sharing may also manifest at a more internal level without external movements, through the seen [80, 103, 119, 127] or heard [56, 57] movements of others which induces mirror neuron activity in the premotor cortex, typically associated with empathic process [43]. Another approach explored for eliciting embodied empathy through technology is reinstantiating some of the conditions of the embodied experience, e.g. by placing participants in a similar body position [60], or through actuating similar somatic experience onto them [86]. These approaches using kinesthetic sharing to achieve somatic intersubjectivity tend to view intersubjectivity as manifested in the mirroring of bodily states, and is situated inside one person, who is experiencing something reminiscent of what another has experienced.

Moving beyond mirroring, in our design inquiries we explore *intercorporeality*, a notion that foregrounds the social nature of the body and at the same time the bodily and interactive nature of social relationships. Introduced by French phenomenological philosopher Maurice Merleau-Ponty [76], in his response to Edmund Husserl's discussion of empathy, intercorporeality describes the intertwined relationship of our compresent interacting bodies, forming an action-perception loop. This way, our intersubjective interactions can be understood as emerging in-between our acting bodies situated in a shared environment, and cannot be considered in isolation, situated in an individual's mind. Intercorporeality offers

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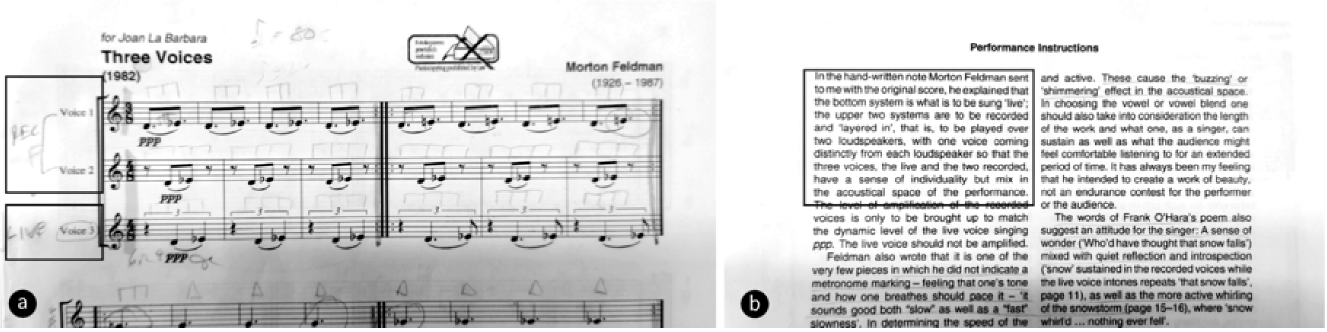
[1] The intersection of melodic lines in a composition. This can cause registral (i.e., where the pitch is located–high or low– within the musical notation) confusion and reduces the independence of the voices.

[2] A microtonal beating occurs when two pitches sounding simultaneously differ by small increments, creating a percussive sonic effect.



Performance Instructions

In the hand-written note Morton Feldman sent to me with the original score, he explained that the bottom system is what is to be sung 'live'; the upper two systems are to be recorded and 'layered in', that is, to be played over two loudspeakers, with one voice coming distinctly from each loudspeaker so that the three voices, the live and the two recorded, have a sense of individuality but mix in the acoustical space of the performance. The level of amplification of the recorded voices is only to be brought up to match the dynamic level of the live voice singing *ppp*. The live voice should not be amplified.

Feldman also wrote that it is one of the very few pieces in which he did not indicate a metronome marking – feeling that one's tone and how one breathes should pace it – 'it sounds good both "slow" as well as a "fast" slowness'. In determining the speed of the and active. These cause the 'buzzing' or 'shimmering' effect in the acoustical space. In choosing the vowel or vowel blend one should also take into consideration the length of the work and what one, as a singer, can sustain as well as what the audience might feel comfortable listening to for an extended period of time. It has always been my feeling that he intended to create a work of beauty, not an endurance contest for the performer or the audience.

The words of Frank O'Hara's poem also suggest an attitude for the singer: A sense of wonder ('Who'd have thought that snow falls') mixed with quiet reflection and introspection ('snow' sustained in the recorded voices while the live voice intones repeats 'that snow falls', page 11), as well as the more active whirling of the snowstorm (page 15–16), where 'snow whirl'd ... nothing ever fell'.

Figure 2: Singer K's annotated score (a) illustrating differentiation between the live sung voice–Voice 3–and the 2 pre-recorded voices–Voice 1 and 2; (b) Performance instructions from Joan La Barbara, included in the *Three Voices* vocal score.

an alternative dynamic soma-centric explanation of the emergence of intersubjective experience to traditional cognitivist paradigms, such as Theory of Mind and Simulation Theory. Embracing intercorporeal explanation means understanding intersubjectivity as an experience and as an interaction encompassing all acting bodies in space, rather than a model or simulation constructed in one's mind [26, 118]. This way, intersubjectivity is enacted through movement and perception loop, where the boundary between subject and object is dissolved as they are joined in a unified singular experience of an interaction of the intersubjective act. This also frames intersubjectivity not as a mere mirroring of one's state inside the other person, but as an interaction, as something generative emerging in-between all the interacting bodies. Recently, researchers have used intercorporeality as a theoretical device to access subjective experiences in various movement contexts such as dance and choreography [22], close-range Human-Drone interaction [63], as well as movement pedagogy in sports [122].

2.2 Designing for Vocal Support and Expression

An integral component in developing an understanding of the somatic nuances of singing we wished to convey to other bodies was to hone our understanding of how the act of singing occurs within the body, and affects our breathing, and whole body. Singing is a profoundly somatic skill demanding a nuanced understanding of one's physicality, an artistic or creative sensibility in making music, and a sharing of one's inner expressive self [75]. Vocal training – regardless of the musical genre or style in question – is typically focused on the training of micro coordination skills [115] such as regulating the air pressure system, manipulating resonance chambers, and often involving a relearning process of otherwise habitual or unconscious physical actions such as breathing and posture [99]. For expert musicians, this process of relearning builds on non-rote[3] effortful and deliberate practice [21, 62], like how athletes build movement connoisseurship through reflective and intelligent practice [2, 134].

Identifying the complexities of using language as a device to 'teach the body in the body's own language', existing work in HCI has sought to facilitate more haptic translations in the somatic sense-making process. Recent examples of work in designing for the singing body have examined the building and navigation of movement connoisseurship through tactile clues [55] or visualisation thereof [54], as well as greater awareness of the laryngeal area [100, 101] through engagement with biosensing technologies, such as electromyography. Additional work has examined topographical change in the torso as a consequence of a singing-oriented breathing practice, utilising novel sensing systems [12]

2.3 Actuated Upper Body Wearables

Compared to extremities such as our limbs, the torso remains a less explored area of the human upper body for wearable haptic input and output. Among these, the majority of haptic systems employ vibrotactile feedback mechanisms. Optohapt [27], a haptic instrument developed by Geldard in 1966, transmutes printed characters on a typewriter to cutaneous patterns using nine vibrating actuators spread across the body. EmoJacket [1] and tactile jacket by Philips Research [65] are haptic garments that employ embedded vibrotactile arrays for enhancing immersive experience and emotional arousal while watching a movie. Other approaches include turning to music to express the dimensions of tactile experience. Synesthesia Suit [58] utilises 24-channel voice coil actuators on a full-body suit for immersive experiences in virtual reality (VR). An interaction mode researchers explored with the suit is synaesthesia between music and full-body haptics by mapping tones from musical instruments on different body parts. In MusicJacket [68] a motion capture system combined with vibrotactile feedback is explored in supporting posture and bowing technique for novice violin players. These works seek to replicate the familiar qualities of human-like touch, leaving possible novel experiences using the distinct qualities of the technology under-explored.

More recently, electrical muscle stimulation (EMS) and transcutaneous electrical nerve stimulation (TENS) technologies have been implemented into haptic suits to actuate the upper body from the inside by leveraging application of electrical impulses to the user's muscles in order to involuntarily contract them [70, 72]. Tesla Suit [135] is a wearable motion capture and full body haptic system for VR that uses EMS and TENS to simulate a wide repository of sensations. Another EMS-based wearable is Owo Vest [136] which provides a sensations library for gaming applications and personal training.

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[3] A non-rote approach to learning constitutes spaced repetition, experimentation, and an active engagement in the learning process beyond just memorization.

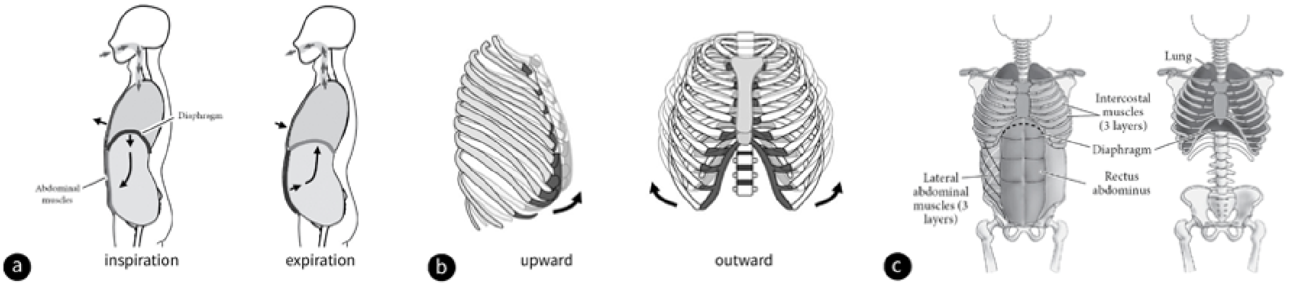

Figure 3: Respiratory physiology in singing [125]; (a) Diaphragmatic movements and the abdominal muscles during normal breathing. Arrows pointing towards and away from the chest indicate the actions of the internal and external intercostal muscles on the ribs; (b) The upward and outward movements of the ribs during inhalation; (c) Principal muscles of respiration (excludes accessory muscles of respiration).

A historically employed mechanism for kinesthetic wearables are rigid exoskeleton systems driven by servo motors. Most relevant to our work, Li and colleagues designed a haptic NIME[1] consisting of a spinal exoskeleton controlled by linear actuators to support posture during inhalation and an elastic belt to capture respiratory rate for vocal training [54].

Beyond the qualities that vibrotactile actuators, linear actuators and electrical muscle stimulation brings on the table, we are interested in other forms of actuation to help develop the repository of sensations that designers can employ. Due to the lightweight and high-power-density attributes of fluidic actuators, for many decades researchers utilised pneumatic and hydraulic transmission systems in applications such as upper body rehabilitation [124], deep touch pressure therapy [48], or generating novel touch experiences [50]. A relevant work in this direction, Force Jacket [17], elicits a rich repository of feel effects, and similar to our interface it combines tactile and kinesthetic feedback within a single design using an array of pneumatically actuated modules with embedded resistive sensors. Takahashi and colleagues' Sense-Roid Type-S [117] presents coupled record and playback wearable pneumatic vests where the actuating vest is made of interwoven artificial muscles and the sensing vest consists of air-filled balloons for sensing the upper body.

3 FIRST STAGE: DESIGNING THE CORSETTO

Adding a haptic layer to the communication between singing and listening bodies, using movement-gestures enacted on the torso, requires careful crafting in order to engage deeply with intercorporeal connections and meaning-making. Hence, we grounded our design explorations on Singer K.'s – a professional vocalist in classical, experimental and contemporary music, and free improvisation – corporeal movements when singing, repeatedly engaged with vocal exercises, aiming to understand and ascribe some of the aesthetic qualities of her expression into on-body haptic gestures throughout our design process.

3.1 Corsetto Design Methodology

Our design process was based on the soma design framework. Soma design [38, 41, 137] is a design stance grounded in theories of somaesthetics [110, 111]. In somaesthetic theories experience is framed as an act grounded in the *soma*—a non-dualistic subjective self (mind) and body. Somaesthetics takes a meliorative stance towards aesthetics, that is, aesthetics is seen as a skill that can be trained. Somaesthetics emphasises that aesthetic experience is not solely engaging with visual beauty, but instead our physiological and psychological capacity to appreciate the richness of the world in which we are situated through all our senses. It considers the lived experience of the body as the conduit and site of meaning-making [39], and views learned behavioural patterns or instinctive behaviours as dynamically adjustable in different situations—a form of intelligence in action [40, 108].

Soma design employs a range of methods to let designer's increase their somaesthetic sensibilities, letting them in turn stage and shape the aesthetic experience for the end-user. In our project, we used somatic connoisseurship, singing exercises to create somatic understanding for the whole team, as well as defamiliarisation methods.

3.1.1 Somatic Connoisseurship. A soma design method employed to enable kinesthetic learning and sharing is to invite a body practice expert to the design team. A somatic connoisseur [83] is an expert of some bodily practice, for example, a professional singer. Singer K. took this role in our project. She is a professional vocalist in classical, experimental and contemporary music, and free improvisation, and also a designer. Singer K.'s expression – a deeply human, shared, universal experience and at the same time specialised somatic expertise – and her somatic connoisseurship was the guiding light in our design work. She devised exercises that let the design team share some of her expertise – not through analysing, but through participating and sharing her practices, forming an intercorporeal understanding.

3.1.2 Singing Exercises Sessions. Through engaging in a total of seven exercise sessions[4] with Singer K. the whole design team gained an understanding of the biomechanical components of singing. Singer K. formulated the exercises around the various physiological phenomena she experiences during her singing of

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[4] These exercise sessions were formatted in a singing lesson style format, comprising a vocal warm-up, and followed by individual exercises developed specifically by Singer K. (included as exercise session schematics included in Supplementary material) to address the various compositional and sound phenomena present in Feldman's musical score.

Three Voices: microtonal beatings; resonant couplings between self and external space; and heightened internal awareness of bodily mechanisms such as contraction of external intercostals (Figure 3a), ribcage expansion and collapse (Figure 3b).

3.1.3 Defamiliarisation of Singing and Listening. One key exercise that informed our design approach was a defamiliarisation exercise [71]. Defamiliarisation is a strategy for making the habitual strange, thereby letting the tacit behaviours and, in this case, muscle movements come to the fore. In this exercise named *Singing Body Listening Body*, one person sings a short phrase while a second person places their hands or fingertips on different parts of the singer's body. The Listening Body wears noise-cancelling headphones during this exercise, and uses their sense of touch alone, near the larynx, to develop an embodied understanding of how the larynx of the Singing Body is vertically displaced during the singing of different pitches[4]. After three repetitions by the Singing Body, the Listening Body attempts to sing the phrase back, based on their touch-understanding of how the sung phrase felt.

Through this exercise we came to understand which parts of the singing body were most significant for the listening body to engage with in order to understand what they needed to sing back. That, in turn, helped us understand where certain kinesthetic motions occurred, as well as the shape or size of the somatic output the singing body produces when singing.

3.2 Choosing Corsetto's Technological Material

Based on the insights from these exercises, we started to devise pneumatically-activated 'modules' that could be placed on the different parts of the body employed in singing. We decided to work with pneumatics due to their well understood mechanics, intrinsic compliance with the human body, and attractive characteristics as actuators, such as high frequency response, high force-to-weight ratio, and large work density. We picked an emerging technology in soft robotic muscle fibers, OmniFiber [52] for their seamless integration into robotic garments due to their fiber-like geometry, as opposed to bulky pillow-like actuators that are often limited to provide more crude feedback [50]. Our design choice of this particular technology arises from both mechanical affordances of the material as well as how it matches the movement qualities of a singing body.

At an early stage, we dressed Singer K. in a simplified version of Corsetto that solely focuses on breathing as the movement material. This incarnation of the Corsetto consists of three modules that peristaltically[5] compressed and released her rectus abdominis and external intercostals (Figure 3c). She reported: "*...it feels very human. It has this firm softness that really feels like muscles shifting. It is such a curious feeling, organic and genius.*" She reflected on the curious sensation as connected with the granularity of the garment's movement: "*It moves like I do, with the same kind of strength, and range of motion... It's kind of magical, feeling this garment move as it does – this deeply human-like movement*". This human-like feel of the rich and nuanced movement of the soft robotic material afforded experiential qualities that intrigued us. They were reminiscent of intercorporeal interactions we may have between fine movements of our touching bodies, similar to those we had experienced through the *Singing Body Listening Body* exercises.

3.3 Corsetto Modular Garment Design and Fabrication

With a focus on breathing, spinal posture and sternum vibrations as core movement materials, the robotic garment constitutes soft mechanical artificial muscles to enact movement gestures on the listening body, much like Feldman's vocal gestures. To enable these soft actuation mechanisms within the same material system, we fabricated a 'haptic textile swatch' (Figure 4a) with different geometric integrations of OmniFibers into fabrics using embroidery machinery and techniques. Together the swatches enabled a rich repertory of soft mechanical stimulation such as vibrotactile feedback, lateral stretch (Figure 4, b1), compression (Figure 4, b2), and biaxial push and pull motions.

3.3.1 Garment Design Process. Informed by Singer. K's connoisseurship, we tested the swatches on different parts of the body: over the larynx, and the sternum, on the spine, around the ribcage (Figure 4c), and abdominals to approximate her somatic experience of singing. We found, for example, that wearing an actuator on the larynx was distressing. As laryngeal muscles are key to singing, we decided to avoid stimulating this area. Instead, we focused on breathing, spinal posture and sternum vibrations as the core movement materials.

Finally, based on a range of considerations, such as making the garment easy to put on and off, comfort, and ease of adjustability to different body shapes, our final garment design can be seen in Figure 7. The design came about after four iterations and testing the technology on 30 different bodies over the course of 12 months. In the end, we settled on six actuation primitives embodied in sheet fabric forms (Figure 5b) that were put together into the style of a singer's corset.

For custom positioning of the modules, we introduced twelve adjustment points with buckles and elastic cords for mechanical self-fitting (Figure 5a). Finally, we connected each control point in the corset to a pneumatic controller outlet port with polyurethane connection tubes for individual control (Figure 5e).

We developed a total of six Corsetto garments (Figure 1). Each consisted of two identical rib modules with three independent actuating elements on each side of the body that correspond to the intercostals (Figure 5, b4-b5), one abdominal module with two independent actuation elements that correspond to the rectus abdominis (Figure 5, b1), one lower back module with two independent actuating sections that correspond to the lateral muscles (Figure 5, b2), and a longitudinal spinal module for torso posture (Figure 5, b3), with six interconnected elements.

3.4 Corsetto System Architecture

To actuate the Corsetto Garment, not only did we need a way to program the pneumatics, but also a higher level 'haptic programming language' that would allow us to compose the haptic gestures in the Corsetto whilst allowing synchronisation with the vocal parts for the *Three Voices* piece. These haptic gestures needed to be triggered by the vocal gestures sung by singer K in a live performance. As

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[5] Peristaltic motion refers to a sequence of wave-like contractions and releases in a muscle.

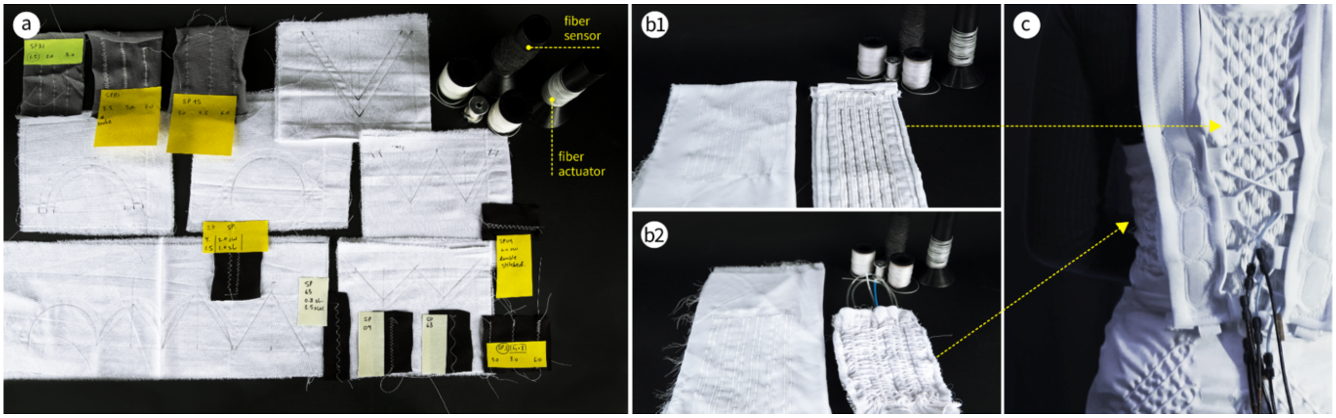

Figure 4: Haptic textile swatch (a) Embroidery patterns used to test different geometric configurations of actuating fibers within a textile; (b1) a fabric swatch that shows the embroidery patterned area without the actuator (left side) and the actuator-integrated embodiment (right side) providing a maximum strain of 25% by linear orientation of the fiber muscles; (b2) a second swatch with similar arrangement of unintegrated and actuator-integrated serpentine configuration, that provides maximum compression force output due to dense arrangement of the fiber muscles; (c) linear and serpentine swatches integrated into the final corset design.

Three Voices is a piece with different musical movements[6] featuring different vocal gestures, it would be redundant to pre-program the haptic gestures as one long sequence. It would also be hard to guarantee that such a long sequence of haptic gestures could be synchronous with Singer K.'s live voice. Instead, the haptic gestures needed to be triggered by the vocal gestures in real time. The haptic gestures also needed to convey the nerve of a live performance: the glitches, the small inhales, the organic feel, triggered by Singer K. singing live, thereby rendering a dynamic, haptic fourth voice.

We developed a system architecture (Figure 6) consisting of three main components: the soft robotic garment, a FlowIO-based [109] fluidic control platform with an auxiliary pressure regulator, and a software stack including most importantly, the Composer (Section 3.6). The FlowIO-platform is a miniature pneumatics development platform for control, actuation, and sensing of soft robots and programmable materials. The robotic garment has a modular construct comprising OmniFiber-based fluidic fabric muscle sheets. When the robotic garment is connected to an array of three FlowIO devices (Figure 5d), a range of haptic expressions are enabled with the orchestration of these modules enabled by the central controller software. The expressions range from minute tactile stimulations to powerful vestibular ones; such as sternum and rib cage (Figure 7b) vibrations, abdominal compression (Figure 7a), and spinal drift (Figure 7c) that prompts the body to sway.

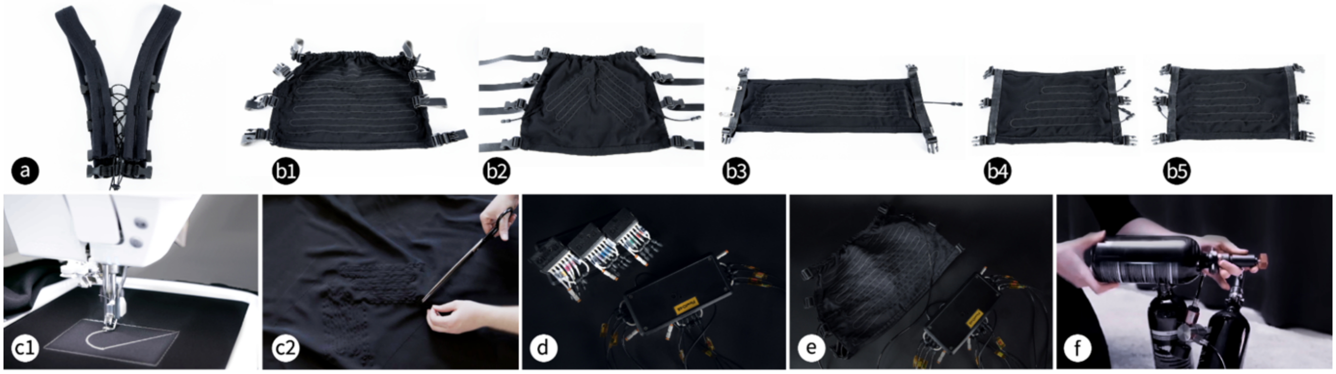

Figure 5: Corset design and fabrication pipeline; (a) Mechanical adjustments for body fitting; (b) Corsetto's final machine embroidered actuated modules (b1) abdominal; (b2) lower back; (b3) spinal; (b4) left rib; (b5) right rib; (c) Tailored fiber placement process; (c1) over-embroidery patterning of OmniFibers; (c2) bilayer fabric structure with embedded fiber actuators; (d) FlowIO module enclosure (e) Abdominal module connection to FlowIO ports 1&2; (f) FlowIO to serially connected compressed air tank integration.

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[6] A self-contained part of a musical composition or musical form.

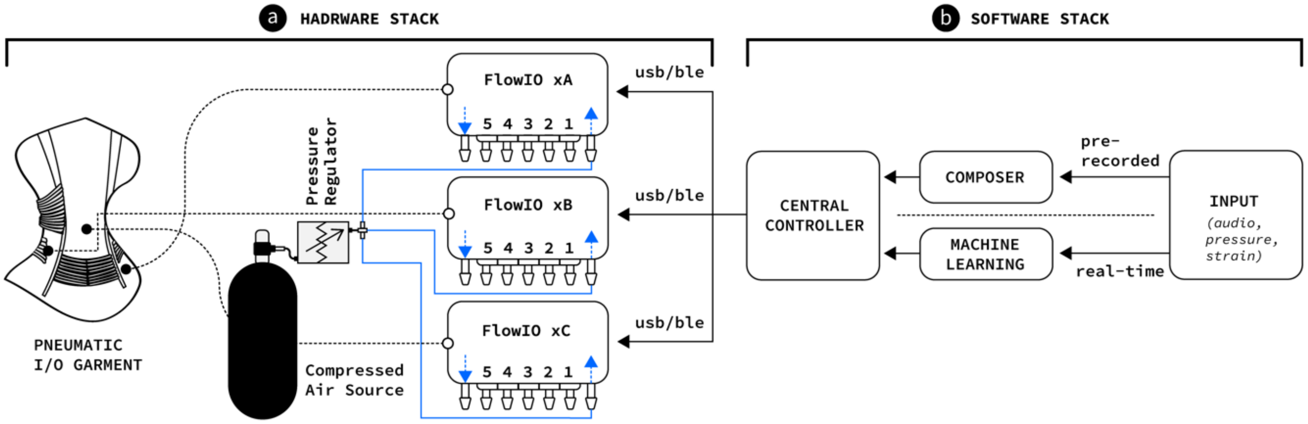

Figure 6: Corsetto system diagram; (a) Hardware stack; (b) Software stack.

3.5 Corsetto Hardware Stack

Corsetto's hardware is composed of several modular parts: the garment, three pneumatic controllers, a pneumatic pressure supply, and a pressure regulator (Figure 6a). A Corsetto garment is made of 12 actuators, grouped into sets of 4 where each group is controlled by a single FlowIO device. FlowIO is equipped with five control ports connected in a single manifold architecture, an air inlet, and an exhaust port, all of which are controlled by high-flow rate (11 LPM) electronically operated valves. Such flow-rate allows for rapid transitions and high frequency response up to 40 Hz which allows the embodiment of real-time quick haptic gestures – e.g., a rapid inhale – in the garment. Having a range of flow rates was significant in our design of a system to reflect the expressivity of Singer K's breathing during the performance. Her usage of quick inhales to blend seamlessly with the other two vocal lines was a nuance that we aimed to reflect in the affordances of Corsetto.

Further, a total of 12 out of the 15 control ports are connected to the actuators in the garment leaving a remaining port on each FlowIO. This port is employed as an additional pressure exhaust to accelerate the response time upon release of air pressure. The choice of attributing a secondary exhaust allowed us to achieve a larger range of exhaust rates to account for the varying expiration/inspiration rates of the singer.

By using serially connected pressurised air tanks (Figure 5f), capable of holding 1.5 L of compressed air at 200 bar pressure at room temperature, enabled silent actuation as opposed to using compressors, as well as enough air resource −35 minutes of continuous usage− following the requirements of the *Three Voices* piece. Finally, the tanks are connected to FlowIOs inlet valve via a manual or digital pressure regulator (Festo VEAA proportional pressure control valve, 0-10 bar), set to operate the actuators between 0 to 5 bars of air pressure enabling varying force feedback and actuation speeds.

3.6 Corsetto Software Stack

The software stack (Figure 6b) for the Corsetto platform does the work of communicating the garment, the FlowIO controllers and the pressure regulator. But most importantly, it offers a suite of tools for arranging compositions for the FlowIOs that we group under the name "*the Composer*". Compositions for the Corsetto can be done either directly or by parsing musical notation. These arrangements can then be saved, loaded, and sequenced together in order to create complex orchestration.

The detailed software stack in Figure 8 was developed iteratively and modularly. The two main modules are: (1) the FlowIO firmware [140] and (2) the central controller. The firmware is a

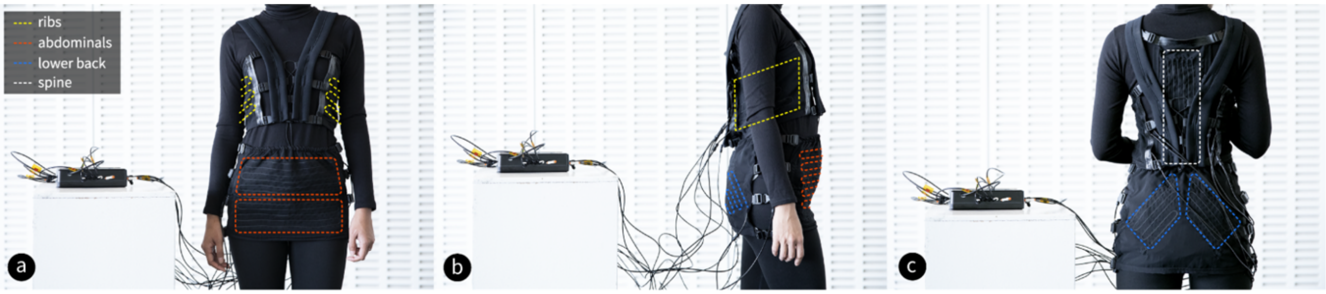

Figure 7: Corsetto hardware stack; (a) Corsetto garment front view demonstrating rib and abdominal modules; (b) side view demonstrating rib, abdominal, lower back modules; (c) back view demonstrating lower back and spinal modules; connected to three FlowIOs.

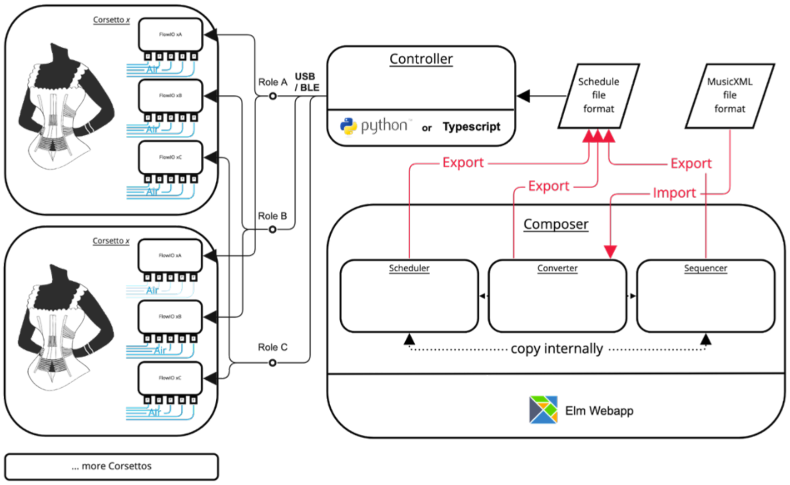

Figure 8: Corsetto software stack consisting the firmware, a central controller and the composer suite.

piece of software running on each FlowIO device, and is in charge of receiving commands from the central controller and operating the valves and the pressure regulator on the FlowIO accordingly, as well as sending telemetrics, such as the battery level. The controller is a program that runs on a laptop and is capable of controlling and orchestrating multiple FlowIOs simultaneously. We describe the two components of the software stack and the Composer in their latest incarnation.

3.6.1 Firmware and Central Controller. The firmware, composer and controller components were programmed using different programming languages and stacks: the firmware was programmed using C++ and the Arduino software stack, the composer was programmed using the Elm programming language, and the central controller uses Python. A detailed account of the software system is given in Appendix I.

FlowIO comes with low-energy Bluetooth (BLE) based communication protocol which was used in early explorations of the material, but was superseded by our own firmware utilising serial communications over USB. USB was chosen for its low-latency and its support for a large number of devices concurrently when using a USB hub, to support the 18 FlowIO devices for 6 Corsettos.

3.6.2 The Composer. The Composer suite is an arrangement of three separate tools (Figure 8): (1) the ***Scheduler*** (Figure 8a) that allows the creation of scheduled instructions to be enacted all six FlowIOs simultaneously to run the haptic gestures in the six Corsetto garments; (2) the ***Converter*** (Figure 8b) that supports converting MusicXML files adorned with haptic scores (further explained in Section 4.1) into schedules; and, finally, (3) the ***Sequencer*** (Figure 8c) lets us sequence several smaller schedules into more complex, whole compositions.

The *Scheduler* (Figure 9a) uses FlowIOs native message format to schedule a sequence of primitive instructions, controlling which valves are to be opened or closed, as well as operating pumps or a flow regulator, at times given in milliseconds since the sequence's onset.

The *Converter* (Figure 9b) tool converts sheet music (in the open standard MusicXML format) into schedules compatible with FlowIOs native protocol. Singer K found it more straightforward to compose haptic gestures for the Corsetto, by treating the system as if it was a musical instrument, using conventional sheet music notation. To turn a sheet of music into a haptic score, the sheet music is loaded into the converter and parsed. The user/composer is asked to associate each 'instrument' with a FlowIO role and a FlowIO port, and specify how dynamics are to be converted to pump or regulator controls. Then, the user selects the beats per minute (BPM) value for this sheet music which is used to determine the start time of every instruction.

The *Sequencer* (Figure 9c) tool enables sequencing several smaller schedules into a larger composition. It was created after realising that even a short sequence of 45 seconds can contain thousands of haptic instructions. Dissecting larger sequences into smaller ones allows us to manually sequence these individual gestures that were composed by Singer K into a complete haptic composition. The roles are also displayed in the Sequencer, so the user can see which devices are needed in each part of the haptic piece. As with the Scheduler and the Converter, the complete sequence can be saved as a JSON file, using a format similar to that of the Scheduler.

Finally, based on a range of considerations, such as making the garment easy to put on and off, comfort, and ease of adjustability to different body shapes, our final garment design can be seen in Figure 7. The design came about after four iterations and testing the technology on 30 different bodies over the course of 12 months. In the end, we settled on six actuation primitives embodied in sheet fabric forms (Figure 5b) that were put together into the style of a singer's corset.

4 SECOND STAGE: CREATING HAPTIC SCORES

Once the Corsetto took shape, our next step was to devise a notational system for haptic gestures for our labelled vocal gestures (see Section 3.7). These haptic gestures were composed to reflect

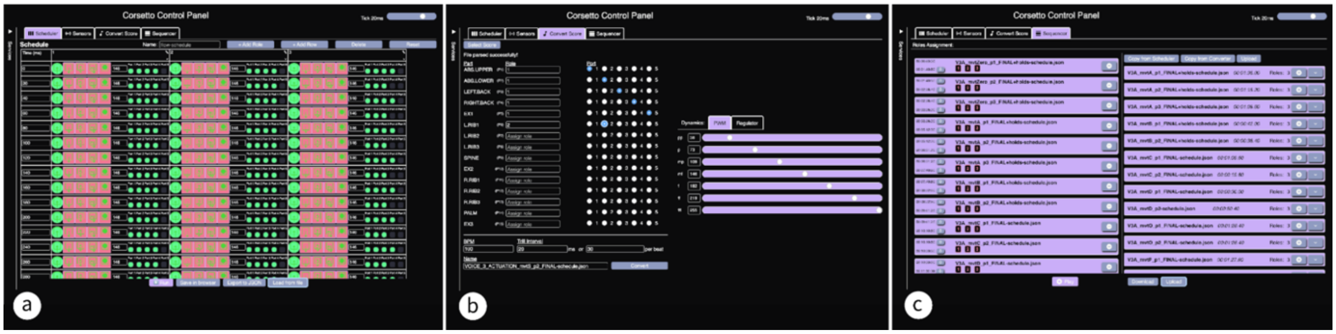

Figure 9: Corsetto Composer suite: (a) The Scheduler; (b) The Converter; (c) The Sequencer.

not only the somatic experience of singing of one of the three vocal lines[7] in Three Voices, but also consider the collective sound-world created by the experience of listening to all three singing voices together. The specific phenomena we wished to convey through the haptic gestures was an interpretation of Singer K's somatic movements when singing; her re-feeling of her body when singing with and against her pre-recorded voices, but also the microtonal beatings which were a key musical feature of the Three Voices music. As mentioned earlier, these microtonal beatings form swirling 'sound bodies' in the air, creating a sensation of a physical, touchable body of sound. (We believe the reader would be helped by listening to a recording of the Three Voices [130] before reading further.)

Singer K. conducted the creation of haptic score, utilising her dual perspective as a singer-composer, and as a performer within the work – singing polyphonically with the two pre-recorded versions of herself. As a composer, Singer K. approached the haptic score composition by examining how to somatically convey the sonic experience of listening to all three voices together, from the audience perspective. Hereof, we considered aspects such as the spatiality of where sound was experienced on a listener's body. Singer K's perspective as a listener – in her polyphonic singing with the other two pre-recorded voices of herself – is incorporated into a haptic *Fourth Voice.* In sections of the piece, there are many instances of conflicting time signatures, polyrhythms, contrasting texts, and tightly composed harmonies which alternatively merge and juxtapose the other two notated voices. The experience of being in-and-out of phase both rhythmically and harmonically was incorporated into this *Fourth Voice.* Singer K.'s experience of singing *against* the other versions of herself –the other two vocal parts– became incorporated into this haptic *Fourth Voice* through the experience of the microtonal beatings the singer was performing live against the two other voices, and the swirling sound bodies in the air. Consequently, the *Fourth Voice* became in effect a harmonic haptic reduction of all three voices, creating a new 'voice' that moved in- and out-of-phase with all three voices throughout the course of the vocal quartet. Given the complexity of the musical piece, we resorted to machine learning to automate part of the process of haptic scoring which mainly enabled breaking down complex vocal phrases to smaller voice samples – microstructures – as detailed below.

4.1 Corsetto Machine Learning for Vocal Gesture Recognition

To establish a less tedious workflow of haptic scoring to finally arrive at whole compositions, we explored a machine learning approach. We aimed to both support the composition process, and automate the translation of vocal gestures into haptic gestures in real time during the live performance.

To achieve this, Singer K. prepared 3,045 voice samples based on her recordings of voices 1 and 2 (the pre-recorded voices) and labelled them resulting in125 distinct vocal gestures. The labels represent complimentary haptic gestures based on musical and thematic components of Feldman's score, thus capturing a systematic breakdown of the entire score based on these microstructures: *static, sliding, refracted gesture, spatialised body, melismatic, swirling, discordant, harmonic, syncopated/polyrhythmic* and *unison* (see Table 1). For refracted, spatialised, and syncopated/ polyrhythmic, the expression labels refer to a transformation of the original vocal gesture (i.e., if it is longer, shorter, in a different time signature, transposed up or down, etc). On occasions where this occurred, we allocated a primary and auxiliary label to denote the haptic action and any applicable transformation to the original phrase.

Singer K chose and articulated labels for haptic gestures, to represent both the movement happening in her body when singing each vocal gesture, as well as how she experienced herself when performing the gesture in context of the other two vocal lines. Additionally, four key gestural themes were identified and labelled as: *glass arching, that snow falls, who'd have thought,* and *wind lift.* During the labelling process, we noted that the harmonic and rhythmic relationships across the three vocal parts, as well as Feldman's transformation of composed vocal gestures throughout the piece necessitated an understanding of how these "expression labels" existed in relation to each other (Figure 9b). That is, that a vocal gesture frequently was classified by several "expression labels" based on the harmonic relationship to another vocal part, whether the rhythmic structure was in or out of phase with another vocal part, and even if a transformation of the composed cell had occurred.

The machine learning model, using Convolutional Neural Network (CNN), after exploration of different model parameters, achieved

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[7] Voice 3, in this case.

Table 1: An example list of identified expression labels from the voice recordings, and the primary and auxiliary haptic gestures they denote

ID LABEL	PRIMARYVOCAL GESTURE	AUXILIARYVOCAL GESTURE	PRIMARYHAPTIC GESTURE	AUXILIARY HAPTIC GESTURE
3_2_5	Sliding	Refracted	Tension-Release	Lifting-Collapsing Sequence
3_2_8	Static	-	Local Compression	-
3_15_12	Sliding	Melismatic	-	-
3_1_11B	Sliding	-	Tension-Release	-
3_1_13B	Wind Lift	Refracted	Wind Lift	Swaying Body Sequence
3_2_16	Static	Harmonic	Tension-Release	Trill

94.1% accuracy in recognising the different gestures. A more detailed account of the CNN model provided in Appendix I. We hypothesise that this CNN model would offer new affordances for composing haptics. For example, identifying vocal gestures produced by Voices 1 and 2 in Feldman’s score could help synthesise their vocal gestures into constructing an entirely novel haptic actuation gesture based on the musical synthesis of all three singing voices. With that, we wanted to make a space for unpredictability in the generation of our haptic gestures – thereby contributing to the nerve and liveness of the performance experience.

Although the machine learning model was not used in the final performances, the processes of breaking the musical piece into small gestures and labelling them with microstructure and themes played a crucial role in articulating the haptic gestures that should accompany each part of the musical piece. The articulation of the haptic gesture integrates both the movements of Singer K’s singing body, with Singer K’s experience of singing along with the two other voices and interaction of the three voices, for example in the form of microtonal beatings.

4.2 Haptic Scores: A Notational System for Torso Haptics

Our aim to tangibly represent the complexity of the vocal piece in the Corsetto created the need for a notational system to emulate the movement material of a singing body, and compose our

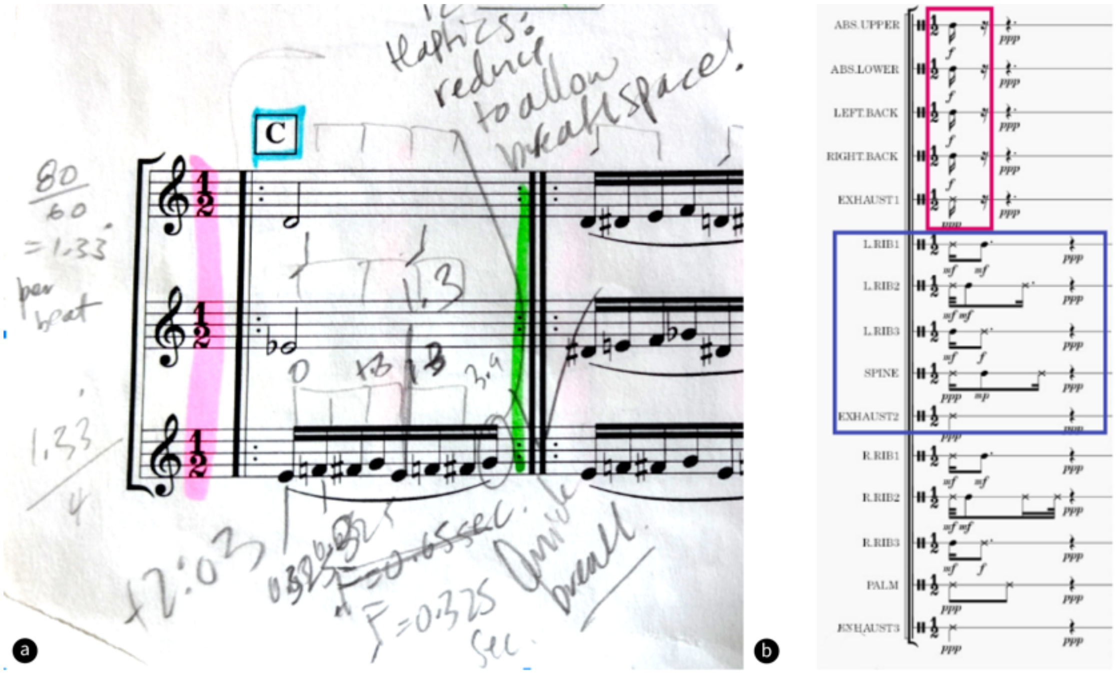

Figure 10: (a) Singer K’s score notations for haptics in her score. Depicts calculations for the length of actuation for notes in this moving passage. 10b depicts the same section as in 10a, in the haptic scoring. (b) The red box is emphasising the decision made for a 0.325 second actuation in the abdominal and back regions of the Corsetto, followed by a release of the actuation to parallel Singer K’s experience of singing the phrase and progressively losing air. The blue box is emphasising the staggered actuation in the rib region, reflecting the peristaltic motion of the ribcage expanding as Singer K sings this phrase.

haptic gestures. This was also crucial for translating torso gestures into tactile and kinesthetic feedback, and building an intermediary language with the pneumatic control hardware FlowIO.

We started by separating the biomechanics of singing according to the regions of the body where significant activity for producing vocalised sound takes place. The score for Feldman's *Three Voices* is notated using conventions of European classical music, and we elected to utilise this same approach to notating our haptics. Besides being a professional singer, Singer K is also a composer. She observed that positioning the Corsetto garment as an additional musical voice–and thereby notating its activity in line with the *Three Voices* musical score–would facilitate a process of devising an approach to composing haptics (Figure 10a). We strived to synchronise the haptic *Fourth Voice* with the audio recordings and emulate the live vocal performance by Singer K.

4.3 Haptic Scores: A Notational System for Torso Haptics

The modularity and independent working of each individual actuator in the Corsetto modules functioned similarly to an orchestral section –with each actuator following its own respective score– and therefore basing the haptic score on an existing notation software for scoring music was the most practical choice. We selected a percussion instrument which had three notehead variations, representing three different ways the instrument could be played (Figure 10b). Each notehead was mapped to one of the three FlowIO commands: inflate, deflate/release or hold. As the sheet music contained dynamics notation – pianississimo[8] to fortissimo[9] – these indicated the regulated air pressure or flow rate for the current note to represent the dynamics in felt form.

We notated the haptic score as an accompaniment to the sheet music score, using the individual expression labels generated during the ML labelling process, mapping each expression to a set of actions that FlowIO can read and perform synchronously to the vocal staves. Additionally, we developed a notation for a haptic trill[10] to designate fast switching between activation and release states. This rapid switching between actuation and release through the haptic trill became an evocative tool in conveying the musical interplay of the colliding sound bodies in various musical movements within Three Voices. The base music score (Figure 11a) was notated using open-source music notation software MuseScore [141] (Figure 11b) and saved as MusicXML. Using the Converter, the MusicXML file was converted to FlowIO instructions (Figure 11c).

We designed a range of haptic gestures used to compose the full score for the haptic voice: trill, full body trill, tension-release, local compression, peristaltic compression, and a range of full haptic sequences that compose with these simple gestural elements such as the swaying body sequence, lifting and collapsing sequence (Figure 12, a-b) to pair with the musical themes or leitmotifs[11] identified by Singer K. in Feldman's musical score (see Section 4.1). The full body trill utilised the fast-switching activation-release command in the FlowIO, haptically materialising the microtonal beatings Singer K. was experiencing. The localised trills similarly used this fast switching between inflation-release, centred around the rib modules. The tension-release gesture encompasses a general sequence of compression followed by release, applicable across all of the modules. The local compression gesture restricts actuation to the four active fabric modules in the abdominals and lower back. The peristaltic sequence –localised to the rib modules– utilised a timed offset of actuation across active sections within the one module region where each section is actuated at different times using a staggered onset.

5 THIRD STAGE: STAGING IMMERSIVE LIVE OPERA PERFORMANCES

In the third stage of our process, after several dress rehearsals, we staged two live performances of our haptic quartet based on Feldman's original *Three Voices* score. For both performances, the Corsetto's *Composer* tool was leveraged for haptic orchestration of the garments. Each performance lasted for 35 minutes preceded by 15 minutes for the donning and doffing. After the performances, we documented the audience's experiences through micro-phenomenological interviews.

5.1 Process and Evaluation Method

To establish a less tedious workflow of haptic scoring to finally arrive at whole compositions, we explored a machine learning approach. We aimed to both support the composition process, and automate the translation of vocal gestures into haptic gestures in real time during the live performance.

To achieve this, Singer K. prepared 3,045 voice samples based on her recordings of voices 1 and 2 (the pre-recorded voices) and labelled them resulting in125 distinct vocal gestures. The labels represent complimentary haptic gestures based on musical and thematic components of Feldman's score, thus capturing a systematic breakdown of the entire score based on these microstructures: *static, sliding, refracted gesture, spatialised body, melismatic, swirling, discordant, harmonic, syncopated/polyrhythmic* and *unison* (see Table 1). For refracted, spatialised, and syncopated/ polyrhythmic, the expression labels refer to a transformation of the original vocal gesture (i.e., if it is longer, shorter, in a different time signature, transposed up or down, etc). On occasions where this occurred, we allocated a primary and auxiliary label to denote the haptic action and any applicable transformation to the original phrase.

5.1.1 *First Performance.*

All three participants in this session were HCI researchers, who had previously experienced versions of the garment. For anonymity, we have pseudonymised their names as Kirsten, Maria and Mia. We staged this performance inside a small media room with blackout curtains allowing us to establish an intimate and private environment (Figure 12c).

5.1.2 *Second Performance.*

Our second session was another small-scale performance for three participants. All three participants were professional musicians, with musical backgrounds as vocalists or players of woodwind instruments. We have pseudonymised their names as Josie, Julian and Ethan. During this second performance, we moved to a small black box venue, with lighting facilities and curtains to achieve a full blackout environment.

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[8] Notated musically as 'ppp'

[9] Notated musically as 'ff'

[10] A musical trill is a rapid alternation between two notes.

[11] A leitmotif (or leitmotiv) is a short, recurring musical phrase which is commonly used in the operatic tradition to refer musically to a person or place.

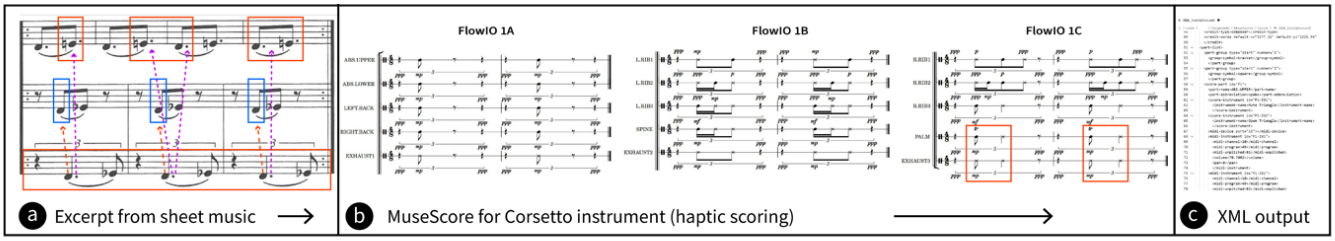

Figure 11: Haptic Score excerpt. (a) Depicts mappings across all 3 notated vocal parts (b) Depicts instance of trill, developed from mappings between vocal parts depicted in Figure a. (c) depicts JSON representation of FlowIO instruction of this vocal sequence.

5.1.3 Micro-phenomenological Interviews. Aiming to capture fine grained information of the audiences' tacit bodily experiences of the garment during the music performance, we used micro-phenomenological elicitation as the interview technique. Micro-phenomenology is a form of guided introspection that elicits highly detailed accounts of an individual's recounted experience as it is re-lived through a process of evocation [92]. The central objective of micro-phenomenological method is to draw attention to tacit pre-reflexive physical or experiential sensations of a specific moment in an experience which are typically overlooked or not attended to in the immediate experience, while avoiding priming interviewees with guiding questions. Micro-phenomenology has recently attracted attention in the HCI community [96] due to its unique value for exploring experiences, which might be tacit or strange for participants themselves, and thus difficult to articulate.

5.1.4 Thematic Analysis of Interviews. Three interviewers trained in the micro-phenomenological method conducted 45-60 min long interviews with 2 participants from each of the performances. We invited the interviewees to explore a micro-moment of their experience that carried meaning for them. Even though the micro-phenomenological method includes an analysis method [123], we chose to apply thematic analysis [34] instead. As participants picked different moments to unpack, achieving a generalised micro-structure of a specific phenomenon expected in micro-phenomenological analysis would have been neither possible nor useful for understanding the richer diversity of experiences and thematic threads connecting experiential aspects of the whole performance. Given the micro-phenomenological analysis' focus on discovering a generalised structure of a singular and brief phenomenon, more often than not an integration of micro-phenomenology in HCI includes only the elicitation method, then accompanied by a different analysis method [6, 7, 14, 25, 37, 66, 85, 93, 95, 112] way, while the elicitation method helps to focus in and articulate tacit experiences, a thematic analysis allows to uncover shared themes across multiple diverse but related experiences, which may have distinct structures, but relate through how participants make meaning from them. We followed this recommended approach. The data was transcribed and analysed by two authors. First, the authors familiarised themselves with the data, identifying meaning units, and assigning initial codes. Then they iteratively revised the codes through discussion, and grouping codes into themes. Through discussion with the rest of the authors, the overarching emerging thematic patterns were identified.

5.2 Phenomenological Findings

While there were many intriguing experiences elicited by the interaction with Corsetto, we present the most relevant findings pertaining to the somatic intra- and intersubjective experiences of the fourth, embodied voice.

5.2.1 Somatic Materialisation of Voice. At the most fundamental level, Corsetto elicited a somatic materialisation of the voice, allowing it to be experienced as a haptic on-body sensation. Josie[12], a professional saxophone player, reflected how "the singer is kind of re-enacted with the pillows", through the orchestration of the

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[12] Names have been pseudonymised.

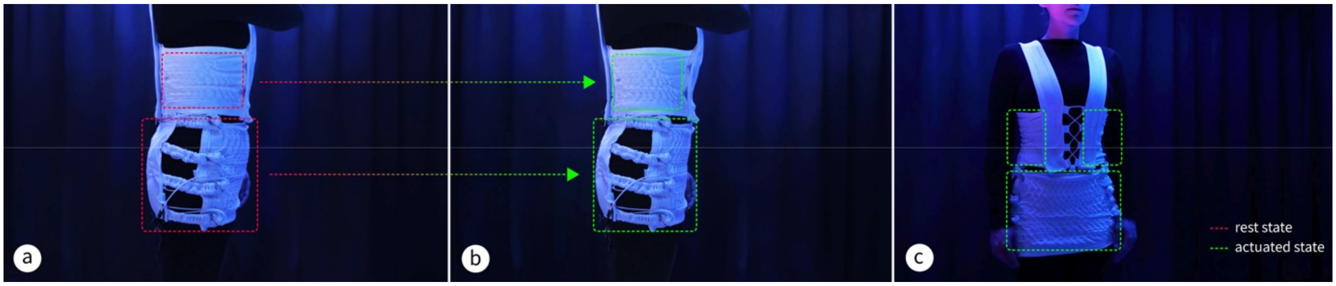

Figure 12: One of the audience members wearing the Corsetto after the first performance took place; (a) side view at rest state; (b) side view of actuated ribs and abdominal modules; and (c) front view of actuated ribs and abdominal modules compressing onto the torso of the listener by ∼18 %.

haptics. She commented on how this "was like a Phantom version of Singer K. . .." materialised through the haptic voicing of Singer K.'s body. What supported this perception was Josie's experience rooted in her own professional breathing practice as a musician: "I felt how the patches were pressing against my skin [...] I was like, okay, true, those are kind of the muscles that I use when I play saxophone as well. And then when you start breathing out, like the corset, I would say I was thinking if I actually do the same thing when I'm playing the saxophone.". But even without professional training, as a listener this materialisation allowed Kirsten to feel the voice as haptic perception "...then I felt something in my chest. I felt touched by the gesture of... it was not only the corset but it was also the voice."

This materialisation allowed the audience to form a relationship with the corset either by engaging in a dialogue with it or perceiving it as a medium for kinesthetic sharing of the singer's experience.

5.2.2 Narrative Dialogues and Kinesthetic Sharing. Participants made meaning differently from their experience of Corsetto. Particularly, the audience with professional musical training tend to interpret Corsetto as representation of the singer letting them pick into her inner somatic experience, supporting kinesthetic sharing. Julian, a professional opera singer, read corset's movement as an insight about the singer: "*I could feel it sometimes very strongly in my back. And I was thinking, wow, Singer K. surely is strong in her back.*" Julian's interpretation of the strength of the Corsetto's haptics indicates its kinesthetic sharing of Singer K.'s somatic experience and the nuances in how her particular body articulates a movement that he recognised within his own practice as a vocalist.

Josie also interpreted the corset as "*feeling the singer as breathing on you*" through the correlation between the somatic touch of the corset and the music. At first it felt like *"this strange body, an unfamiliar body, that somehow felt familiar".* But then she quickly began to recognize Singer K in it, feeling amused and privileged to have the unique perspective on Singer's K breathing.

Other audiences made meaning from Corsetto as the other artificial entity with some human quality that they engaged in a "*dialogue"* with. To engage in the dialogue participants had to negotiate with this *other* through their breathing: "*I was like, okay, let's have a conversation, like a dialogue between breathing patterns*" [Maria]. At first it was a struggle and felt confusing, even as if the corset was "*arrogant*", ignoring what Maria is trying to say: *"the listening part – it wasn't mutual. I was listening, but this thing wasn't, which was a reminder of the artificiality as well*". Maria herself was surprised by her inclination to interact with the artificial corset like with another human: "*Although it came from a very non-human thing, I was able to attribute very human characteristics* [...] *I was attributing the openness of a human dialogue to the openness of a dialogue with a non-human entity, which should [...] be different*". After the initial struggle, Maria allowed herself to surrender: "*it was a point where I decided to just try to listen. And then it's when things became more available. And then I could actually stop trying to dialogue with – is when things made sense, [...] because I could find my own way and the thing was doing its own way and I could really listen.*" Surrendering and listening allowed Maria to hear the narrative shared by the corset.

During one of the dress rehearsals, Maria shared her experience as an unfolding narrative of life and death told by the corset. During a hardware failure, one of the modules began to leak air, which led to her reading a new perspective on the composed haptic narrative: *"This thing was decaying.... It was like decaying but still breathing on me, I could feel it. [...] it felt fragile. And I was touched by the fragility of this thing, [...] and then I remember... it was like resistant to die, but it was something about there... like "I'm dying" and it was resisting".* The fragility of this somatic information exchange touched her and prompted her to reflect on how she could relate to the struggle of the Corsetto to maintain its haptic narrative: *"...it was like the corset was like a being or something that was trying to hold my hand. And that I was trying to help and say "Yes, I'm here with you." So that was represented through, like breathing together, not in sync, but together."*

However, beyond the dialogic negations with artificial other and perceiving the corset as a medium communicating the singer's kinesthetic experience—both of which retain the subject-object divide, at times, the experience became unified where the boundary between subject and object dissipated.

5.2.3 Dissolving Boundaries. These dialogic sections oscillated with moments of "*coming together into one expression*" [Kirsten], where all elements of the performance were unified in a singular fused somatic experience: *"my body and all of this activity is one, and the voice is one".* Kristen describes: "*This enactment on top of my torso, it is making me enclosed and that the voice is Singer K.'s voice. And the recorded voices are inside of that enclosure with these rapid movements. And I feel like my torso is very big. I'm not directing attention outward socially. I'm not directing attention to one part of my body, my lungs or whatever. <...> But this whole bit is like that's surrounded by all of this activity. So, my body and all of this activity is one, and the voice is one.*" This unified experience represents the moment where there is no longer a struggle between the inner and outer experience, in an attempt to form a dialogue while being hyper aware of the separation of the agency of one's own breathing, the voice and the Corsetto. Instead, in these moments the experiences become fused where the inner and outer somatic expressions seem as inseparable parts of one performance, where agency cannot be attributed to an individual "*I don't know what's happening anymore. I don't know if this thing is breathing on my behalf or if I am trying to breathe*" [Maria]. Even the audience become co-constructors of the performance: "*The voices are not listening to one another. They're totally integrated with one another in very rapid succession. [...] We're just inside of this jointly producing it.*" [Kirsten].

This dissolving of boundaries was facilitated by merging of inner and outer experience. While the corset was pushing from outside, Maria felt that experience from within: "*like a balloon here, just right where my ribs start [...] like something inside.*" She describes how the analytical focus on herself and how she looks to others dissipated in this moment: *"there was something that was pushing me to put myself in the background and listen. It might be that the presence of the corset was so overpowering that I couldn't ignore it."* Maria then described how she was transformed: *"I felt like my breathing patterns slowed down. I am breathing slowly...it's like I'm containing, actually, I became a container like my heart."*For Kirsten described this boundary dissolution was stimulated by an intense experience of all four voices joining in a "fascinating" chaos: "*everything was acting on my body, over the shoulders, around the ribs, around the belly, down belly, my spine, everything completely, like, totally intense, like, everywhere. And Singer K's singing and those two extra voices were also chaotic. It was all extremely chaotic, and it was amazing. [...] it all came together.*".

When the experience became unified into a singular expression it transformed the perception of time and space and ultimately offered the audience an experience of wearing opera performance on their body.

5.2.4 Suspension of Time and Space.

When negotiating in a dialogue with the Corsetto, Maria experienced a suspension of time: "*And time stops for a second because it's like it feels so... present. So present and this urge it's just like... something that wants to escape.*" Maria spoke of this suspension of time as a meeting-in-the-middle between her conceptualisation of time, and that of the Corsetto: "*what's happening here is that the corset was going faster. But I was going slower... we were like sort of meeting in certain specific points all the time.*" These meeting points between Maria and the Corsetto were acts of "sensemaking moments. . . of entering it into its world" through suspending time, and also echo Feldman's manipulation of time with slowly evolving repeated structures.

Kirsten spoke of the moments of dissolved boundaries as altering her understanding of her bodily relation to the space: *"Then I stopped being anywhere in the room. I was just inside of the experience. Everything was coming together inside of that experience...*" The rest of the space was also transformed and unified: "*it didn't have spatiality in the same way that other passages had. [...] I could no longer place Singer K. over there for me*". Kirsten's observations of "*not being placed anywhere*" reflects a similar instance of sensemaking between her and the Corsetto, where her sense of space and spatial relations completely altered, placing everything in the centre. While initially being aware of the performativity of wearing the Corsetto and thus being a part of the performance, this intensified moment of voices coming together has created a moment of full absorption into the experience. Kirsten describes "*I stopped caring about the social setting. <...> I was inside of the movement, and everything was there with me: the voices, the corset, my torso. And it was just me and this experience.*"

5.2.5 Wearing the Performance.

This transformation of space offered an unexpected capacity of Corsetto to bring an experience of wearing the whole performance. The Corsetto's disruption of one's somatic understanding of the space-sound relationship rendered an experience of the performance as a dynamic sonic-tactile event: "*I was just like, no, this is just me and it's going around. [...] I don't want to say that it has a circular movement. I want to say that it's here. The whole spatial experience is here. The corset is all here. It's not placed in different parts of the room. And in fact, I'm just in the middle of this chaos.*" [Kirsten].

Kirsten sketched (Figure 13) and described this as a moment of chaotic entanglement, where the sound of the performer's live voice, the sound of the pre-recorded voices, and the somatic materialisation of the voice of the corset became intertwined and inseparable from one another: "*But at this point, when this chaotic enactment with all that was happening, I felt like her voice was there on me. All the voices were on me, and they could not be separated from the activity in the corset.*"

Going beyond instances of kinaesthetic sharing and dialogues with an artificial other, this complex and layered account of Kirsten's somatic experience of the entire musical performance, facilitated through blurring of the boundaries, reveals that the corset became a mediator of an entire performative experience. Kirsten experienced the whole performance, as an entangled experience of voice relating to her body in a displaced sense of spatiality and dissolved agency. She reflected how this further subverted her understanding of who she could hear singing: "*And then I came to a phase where it was unclear to me who was singing. It felt like it was no longer Singer K. singing. And the other two pre-recorded voices. . . It was like, well, it might be Mia singing right now. It might be Maria singing, or it might be me singing.*"

Kirsten discussed "*being inside of* [her] *body on and off*" and Maria experienced a fluctuation in her perception of her outer and inner body. Kirsten reflected on how this oscillation between moments where everything was "coming together" with sections where it wasn't, was necessary to guide the audience through the narrative arc of the performance, by pulling them in and out of their body building up to the final passage of the piece: *"I've been inside of my body on and off with these very strong experiences of stuff coming together, but then also passages where this is not happening and where it's boring or where I feel like now I'm only focusing on this and not on that, and it's not coming together. They're speaking different languages. What's going on? But then by being exhausted and having been in these few moments of being inside of these things, that's when I can allow the fact that, oh, now Singer K. is singing something else than the two other voices on the corset.*"

Through this transition Kirsten could aesthetically appreciate the thematic content of the opera peace engendered in the singer's voice, speaking of the friends' passing. Kirsten describes: "*And it was only when I was exhausted after all of these different passages, <...> I could become open and sentimental and willing to see the passion in the humanness. <...> because her friends were dying and I could feel it. <...> So, this feeling, like the darkness of the room, the two voices, the two other voices, the recorded voices and the corset, and you guys and me, we're all in this dark place and things are together, and then she is to the right, and she's letting her voice go up and beautifully leaving all of this mess that we're in behind and letting us follow her on the fragility of the humanness and beauty of the humanness.*"

In this respect, through the Corsetto's disruption of the wearer's understanding of the space-sound relationship, the phenomenological experience of wearing the *whole* performance haptically paralleled Feldman's compositional approach in *Three Voices.* The haptic interpretation of the varying vocal lines, and orchestration of the haptics to achieve the entangled experience of voice which Kirsten described haptically reflected Feldman's usage of microtonal beatings, interconnected vocal lines and closely set harmonies - Feldman's swirling and physical sound bodies were brought to, and transgressed, the surface of the skin.

6 IMPLICATIONS AND LEARNINGS

Here we summarise some considerations for future designers of intersubjective haptics, and reflect on the significance of carefully

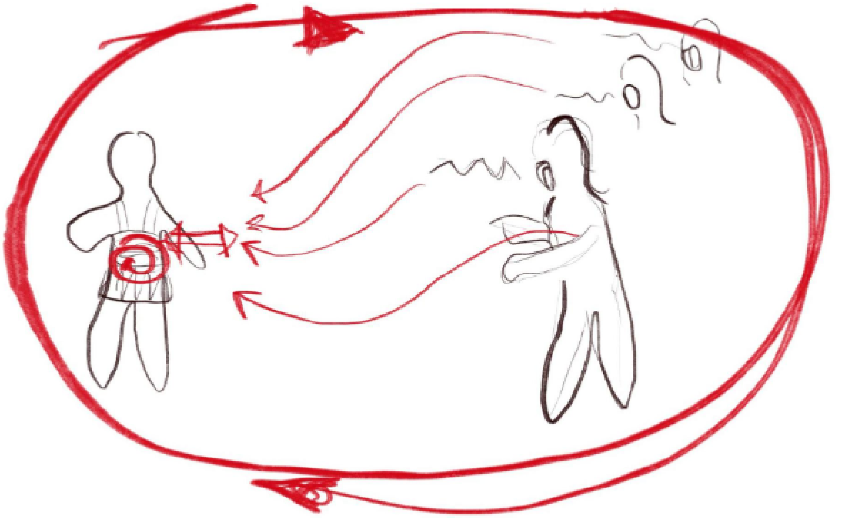

Figure 13: Kirsten's post-performance hand drawn sketch as a way to articulate and record her experience of wearing the whole performance on her body.

crafted technologies as a generative medium for exploring novel ways of designing and exploring intersubjective experiences.

6.1 Implications for Design

6.1.1 Designing for Intersubjective Experience. Through our design process we learnt how intersubjective experiences are complex phenomena, not necessarily straightforward arriving from mirroring or touching the other through technology. We were able to translate tacit experiential knowledge carried within our bodies to build a completely novel experience. Beyond hearing and feeling the sound waves of the immersive opera, the audience was able to feel an on-body sensation of the haptic voice. Other designers can utilise our findings to explore how soft robotics and other interactive on-body technologies can go beyond creating a simple one-to-one mirroring experience and instead explore a novel space, negotiating the interaction between inner and outer.

Breathing and touch arguably are uniquely potent materials for exploring the intercorporeal phenomenological blurring. Phenomenologist Matthew Ratcliffe describes the unique place of touch in our experiences, which both separates our bodily self from the surrounding others, while also forming a bridge uniting us with the world in an inextricably unified experience [84]. This parallels Lacanian conceptualization of breathing [22] as permeating the border between inside and outside, marking our embeddedness in the other. This highlights an intriguing potential of technology to explore somatic intersubjective experiences in new and exciting ways. While the phenomenology of the entanglement of our bodies leading to the dissolution of the boundaries between inner and outer, and self and other have been uncovered and described in our unmediated experiences by phenomenologists (see discussion of intercorporeality above) and highly trained meditators, Corsetto allowed to make this phenomenon more tangible for wearers without phenomenological or mediation training.

We situate this work as an initial engagement with the concept of 'intersubjective haptics' and hope that our considerations in arriving at an intersubjective experience of voice sheds light on considerations for future designers of intersubjective haptics.

6.1.2 A Somatically Grounded Design Process. While it makes sense to start in pre-existing experiences, such as a singer's muscular torso movements, new technological materials offer affordances that may alter and add to those experiences. In the two first stages of our process, it was important to let the aesthetic affordances of the haptic material 'speak' and guide our design explorations. We had to devise ways of experiencing both the haptic textile modules, shaping them but also shaping our experiences by what they afforded. We also repeatedly had to return to the tacit, habitual somatics of Singer K's singing body in order to find the meeting that would allow for an intersubjective experience to arise. A similar somatic sensitivity was needed when eliciting the audience participants' experiences. The micro-phenomenological interviews let us enter into their somatic experience. The complex nature of the various phenomenological findings we elicited from these interviews indicate that a more extensive understanding and discussion is needed in future work, and possibly one where more audiences engage with the Corsetto experience.

We speculate that what has allowed for this novel experience of the intersubjective haptic voice, was (1) our slow and introspective design process through the three stages guided by attending to our bodily experiences, as well as (2) the choice of the novel on-body technology that allowed a very rich and fine-grained actuation and composition through haptic scores that is felt nuanced, complex, and intriguing, forming a somatic dialogue between the wearer and the corset. While other systems explored communicating other's breathing through visuals or inflatables, most often they only offer a mirroring of a simplified breathing signal that collapses the complexity of all the muscles, rhythms and forces involved in breathing into a single sine wave. This limited representation allows one to pick into other's breathing, but it does not allow to create a rich space for the dynamic negotiation between subject and object, self and other, ultimately blurring this boundary.

6.2 Implications for Technology Developers

6.2.1 Technology-Context Matching. When composing the haptics, it became very clear that using pneumatics to work both with and against the body of the wearer was significant in shaping the overall experience. On a functional level, the actuation frequency at which the garments' modules could respond alongside other attractive mechanical properties such as high compressive forces (~30N) and actuation strains (up to 30%), enabled a dynamic liveness. This would have been compromised with most alternative artificial muscle technologies which trade-off between actuator performance and skin safety, response time or power consumption [23, 24, 97, 106, 129]. There are of course drawbacks with pneumatics such as introducing noise, but through using compressed air, we were able to minimise disturbing noise. Beyond its functionality, we found that pneumatics had a strong resemblance to how singers coordinate their internal air pressure, as well as muscular pressure to support their voice.

6.2.2 Shaping and Being Shaped. Whenever a new technological material is added, we should, as philosopher John Dewey argued, "empty the material of all its potential" [18]. It is not enough to only engage with the experience of the singing body as this will only be one half of the material. We also needed to "empty" the technological material of all its potential, exploiting its affordances to their fullest. Our design process became a journey back and forth between these two poles in order to make them come together into one aesthetically rich experience. The earlier phases of our enquiries engaged more heavily with Singer K.'s singing body, finding ways to understand and mirror aspects of her somatic expertise and expression in the haptic garment. The later phases became more influenced by the aesthetic potential and affordances of the technology we were shaping. In those later phases, we always returned to the expertise of the singing body, alongside building, feeling, and iterating with the actuated materials. Only through this double engagement was it possible to build Singer K.'s somatic experiences into the design.

6.3 Implications for the broader community

Based on this holistic endeavor, our work offers insights for a diverse audience interested in developing technologically-enabled intercorporeality.

- Creative technologists developing wearable complex cross-body experiences in HCI and HRI can learn from this complete instance of using technology holistically to facilitate intercorporeal, intersubjective experiences. Our approach offers reflections on adapted technologies (pneumatics) needed for custom-made and bespoke systems. We also propose an open-source pipeline for working on shaping and translating embodied vocal experience.
- We offer wearable system designers insights on application-based development of robotic textiles and actuated garments targeting specific muscular functions associated with vocal production. Testing the system on a wide variety of bodies through flexible, comfortable corsets producing a defamiliarisation effect illustrates a unique way to balance comfortable ergonomics and surprising estrangement.
- Singers can reflect on a new level of sharing and connecting through their art. Although there are many ways in which the voice resonance can reach a deep level of intersubjective connections, our approach proposes to explore the voice as an external object to increase awareness of the intercorporeality of vocal practice.
- Besides performers, our project also provides a tool for novel musical composition for the "body instrument". By writing music and movement directly for the body, Corsetto and its holistic technological architecture and composition framework enable composers to try their palette on new degrees of expressivity and ways to touch artists and their audience through intercorporeal experiences.

7 CONCLUSION

We introduced Corsetto, a robotic upper body garment, designed to perform a repertory of haptic gestures triggered by a singer's vocal expressions. The design of Corsetto built on the expertise of a classically trained opera singer's expertise who shared her tacit, professional, bodily knowledge with the whole design team through touch and kinesthesis. Once the Corsetto started to take shape, we devised a system for composing haptic actuation schedules. The composition rendered a new reading of the *Three Voices* piece as a somatically entangled haptic quartet. In the participants' accounts of the performance experience, we gain a richer understanding of the qualities and richness of the particular intersubjective experience we had come to design for: the ways in which is created a somatic materialisation of the voices; how it at times allowed to kinaesthetically shared Signer K's somatic experiences or negotiated dialogues with an artificial other; how it went beyond sharing by blurring boundaries between inner and outer aspects of participants' bodies; at times rendering a fusion of all the bodies in the room into one holistic experience, eliciting instances of wearing the whole performance; and how, at times, it helped express Feldman's artistic intentions of upheaving time and space, representing human life and death. This offers a unique case of technology manifesting the emergent intercorporeal entanglement between multiple bodies, extending our understanding of how technology may support intersubjective experiences. Our inquiries became a process of discovery and uncovering: Discovery of what there is and what there could be; an uncovering of somatic experiences, shared sympathy, and bodily engagements.

ACKNOWLEDGMENTS

This work has been supported by Hardware for Energy Efficient Bodynets funded by the Swedish Foundation for Strategic Research project CHI19-0034. The work was also partially supported by Swedish Research Council project 2021-04659 Validating Soma Design and Social Sciences and Humanities Research Council of Canada.

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A APPENDIX: THE CORSETTO SOFTWARE STACK

As outlined in section 3.6, the Corsetto's software stack is composed of several interconnected software systems, which were designed iteratively and in order to address different needs of the system at the different stages of the design process.

A.1 FlowIO Firmware

FlowIO comes with an open-source firmware that can be controlled through a web-application using the WebBluetooth standard as transport layer, which was used as our stepping stone for designing our FlowIO firmware. The firmware is divided to a hardware abstraction layer that provides C++ programming interfaces for the valves, pumps and pressure sensor controls; and Arduino program using the said interfaces. In the provided interface, a FlowIO command is represented as 3 bytes for the "action" to be taken, the desired valve states, and the pump(s) operating control given as a value between 0 and 255 (where 255 denotes maximal voltage for the pumps). Our system, developed iteratively, was kept for the most part compatible with this command structure.

During the design process, our firmware version was first expanded to support new features such as more sensors and controlling a flow regulator instead of a pump. Then, it was rewritten to include only the minimal features needed for our specific use case of controlling 18 FlowIO devices using USB serial communications, instead of WebBluetooth which is limited to 7 devices at a time. In the serial communication mode, the 3 bytes are represented textually as "[Action Symbol], [Valves Binary String], [Base-10 Integer]" terminated by a newline character.

A.2 The Scheduler

Similar to the firmware, our scheduler was iteratively developed out of the web-application provided by FlowIO, which served also as the controller system sending commands to the FlowIOs. The FlowIO web-application comes with a scheduler that is capable of creating instructions for a single device at a time, represented in the same "Action, Valves, Pump" format discussed above. We required additional features, namely, saving and loading of schedules, and writing a single schedule for controlling multiple devices. Based on the original scheduler, we created a new scheduler program, also a web-application, which was made compatible with the native FlowIO firmware. Our new scheduler introduced an abstraction of a "Role", in order to decouple between individual devices and their instructions in the multi-device scheduler. When executing the instructions, each role can be assigned any number of devices that will receive the instructions. The schedules created by our Scheduler can be saved and loaded as JSON documents.

A.3 The Controller

As discussed above, the controller in the native FlowIO system is coupled with its scheduler. Our controller had gone through several iterations, starting with abstracting the original controller code into a separate library, and then using this library with our multi-role scheduler to create a new web-based controller fully compatible with the original FlowIO controller. In parallel, the machine-learning explorations described in 3.7 led to the development of a control program written in Python. When it became obvious that Web-Bluetooth had latency and reliability issues when using 18 FlowIO devices simultaneously, the controller written in Python for machine-learning exploration was adapted for sending instructions over USB, using the protocol described above.

The controller starts by reading a schedule file given to it as an argument when launching the controller. It proceeds searching for all USB serial connection devices by their MacOSX file name conventions, e.g. "/dev/cu.usbmodemN" where "N" stands for a number assigned by the operating system. It then attempts to establish a serial communications connection with the device using 230400 baud rate. Next, each connected device is sent the special command "name?", to which it most responds with a device name starting with the string "FlowIO_", followed by an identifier. The identifiers are matched against the roles in the supplied schedule according to predetermined role names. Then, the controller displays a message to the console listing the devices connected, and waits for the user to hit the "Enter" key to start playback of the instructions.

A.4 The Composer Suite - Converter

After considering several strategies for composing the instructions that will control the micro-fluidic system of the Corsetto, strategies such as manually writing the activation sequence for the valves using the scheduler described above, using a graph based representation of the change in pressure over time, or using a proportional-integrative-differential (PID) control [ref] to match the pressure in the modules with pre-recorded or live sensor readings, we opted for allowing singer K. to compose the instructions as if she were composing for a musical instrument. In this new instrument, each module is represented as a percussion instrument stave, where notes represent increase in the pressure; pauses represent release of pressure; and "x"-head notes represent holding the current pressure. The notation is then closely matched with musical notation for the singing voices, where pauses are used by singer K. for inhaling. In addition, we included notation for a "Trill", which is a fast alternation between pressurising and depressurising the module, and for dynamics that represents the maximal pressure for the module. A version in which multiple modules are represented on a single stave was tested, but singer K. found the single module per stave line to be easier to read and compose for.

The converter can process music notation in the MusicXML open standard format [ref]. The document is parsed, any information other than the scores themselves is discarded, and scores themselves are transformed into an intermediate representation. In the intermediate presentation, every instrument is indexed by its name and is associated with timing information and handling only the allowed note kinds (regular, pause and "x"-head). The user is then presented with the list of instrument names and is asked to associate each name with a role and a port, thus establishing a mapping between the instrument to a specific Corsetto module. The user is also asked to set the dynamics values which control how each dynamic symbol is translated to pump or regulator instructions, and is asked for the BPM that will be used to convert the musical timing information to concrete timing information. The user can then initiate the conversion process, which will consolidate the intermediate representation into actual instructions. The consolidation process validates that all the instructions are indeed possible, that is, that there are no two instruments in the same role that try to play a note and pause at the same time, because such a combination will require simultaneous inflation and deflation in the same FlowIO device, which is impossible. Dynamics are also consolidated such that the strongest dynamic for the same role will be used. Trills are consolidated in a more permissive manner: if a trill (switching between inflation and deflation rapidly) is in contradiction to an inflation instruction, it will instead switch between inflation and hold. If the conversion process fails the user is presented with a message stating which instrument(s) and in each bar an issue was encountered. The resulting schedule can then be saved in a JSON format, or sent to the scheduler or sequencer parts of the composer suite.

A.5 The Composer Suite - Sequencer

Composing haptic notation resulted in a large number of 45 seconds to 3 minutes instruction sequences. In order to combine these sequences to a larger composition, another tool was developed - the sequencer. The sequencer allows loading JSON schedules, arranging them in a sequence, playing the sequence in a gapless manner, and exporting the sequence to a JSON file in a format very similar to the original schedule format. In order to make the sequence play in a gapless manner, the timing information for each schedule needs to be updated, and the last instruction of each schedule needs to be replaced with the first instruction of the next schedule, otherwise we will end up with two instructions timed for exactly the same time. In Figure 7c shows the sequencer, on the right-hand side are the different schedules and on the left-hand side are the schedules in their correct sequence.

A.6 Machine Learning Apparatus

To establish a less tedious workflow of haptic scoring to finally arrive at whole compositions, we explored the use of artificial intelligence (AI). Our aim was to both support the composition process, as well as automate the translation of vocal gestures into haptic gestures in real time during the live performance.

To do so, a collected dataset of 3,045 voice samples resulted in 125 distinct vocal gestures (from 2 to 13 seconds) from the Feldman score recorded by Singer. K. In this context, a vocal gesture is defined as a composed musical phrase used in the construction of the piece. These were then transformed into spectrograms, representing the vocal gestures as images of 128x32 pixels (Figure 9a), to train an automatic classifier for recognising vocal gestures. A supervised deep machine learning methodology was then applied to train a Convolutional Neural Network (CNN) on these images (see Figure A,1a). CNNs are commonly used to recognise images, but have to be carefully designed for the particular context of recognising spectrograms of vocal gestures. This vocal gesture recognition was preliminarily tested in how machine learning may facilitate the dynamic switching between the CNN's prediction of the vocal gesture it was hearing, and what was actually sung by Singer K.[13], as many vocal gestures in the Feldman score are quite similar in pitch and only differ in terms of the rhythm.

The piece of music in question –Three Voices by Feldman– presents strong characteristics of Feldman's post 1970s compositional period, featuring a focus on long durational composed form, and short musical phrases with frequent repetitions. These short phrases were used as the structural base for the vocal gestures identified throughout the score. Hundreds of experiments were conducted with different CNN architectures to find a working model able to accurately recognise the vocal gestures, until we reached a 94.6 % accuracy in recognising them.

B B APPENDIX: CORSETTO GARMENT FABRICATION

B.1 Machine Embroidery Pipeline

To make the modules robust, durable and replicable, we chose a tailored fiber placement technique using embroidery, where the active muscles are embedded in between a bilayer sheet fabric. The embroidered trajectories were designed in Adobe Illustrator, with the vector image of each design converted into a VP3 file format [139] for mass fabrication on a Pfaff Creative Icon embroidery machine.

Adaptable to curvy organic forms, embroidery enables easy tailored placement of the fibers, and is compatible with a variety

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[13] As during performance, there may be variances according to misreading the score at certain moments, or needing to take emergency breaths.

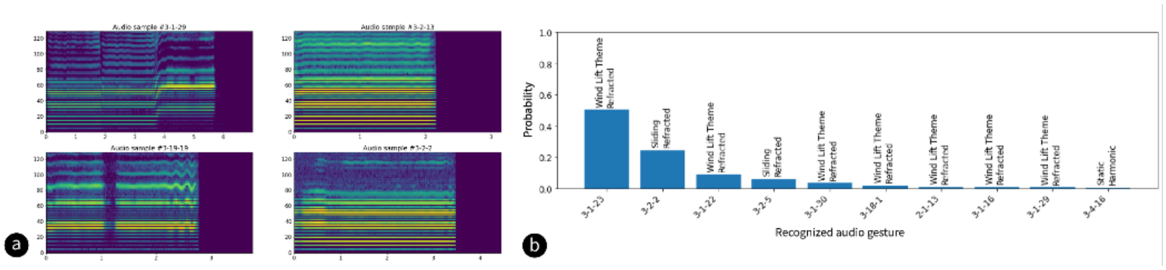

Figure 14: (a) Examples of spectrograms from 4 samples representing different audio gestures to recognise; (b) Output example of the trained model for audio gesture 3-1-23, showing the recognised gestures and corresponding expressions to actuate, ranked by probability. The audio gesture 3-1-23 is correctly recognised by the model with a probability of 50%, and refracted expression of the wind lift theme will be actuated.

of substrates. As the substrate layer, we used a one-way stretch crepe-de-chine in order to allow for mechanical compliance and stretchability in the course[14] direction, where we placed the fiber muscles in a horizontal alignment parallel to the tensile direction. This way, the stored elasticity in the fabric, once it actuates and contracts, allows a full recovery due to the inherent elasticity of the knit substrate. For the top layer, we used a one-way stretch chiffon with similar mechanical properties to the substrate layer while also allowing for the visibility of the fiber actuators due to its translucency, for aesthetic purposes.

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[14] The total amount of horizontal rows in a knitted fabric.