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Borrowed Gestures: The Body as an Extension of the Musical Instrument

Abstract: This article presents design and performance practices for movement-based digital musical instruments. We develop the notion of borrowed gestures, which is a gesture-first approach that composes a gestural vocabulary of nonmusical body movements combined with nuanced instrumental gestures. These practices explore new affordances for physical interaction by transferring the expressive qualities and communicative aspects of body movements; these body movements and their qualities are borrowed from nonmusical domains. By merging musical and nonmusical domains through movement interaction, borrowed gestures offer shared performance spaces and cross-disciplinary practices.

Our approach centers on use of the body and the design with body movement when developing digital musical instruments. The performer's body becomes an intermediate medium, physically connecting and uniting the performer and the instrument. This approach creates new ways of conceptualizing and designing movement-based musical interaction: (1) offering a design framework that transforms a broader range of expressive gestures (including nonmusical gestures) into sonic and musical interactions, and (2) creating a new dynamic between performer and instrument that reframes nonmusical gestures—such as dance movements or sign language gestures—into musical contexts. We aesthetically evaluate our design framework and performance practices based on three case studies: Bodyharp, Armtop, and Felt Sound. As part of this evaluation, we also present a set of design principles as a way of thinking about designing movement-based digital musical instruments.

Borrowed Gestures

This article introduces *borrowing* gestures from musical and nonmusical domains into movement-based digital musical instrument (MDMI) design and performance. We use the term "borrowing" to develop an extended gestural vocabulary by incorporating movement patterns either from performative and communicative gestural domains (such as dance, communication, and sign language) or from ancillary (i.e., sound-accompanying) musical gestures. Our motivation draws from transferring borrowed gestures' expressive qualities and metaphorical representations into music performance, extending the gestural affordance of digital musical instruments (DMIs) by embodying not only musicians' bodies but also their body movements in the physical interface, and by offering shared performance spaces.

The gestural interaction of DMI practice currently ranges from sonification of full-body movement to gestural controls that may be more nuanced (see Figure 1). This figure shows a sample continuum of embodied interaction in musical practice. The continuum starts with artificial intelligence–based systems for music creation or algorithmic composition with little to no human input, and extends to full-body interaction and movement-based performance practices such as dance, mime, or theater. The light gray bar indicates limited embodiment, the dark gray bar indicates instrumental gesture-based interaction, and the black bar shows large-scale body movements that are greater in space and time than musical gestures. In this continuum, DMIs range along the axis from reduced embodiment to large-scale body movements. Although some forms of DMIs provide more embodied interaction, other DMIs, such as knob and button–based or black box instruments, limit interaction to a small gestural space in terms of affordances such as physicality, function, or expression.

Despite the wide variety in gestural interaction, there is a region of unexplored possibilities between nuanced musical interactions and expressive full-body movement. By borrowing gestures from other artistic disciplines, we extend interaction primarily through transforming the use of gestures that were originally nonmusical into sound-generating actions. One gesture's function, form, or intent is used as a sound-producing gesture to excite the instrument or modify the existing sound (Jensenius

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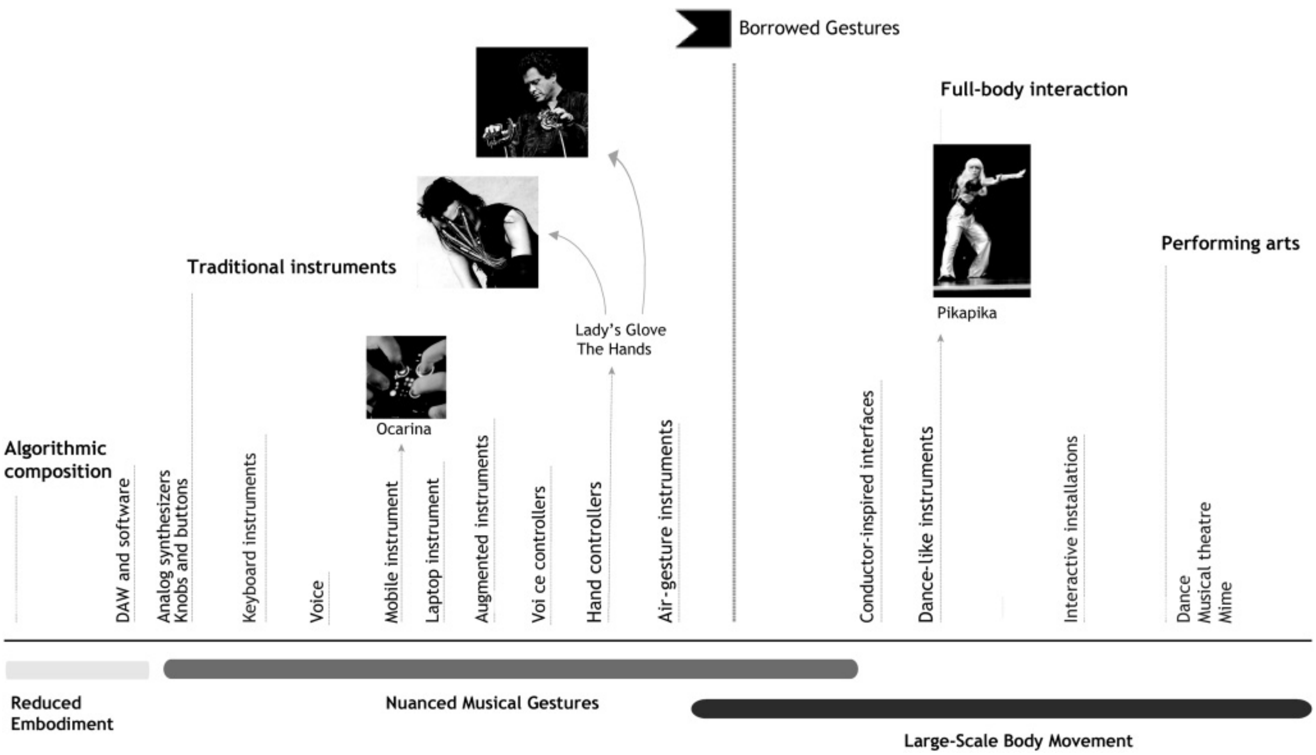
Figure 1. A continuum of embodied musical interaction. It starts with algorithmic composition and extends to nonmusical movement-based performances.



and Wanderley 2010). This approach also allows us to understand expressive qualities (Dahl and Friberg 2007) and metaphors (Buchanan 1992; Johnson and Larson 2003) behind the gestures' overt meanings and functions in one domain and to adopt them into DMI design and music performance. For example, incorporating dance gestures into the physical interface allows performers to interact with the interface through dance-like expressive body movements while still controlling the sound using musical gestures. Another example is utilizing sign language gestures as the main interaction mechanism in musical interfaces. Both examples carry borrowed gestures' figurative meanings and artistic characters. Such qualities are communicated as metaphors, although we do not directly imitate these gestures' overt meanings or original functions. Johnson and Larson (2003) discuss this understanding of musical motion as being metaphoric, and they describe these metaphors as being grounded in "our basic bodily experiences of physical motion." Our framework of borrowed gestures adopts a similar concept across multiple gestural domains.

Finally, the interdisciplinary structure of this extended gestural vocabulary creates a performance space that can be shared among performers playing together and between the performers and the audience, who may have different artistic backgrounds and physical abilities (see Figure 2). For example, one of our case studies, Bodyharp, borrows dance gestures. The performers play the Bodyharp in a cross-disciplinary space shared with musicians and dancers. (This, and the following two case studies, are discussed in greater detail later in the Three Case Studies section.) In our second case study, Armtop—a laptop instrument—combines instrumental gestures with the conductor's gestures to enhance the communication between Armtop's performer with the audience and with the other performers in a laptop orchestra, which can present

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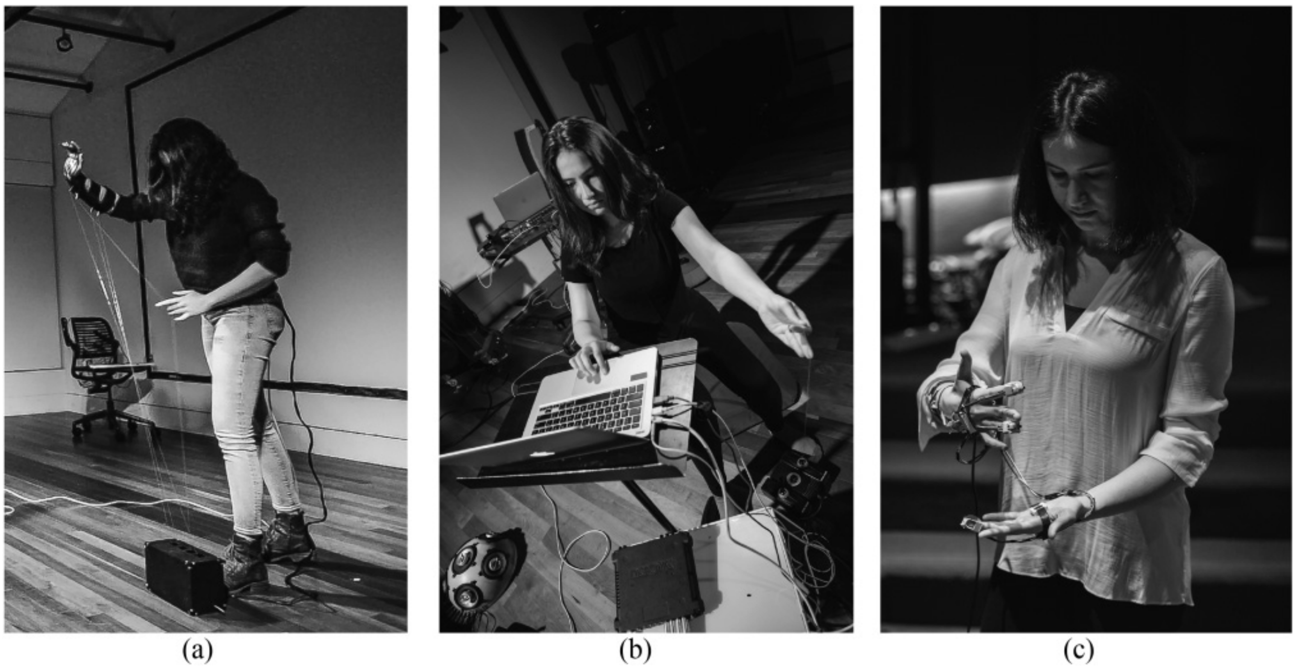
Figure 2. Three case studies of movement-based digital musical instruments: Bodyharp (a), Armtop (b), and Felt Sound (c).



an unfamiliar musical setting for the audience. Similarly, our third case study, Felt Sound, uses communicative gestures to focus on the experience of audience members with hearing impairments. In Felt Sound, we borrow nonmusical gestures from sign language to offer a context shared between listeners who are deaf or hard of hearing (D/HoH) as well as the hearing listeners. The tactile sensations of low-frequency and high-amplitude sound create a shared physical experience for all participants. By incorporating gestures from nonmusical domains, we designed musical interactions that can fill the gap between music and other artistic domains. This approach prioritizes inclusive performance practices, while valuing the expressive potential and versatility of nonmusical gestures.

The Body As an Extension

In crafting musical and movement-based interactions, the body creates an intermediate medium, physically connecting the performer and the instrument. The instrument can be considered as an extension of the body (Nijs et al. 2009) just as much as the performer's body can become an extension of the musical instrument. This conceptual melding offers new ways of thinking about movement- and body-based musical interactions. First, it provides a design framework for performers as well as for composers writing for the instrument, thus transforming a broader range of expressive gestures (including those from nonmusical domains) into sonic and musical interactions. Second, this conceptualization creates a new dynamic between performer and instrument—in other words, a different aesthetic that reframes nonmusical gestures into musical contexts. At the same time, this transformation of gestures borrowed across domains offers the audience a familiar gestural vocabulary that is embodied within the interface.

Designing Gesture-to-Sound Interaction

In this design framework, we define gestural interaction based on two levels. We combine nuanced musical gestures from traditional musical instrument

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practice with a combination of borrowed gestures, nonmusical gestures, and expressive body movements. This combination takes advantage of the expressivity of body movements and musicians' mastery of motor skills developed through traditional instrumental practice. Additionally, these borrowed gestures offer familiar interactions to performers while offering them new ways to interact through their body movement and still possessing nuanced control over the sonic outcome.

These nonmusical gestures might have well-defined meanings, functions, or artistic intents in nonmusical disciplines such as dance, communication (spoken language, choreography, etc.), and sign language. Similar to nonmusical gestures, some musical gestures do not contribute to sound production even though they have a strong association with music, such as communicative and sound-accompanying gestures. Regardless of their original context, both communicative and sound-accompanying gestures carry expressive and emotional content through artistic purposes or communicative meanings and functions. Based on these gestural groups, we design a gestural vocabulary by exploiting the expressive qualities of borrowed gestures and familiar interactions of instrumental gestures.

As an example, our first case study examines Bodyharp, which embodies sonified large-scale expressive body movements borrowed from dance while still preserving musical gestures such as string plucking (using a tether interface) and nuanced finger gestures (using an exoskeleton hand interface). The body movements include arm gestures and control of the performance space ("kinesphere"), such as changing the kinesphere in horizontal and frontal planes. Bodyharp's interface allows for arm swings, rotations, and extensions to sonify movement data through strings attached to the performer's arm, as well as through changes in the instrument's vertical dimensions. The performer still controls the sound with interaction that is more nuanced while improvising with other musicians. These body movements, exuding a dance-like quality, create a shared space for the dancers performing together and with traditional instrumentalists. For example, Bodyharp's interface allows the musician to perform with arm and torso movements similar to the dancers' gestures. Likewise, sharing a gestural vocabulary allows dancers to perform more responsively to Bodyharp's gestures.

Related Work

This section first reviews literature on how different forms of "borrowing" are used in DMI design, then gives an overview of musical instruments that are designed based on the performers body, discusses the concept of mimicry both within and outside music literature as well as its relation to the concept of borrowing, and finally shows how musical gestures are defined in the music literature and in this work.

The Concept of "Borrowing"

Designers of DMI generally borrow one or more aspects of the form, function, or interaction from either existing musical interfaces, everyday objects, or musical gestures. The SuperPolm MIDI violin by Suguru Goto (1999) is an example of borrowing an acoustic instruments' form and playing techniques. This instrument translates playing gestures into parameters to control sound synthesis, capturing nuances of violin gestures. Similarly, Perry Cook's SqueezeVox and many similar interfaces borrow forms of musical instruments such as accordions and keyboard instruments. Cook's Fillup Glass and Java Mug adapt forms of everyday objects and repurpose them for musical functions. These designs highlight new uses of familiar objects and their associated forms, interactions, and uses (Cook 2001).

A similar gestural translation occurs in playing computer keyboards as musical interfaces by adapting the physical interface and gestural interaction of typing (Fiebrink et al. 2007; Lee et al. 2016). Another gestural adaptation from musical instruments can be found in laptop instruments. In these instruments, the musical gestures are translated into actions on human interface devices, taking advantage of a laptop's native hardware. For example, the Laptop Accordion imitates classical accordion interaction, simulating an accordion's bellow movement with

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the opening and closing of a laptop's lid as well as an accordion's buttonboard with a laptop's keyboard (Meacham et al. 2016). The Blowtop borrows traditional flute playing interactions and musicians' posture of playing wind instruments (Cavdir et al. 2019). A direct imitation of musical gestures occurs in instruments played with "air gestures"—gestures that create sounds of a traditional instrument without actual physical contact. Design and interaction of air instruments demonstrate mimicry of sound-producing gestures. These nontactile instruments incorporate sound excitation gestures directly from traditional music playing and mainly imitate the traditional instrument's gestural vocabulary, the form of the instrument (without the presence of a physical interface), and the sonic outcome of the traditional instrument (Godøy et al. 2005).

Although borrowing can be observed in musical instrument design, few design frameworks incorporate gestural vocabularies from nonmusical domains into movement-based interaction beyond dance. In this work, we address design and performance possibilities with borrowed body movements that constitute the main sound generation mechanism along with the musicians' nuanced motor-control gestures.

Body-Based Musical Instruments

In the recent DMI literature, designers emphasize an embodied approach that considers the body as a musical instrument, from full-body to biosensory interaction. Tanaka and Donnarumma (2018) explore the body as the musical instrument through electrical and mechanical muscle activity, using electromyography (EMG) and mechanomyography, respectively. Visi et al. (2017) augment instrumental performance using wearable inertial and EMG sensors. Mary Mainsbridge offers another perspective on the body as an instrument by designing musical interactions for full-body movement. She discusses the kinesthetic skills that are less emphasized in "the electro-acoustic music tradition" or in "gestural system design" for musical applications. She develops nontactile instruments to support movement awareness and gross motor skills, addressing the relationship between performers and their body (Mainsbridge 2016, pp. xiii, 98–99).

Each of these interfaces takes a unique approach using the body, biosignals, or body movement as the basis for a musical instrument. The approach behind each design for the body as instrument differs from an earlier example that sonifies body movement through wearable sensors. Pikapika is an early example of fully embodied dance-based and collaboratively performed instruments (by a dancer and a composer, cf. Hahn and Bahn 2002). Hahn and Bahn approach sound-to-body movement mapping by using active body movements as a musical interaction and by amplifying sound directly with "body-mounted speakers." The localized sound sources distinguish Pikapika from its successors, embodying sound sources and incorporating full-body movement into the interface.

Body-based musical interfaces emphasize performers' first-person experiences in creating music, contrary to approaching the idea of an instrument as an external object. Although such experience-based approaches allow users both to explore new possibilities of musical interaction through movement and to develop understanding and awareness of body movement, they still create a degree of disembodiment between the performer and instrumental interaction. For example, instruments sensitive to muscle activity limit the gestural vocabulary to a very small space due to the nature of muscle signals and their activation. Similarly, instruments based on full-body movement require collaboration between musician and mover for sound control, or they rely on visual feedback. Overall, they exclude tactile interaction and nuanced motor control.

Mimicry of Gestures

With or without artistic intention, both performative and communicative gestures can carry expressive features through observing and copying the body movement of others (McNeill 2008a). Research by Barbara Tversky (2019) on mirroring of physical actions—observing and imitating—is concerned not only with the physical sensations of the associated movement but also with

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prediction and expectations about action. David McNeill (1992) describes borrowing as mimicry, recreating a gesture, movement, or an expression not through simple imitation but by carrying its meaning. He discusses how mimicry helps communicators unravel the contexts of others' intentions (McNeill 2008a, 2008b).

From nuanced to larger-scale gestures, involuntary and simultaneous mimicry of others' movements also helps embody performers' expressions and expressive qualities in their body movements. We believe that a similar translation is possible in music performance. To allow for such communication through mirroring body movements, our interfaces map nonmusical gestures or ancillary and communicative musical gestures to sound-producing gestures. This approach allows us to design interfaces based on an interdisciplinary gestural vocabulary. The music performances are focused on movement-based practices that can be shared with disciplines from which the interfaces borrow their gestural vocabulary.

Mimicry of gestures in music is used by Godøy et al. (2005) to describe air-instrument gestures as "mimicry of sound producing gestures (as well as other movements and expressions)." They explain mimicry of musical gestures through "musical imagery," imagining musical sound or "converting mental images (of movement) associated with musical experience." These mental images include both physical and expressive qualities such as "effort, velocity, impatience, unrest, calm, anger, etc." Mimicry, as mirroring other's movements and movement qualities, also occurs in dance practices and therapy as a way to "kinesthetically and virtually capture participants' nonverbal communications" (Moen 2005; see also Karampoula and Panhofer 2018). It refers to imitation beyond physical aspects of movement and focuses on imitation of movement qualities, meanings, and intentions (McGarry and Russo 2011).

Musical Gestures

In music research, the term *musical gestures* is used to denote specific gestures that either carry a functionality that is necessary to produce or modify sound, or that are used as accompanying, communicative, or performative actions that indirectly affect or have no influence on the sound. Although research exists in mapping the different terminologies and putting the definition of gestures in relation to the composer, performer, and audience (Schacher et al. 2015), defining these gestures still remains a challenge, especially for new musical instruments and interactions. Jensenius and Wanderley (2010) categorize musical gestures into three functions: communication, control, and metaphor. This approach develops into a framework to study musical gestures, mainly through their functional aspects: those producing sound, those facilitating sound, those accompanying sound, and those that are communicative.

In distinguishing *musical* and *nonmusical gestures*, researchers introduce different perspectives to the use of terminology. For example, Camurri et al. (2003) explain the term expressive gestures as gestures that convey information about affect and emotion, whereas Claude Cadoz (1988) discusses instrumental gestures that are actively and intentionally performed, either to produce sound for both excitation of instruments or to modify sound generation. François Delalande (1988) refers to these instrumental gestures as effective gestures. Jensenius and Wanderley (2010) define such gestures with excitatory actions (e.g., hitting, stroking, bowing, or plucking) as sound-producing gestures.

As the second category, sound-facilitating gestures are defined as gestures that support the production or modification of sound (Dahl et al. 2010), whereas, as the third category, sound-accompanying gestures are those that are not involved in sound production. Dahl emphasizes the difficulty of isolating the sound-facilitating gestures, as they overlap with, and bridge between, sound-producing and communicative gestures. Delalende refers to these gestures as accompanying gestures, whereas Wanderley (1999) and Wanderley and Depalle (2004) define them as "nonobvious" or ancillary gestures. As the main difference, sound-facilitating gestures influence output sound, contrary to sound-accompanying gestures. Although there might be an indirect change in the sound, musicians might

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perform sound-accompanying gestures solely for expressive intentions or to follow the music in ways that are not primarily involved in sound production or modification.

The last category of gestures, communicative gestures, shares similarities with gestures defined by linguists, such as as "cospeech" gestures, or sign language gestures (Kendon 1975; McNeill 2008a). Communicative gestures generally occur among performers or between performers and the audience. Some researchers extend communicative gestures to composers' intentions in the piece, however. The framework developed by Jensenius and Wanderley (2010) excludes expressive gestures, partly due to the unclear or complex functionality of these gestures. They carry aspects of both communicative and sound-accompanying gestures, in some cases even facilitating sound (Dahl and Friberg 2007). As much as these gestures aim to communicate musical ideas to other performers or to interact with the audience, they can also originate from the performer's interpretations of the musical piece and expressions of emotional intent, and they remain challenging to categorize under communicative gestures.

We finally remark on the use of the terms "movement" and "gesture," since we continue to address them in the rest of this article. Although the terms are sometimes used interchangeably, both have distinct definitions and include elements of motion, action, communication, expression, and emotion. In music, both terms more often intersect and share common qualities. In this work, when discussing movement and gesture in a musical context, we use movement for body movements that include expressive qualities and spatial, temporal, and emotional content. We use musical gesture for musical movements with clear functionalities and forms such as instrumental actions or conductor's gestures. These musical gestures can be observed both in traditional and acoustic instrumental practice, and in new musical interactions.

Because of a similar challenge in defining movement and gesture in dance (Buck and Fox 1998), we refer to movements inspired from dance as dance-like movements or dance-inspired movements. Similarly, gestures borrowed from American Sign Language (ASL) are referred to as ASL-inspired gestures, independent of field-specific definitions of gestures in the sign language literature, which are beyond the scope of this research.

Integrative Approach

Our framework follows an iterative design process that integrates, on the one hand, the body into the physical interface and, on the other, body movement into sound design. More specifically, this process includes three components. First, we approach the design process initially by defining a set of gestures and movement patterns. In other words, gestures come first and the instrument design is based on the gestural vocabulary. This gesture-first stage precedes the design of physical and sonic interaction. Second, the musician's body becomes part of the physical interface as an extension of the musical instrument. This merging between the instrument and the body informs the sound design and mapping to include both nuanced musical gestures and larger-scale bodily movements. Third, we develop cross-disciplinary performance practices to allow performers to compose and choreograph based on the gestural affordances of the instruments. These practices offer a shared space for performers from both musical and nonmusical disciplines, exploiting the two gestural domains. Throughout this design process, we consider how movement-based instruments offer opportunities for collaboration—through their visual, auditory, and kinesthetic feedback channels (Moen 2006). The designer revisits these three steps until the two domains—sound and movement—integrate and until both the performers and the audience can no longer pinpoint the discreteness of each domain. We pronounce the design process to be complete when the resulting interaction and the instrument's aesthetics come not from the individual parts of the system, but when they come together as a whole (Ramsay and Rockwell 2012; Höök 2018).

Initially, we integrate borrowed gestures into sound mapping, physical interface, and performance. This approach leads to considering gestural vocabulary as the first design step. The sound and physical interaction designs follow the gestural

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vocabulary to embody both instrumental gestures and expressive body movements. Whereas borrowed gestures are mapped to more broadly expressive sound control, small-scale and tactile musical gestures are designed for nuanced sound control. The instrument design addresses this dual gestural interaction in two ways: by a gesture-to-sound mapping through both nuanced motor control and expressive body movements, and by offering an extended vocabulary that combines new and familiar interactions. Similar to sound design, designing the physical interfaces based on a specific gestural vocabulary requires rethinking the interaction between the body and the musical instrument. The instrument is approached as an extension of the body, and the body as an extension of the physical interface. For example, Bodyharp's physical interface demonstrates its completeness when the interface includes not only the physical instrument upon which the body acts but also the performer's arm extending the instrument.

The design consideration behind the merging of body and instrument motivates us to bring the perspectives of musicians and movement artists closer, rather than to exchange their roles. Contrary to the common practice of movement-based interaction in music, which exchanges the musician's role with the dancer or the dancer's with the musician or composer, we hope to offer instruments that are more artistically accessible in order to make use of both skill sets. Developing tools and experiences that can be shared across disciplines supports movement awareness by designers and musicians, who are not necessarily experienced or trained as movement artists. We believe that musicians who work with movement artists and the designers of movement-based interfaces need to be able to communicate to both of the domains from which the interface borrows its gestural interaction. This approach requires designing tools that musicians, designers, and movement artists can relate to. By integrating not only musicians' body movements but also their bodies into the physical interface, we offer a shared vocabulary of music–movement interactions.

Finally, we consider composing and performing with these instruments to be crucial for aesthetically evaluating the success of the design method. We aim to offer a performance space for both musicians and nonmusicians. Collaboration between musicians and movement artists in both design and performance brings out new artistic possibilities. Each shared performance becomes an opportunity to artistically assess the instrument's affordability, expressivity, and gestural interaction. By extending the musical gestural vocabulary, we ask what new performance practices and aesthetic possibilities can be afforded across disciplines and communities. This approach requires designing for cross-disciplinary performance and collaboration opportunities. We ask: How can we craft performance practices as a design step that can be shared with multiple artistic communities?

In addition to collaboration for artistic purposes, we find shared performance spaces invaluable for designing inclusive music practices, including both the physical interface and musical experience. For example, in Felt Sound we focus on a specific type of audience, individuals with hearing impairments and ASL signers, to create a shared musical experience for both the D/HoH and the hearing participants. We craft the performance space based on the musical experience we intend to deliver to bring two communities together. Both practices—interface and performance design—encourage inclusion in musical and artistic communication through movement interaction and reframing the body-to-instrument relationship.

Three Case Studies

We applied this gesture-first, integrative approach, which informs gestural and physical interaction, sound design, and performance for increased collaboration, to three case studies. Whereas Bodyharp develops a gestural vocabulary that is inspired by string instrument gestures and dance movements, Armtop and Felt Sound merge instrumental gestures with communicative gestures. For each case study, we discuss the instrument's gestural affordances, physical interface design, sound mapping, and performance practices.

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Figure 3. Bodyharp consists of a wearable interface and a main instrument body. The strings extend from the instrument body and are attached to the wearable arm piece, connecting the musician body to the instrument. The sound is excited by plucking the strings (a) and the sound quality is shaped by moving the strings with the arm (b).

Bodyharp

Bodyharp simultaneously realizes two ways of thinking about an instrument: as an object on which the body acts, and as an extension of the body (Cavdir et al. 2018). The connection between the instrument and the wearable parts completes the physical interface by integrating the performer's body, thus the instrument cannot be considered without its performer (Cavdir et al. 2018; Cavdir and Dahl 2022). These two perspectives derive from how the instrument is played. While one arm controls the length of the strings, the other hand plucks the strings (see Figure 3). This playing technique on the strings draws upon musicians' fine gestural control on their traditional instruments. For example, the finger gestures that are detected by the exoskeleton allow the musician to use finger and wrist gestures of piano playing. This fine gestural interaction is extended by performing with larger-scale gestures such as arm extensions to the sides, arm rotations, bending knees to adjust the strings' length—and thus the instrument's height—and other space- and body-related movements (Laban and Ullmann 1971; Bartenieff and Lewis 1980; Larboulette and Gibet 2015; Fdili Alaoui et al. 2017; Bernardet et al. 2019; Cavdir and Dahl 2022). The design approach that extends the musical instrument with the performer's body combines the familiar gestural vocabulary from musical instruments with nonmusical gestures borrowed from dance and movement-based performances.

Bodyharp's interface affords performing in two gestural domains: larger-scale, dance-inspired body movements and smaller-scale, nuanced musical gestures. The larger-scale gestures are performed by wearing an arm controller that connects the performer's arm to the instrument's strings. This

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connection enables the musician to extend the performance space and to use it more freely than the kinesphere that the traditional musical instruments afford. The musicians can extend their kinesphere by changing the instrument's height and width with the stretchable strings, which also modifies the quality of the sound (Figure 3). The strings in the physical interface permit familiar playing techniques of string instruments, such as plucking, and the stretchable material enables the performer to extend these techniques by stretching the strings through rotation and extension of the arm. Two types of interaction with the strings provide sound control to the musician through three-axis position sensors on the strings and accelerometers on the wearable interface. Tactile sensors on the exoskeleton support this sound control with hand and finger movements.

We designed the action-to-sound mapping based on two approaches. First, the musician initiates and controls the sound instances with nuanced gestures and, second, modifies and shapes the sound qualities with the expressive body movement. The sound is initially produced by plucking the strings or extending the strings over their resting positions. The sound qualities and effects are later shaped by the body movements. After initiating the sound with nuanced gestures, the musician articulates expressive musical effects with dance-like movements. In this way, Bodyharp transforms the functionality of expressive and communicative dance gestures into musical gestures. In a traditional music performance, accompanying and nonmusical gestures do not contribute to sound (Jensenius and Wanderley 2010). In Bodyharp, however, these gestures partake in sound-producing or sound-modifying processes. The similarity of Bodyharp and dancers' gestures in their movement patterns and qualities creates a new communication among performers, including dancers, contact improvisers, and musicians.

In the first performance with Bodyharp, the musician controlled the reverberation parameters and spatialization with arm rotations that are detected by an accelerometer embedded in the wearable interface (see Figure 4). The exoskeleton, connected to the wearable interface, encloses five flex sensors to capture finger bending. We observe that these sensors result in a more intuitive control when they are mapped to low-level sound parameters that can be used for fine tuning, such as control of loudness and timbral parameters, or for triggering new sound engines. This first performance took place in a multichannel solo improvisation (see Figure 3). The surround audio system allowed the musician to reflect on the effects of larger-scale gestures, extending her kinesphere to the performance space that was shared with the audience. The spatial and reverberation qualities controlled by these gesture were amplified at the stage. These features needed to be modified in the following performance, which was staged in a biological reserve and used a single sound source.

The instrument was later performed in a site-specific retelling that involved narrative dance, contact improvisation, and improvisational music performances (a short excerpt can be seen at https://doi.org/10.1162/COMJ_a_00617, and a more extensive excerpt is available at https://ccrma.stanford.edu/~cc/pub/webm/liriope.webm). Figure 5 demonstrates this performance and the stage settings in Jasper Ridge Biological Reserve at Stanford, California. Dancers and contact improvisers responded with their movements to the musicians' movements and sonic expressions. They reported that in addition to listening to the music, the dancers were following Bodyharp's body movements. Similarly, Bodyharp's performer experienced two channels of feedback: movement-based (kinesthetic) feedback, and auditory feedback from her instrument and the other performers. Similarly, one of the other musicians reported that the Bodyharp and the instrument's movements were connecting the expressions of the dancers to the musicians.

Bodyharp offers an intermediate improvisational role between dancers and musicians. The dance-inspired movement qualities not only facilitate the communication between the Bodyharp's player and dancers, they also offer a modality in which the musicians receive an auditory response based on the performer's movement. In a way, body movements shape the sound and in turn, gestures resulting from playing the instrument naturally exude a dance-like quality.

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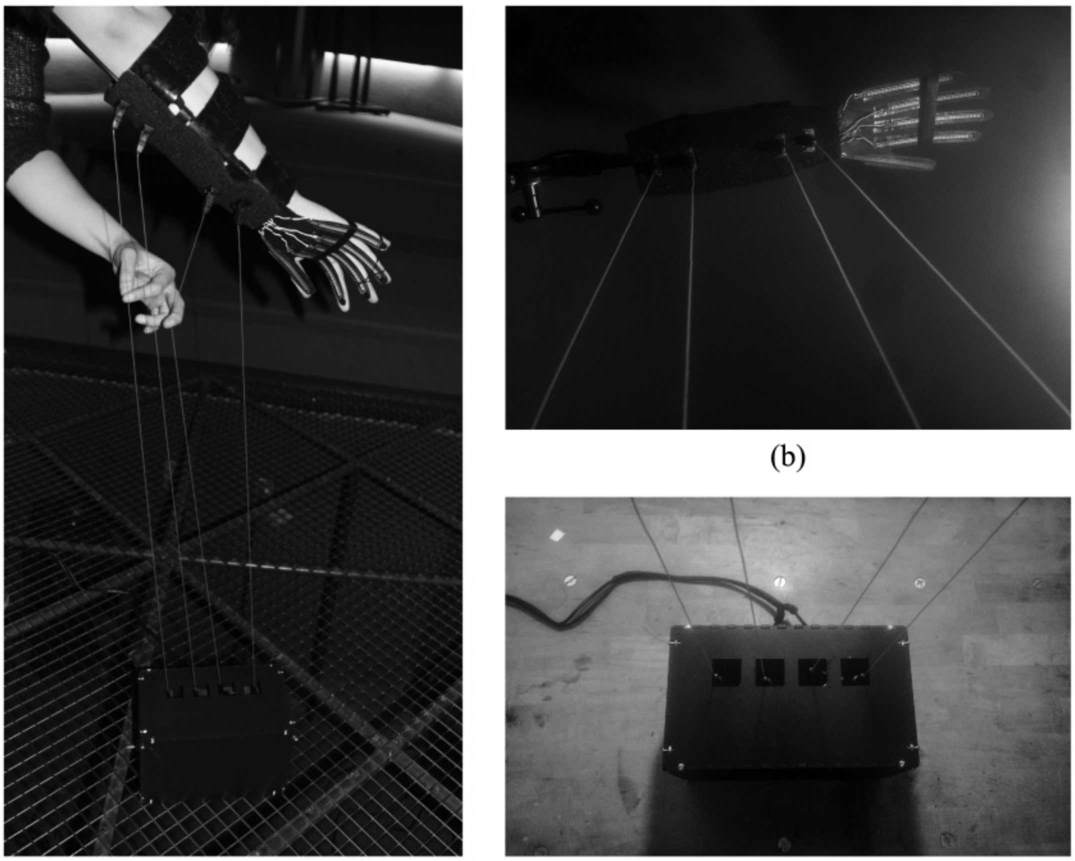
Figure 4. The full interface when the strings are attached to the wearable arm piece (a). The wearable arm piece houses the exoskeleton with a flex sensor for each finger (b). There is also a controller unit located underneath the string attachment band (not visible in the photo). The string pulleys are contained in the main instrument body—not visible, but the strings extend toward the arm to connect the pins (c).



(a) (b) (c)

Armtop

Armtop, a physical laptop instrument, is designed for a small ensemble piece for the Stanford Laptop Orchestra (cf. Cavdir et al. 2019). The instrument setup consists of a standard laptop instrument station that includes a laptop, hemispheric speaker, and position-tracking game controller (see Figure 6). The instrument hybridizes the physical interaction of playing a laptop instrument with the aesthetics of body movement. The interface uses the laptop's native capabilities (keyboard, trackpad, etc.; cf. Fiebrink, Wang, and Cook 2007) to create gestural control mimicking techniques of keyboard playing. We designed its playing techniques to help musicians transfer their musical knowledge to laptop instrument performance (Palmer and Meyer 2000; Feit and Oulasvirta 2013). These gestural skills or patterns that are learned through music practice decrease the cognitive load when performing with DMIs (Gibet 2009). Laptop performances carry little familiar musical gestural vocabulary, and they can be limited in bodily expression, physicality, and communication with the audience. With Armtop, we aim to extend the way that the musician interacts with the laptop by combining the nuanced finger interaction on the laptop trackpad with the large-scale gestural interaction of arm extensions as found in cospeech or a conductor's communicative gestures.

Armtop extends the physical interface with the musician's left arm. Its tether controller allows

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Figure 5. Bodyharp is played in improvisational performances with dancers and musicians in an outdoor setting at Stanford's biological open preserve Jasper Ridge. The improvisational practice is between Bodyharp's performer and dancers, among musicians, and between musicians and actors/dancers as well as solo, as seen in the subfigures.

musicians to modify the sound with three degrees of freedom in their arm gestures: lifting the arm up or down, extending it in or out, and rotating it. These gestures function as both sound-modifying and communicative gestures. Since the sound is initiated by the finger gestures on the trackpad, the arm gestures control the sound effects that follow the sound excitation. In addition to their musical function, large-scale gestures, specifically arm extensions, carry communicative and expressive functions. The communicative aspects are inspired by conductor gestures such as raising one's arm to trigger the sound as if activating the system or providing energy to it (Schuldt-Jensen 2015). Schuldt-Jensen states that the distal motion—the distance, or extension, of the conductor's arm from the body—communicates the amount of sound effect to be played. He further describes the "conductor's space" as the physical space, or kinesphere, that is defined by an extended arm's length forward and to the sides. We adopt this definition of kinesphere in the laptop instrument interface to extend musicians' physical space, affording larger body movements. The tether with the musician's arm defines the kinesphere of the musician. Since the tethers are extensible strings, this flexibility enables musicians to change their performance space to communicate musical expressions that might be limited in laptop performances.

Similar to its mimicking of a conductor's kinesphere, Armtop embodies some expressive qualities of a conductor's gestures that affect the nuances and articulations of the sound. These gestures share similarities with ancillary gestures in music, in other words, the conductor does not intend to affect but indirectly contributes to the sound. With Armtop's gesture-to-sound mapping, arm gestures control vibrato, tremolo, and loudness so that the musician can intentionally explore these sound effects through body movements.

Armtop's first laptop orchestra performance included traditional orchestra roles such as a conductor, a soloist, musicians, and the audience (video excerpt: https://youtu.be/6S80_X23dOc). It was performed as the soloist's instrument with an

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Figure 6. Armtop's interface includes a standard laptop instrument setup (laptop, hemispheric speaker, controllers, etc.), specifically focusing on the laptop trackpad and controller tether.

independent set of controls from the conductor and the rest of the performers. Additionally, Armtop offers visual feedback that displays finger location on the trackpad to support the soloist's gesture-based performance. Because the trackpad is divided into individual pitches, the musician can use the trackpad as a keyboard in terms of its function. The visualization also shows the tether's location and height data. We observed that this visual feedback helps musicians to more easily correlate the fine gestures (such as finger location on the trackpad) with their associated sonic outcomes.

According to the musicians' reported experiences, this additional feedback channel is less needed when the musicians control expressive musical features with body movements. Visual feedback appears more important for nuanced control than for control with body movements. The difference emerges from the smaller kinesphere of fine gestures that more directly affect the sound output, considering that traditional instrument practice requires more precision and specific alignment with the instrument. Both the interface and the small-scale nuanced gestures offer physical boundaries and tactility similar to that of traditional musical instruments. On the other hand, Armtop's borrowed gestures can be performed with free gestures (Leman 2010) for more expressive control, since these gestures afford direct modification of sound with less restriction in physical space.

Thanks to the division of roles in the the first performance, Armtop provided an improved communication between the laptop ensemble members and the audience. The performance stage is shared by musicians and the audience, allowing the audience to observe the musicians' gestural interactions.

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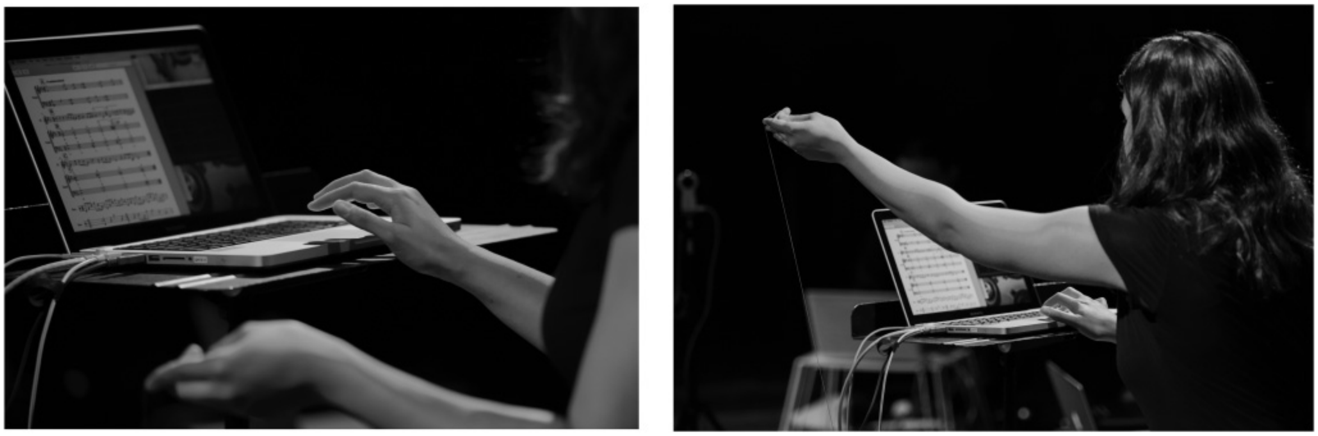
Figure 7. Armtop's two main interaction mechanisms allow musicians to use their existing finger gestures from traditional musical instrument interaction and to add communicative gestures that map expressive features of the sound. The trackpad offers musicians a multitouch keyboard to play the melodic line, imitating piano finger gestures (a). The musician can control gain, vibrato, and tremolo by changing the tether position with distinct arm gestures (b).



(a) (b)

In such a performance space, we can approach Armtop's gestural interaction in two ways: from the performer's and from the audience's perspectives. From the performer's point of view, expression begins with nuanced finger interaction on the trackpad, as shown in Figure 7a. The musician later amplifies this expression with larger-scale arm gestures. Figure 7b shows the arm movements that the musician performs to increase the gain and to add expressive features such as vibrato while simultaneously playing the note on the trackpad (see Figure 7a). Incorporating these levels of body movement improves both embodiment and physicality of the laptop interaction and the performer-instrument connection. Additionally, this integration connects the two gestural spaces through sonic expression and allows musicians to explore musical expressions as a natural outcome of the interaction, beyond directly controlling every sound parameter. The musicians can concurrently focus on both the sonic and bodily expressions. From the audience's perspective, nuanced gestures—finger and hand gestures—are less observable, whereas the larger-scale gestures communicate musical articulations that are almost simultaneously delivered and associated both physically and sonically with the interaction. The two gestural domains provide the audience with a familiar context and a more aesthetically accessible laptop instrument performance due to their familiar gestural vocabularies—conductor's and "cospeech" gestures.

The virtue of the Armtop is that it visually amplifies the musical gestures, expanding the performance space of a laptop instrument performer. The instrument is designed to be seen. Nothing is hidden; the focus is on the physical performance, gestural interaction, and their sonic correspondence. This relationship between body movement and sound reclaims a form of physical aesthetic that is often difficult to communicate in laptop performances, including laptop orchestra performances.

Felt Sound

In Felt Sound (see Figure 8), we explore the expressive and communicative nature of body movement by borrowing signs from ASL, with or without their overt meanings (Cavdir and Wang 2020). With this gestural vocabulary, we aim to shift musicians' attention to a nonmusical gestural expression and to physical sensations delivered through in-air vibrations. Felt Sound offers a shared musical experience not only for D/HoH but also for hearing audiences, by delivering music through physical sensations that are both felt and heard. The instrument provides kinesthetic and vibrotactile feedback beyond visual through gestural interaction and its composition.

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Figure 8. Felt Sound adopts a set of ASL gestures that creates a choreography for non-ASL audience members and a familiar visual feedback channel to the ASL signers. Three images show the consecutive instances of the "music" sign which is performed by waving one hand over the other palm facing up.

Its performance challenges the idea of music as a solely auditory experience. Combined with gestural elements, Felt Sound's low-frequency and high-amplitude sound composition allows performers and listeners to feel the music through their entire body.

The interface combines several modules to capture varying levels of gestures: nuanced finger gestures, hand gestures, and smaller-scale arm gestures from both hands' interacting with each other. We designed the fingertip, enclosure (for passive elements such as magnets), accelerometer, and controller modules to allow composers to customize the interface for their gestural and musical compositions. The fingertip modules include a Hall effect sensor triggered by a wearable magnet and force-sensitive resistors for continuous sound control. Whereas the force-sensitive and Hall effect sensors are fixed on the 3-D printed fingertip structure, the wearable magnet can be placed on either the front or back of the palm, or worn on the wrist, depending on the desired gestural interaction. Similarly, the musician can wear these fingertip sensors all on one hand or distribute them to both hands to capture the interaction between the two hands. Because the detection mechanism is limited to available sensors, the modular design creates the flexibility to extend gesture-to-sound mapping from nuanced gestures (fine finger interaction) to handshape (handform), orientation, and movement elements of sign language (Valli and Lucas 2000). The semantic units of sign language additionally include location and facial expressions (Goldin-Meadow and Brentari 2017). In the first prototype, we exclude these two elements in gesture detection but utilize them as performative elements. Gestures from ASL can appear as either static or dynamic hand gestures when the gestures are based on a movement-and-hold model (Valli and Lucas 2000). Our sensor-based detection model focuses on the dynamic hand gestures. We include a subset of ASL gestures (see Table 1) in the mapping by combining the modules on the wrist, fingers, and hand itself of both left and right hands. For example, single-finger interaction can be extended to multiple fingers to create fist opening and closing gestures. We focus on capturing the nuanced gestures via pressure sensing on fingertips, fingers closing, fingers tapping to the palm, and the fist closing and opening gesture, as well as their dynamic motion using an accelerometer module (see Figure 9).

Additionally, Felt Sound offers an inclusive performance practice for both D/HoH as well as the hearing participants. The concept of "shared"

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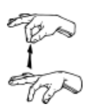
Table 1. Gesture-to-Sound Mapping

ASL Gesture	*Meaning*	*Sound Engine*	*Detection*
	Music	Low-frequency beating	Acceleration
	Show	Trigger drones	Magnetic sensing
	Poetry	Frequency change	Pressure sensing and acceleration
	Empty	Clear all sound engines	Magnetic and pressure sensing
	Discover	Add a new sound engine	Magnetic and pressure sensing

experience of music performance has not been explored much as an explicit feature of accessible DMI discourse. This approach offers a musical form that challenges the definition and adaptation of popular music, made for hearing communities, for D/HoH musicians and listeners. It rather offers an equalizing musical entry point to both communities. We believe that regardless of the help from technology, music composition and performance can become more inclusive music. Contrary to informing D/HoH listeners about the missing musical components, we are motivated to communicate musical experiences through multi-feedback channels, primarily auditory and kinesthetic experiences. Our approach focuses on delivering musical experiences through physical sensations, emphasizing felt experiences (Sheets-Johnstone 2020). This approach allows us to design a more inclusive performance space, drawing gestural and auditory components from two domains. Its performance invites both communities to share a physical experience rather than a conventional music performance. The high amplitude, low-frequency sound output from the multichannel surround subwoofer array can be physically felt through the body. The listeners are encouraged to sit close to, preferably in front of, the subwoofers to experience in-air acoustic vibrations. These vibrations deliver spatial information that differs from localized vibrotactile feedback modalities. Instead of delivering musical information of popular music from the hearing culture, Felt Sound creates music and performance practices that can reach to both communities with the same physical sensations. This performance form invites all listeners to familiarize themselves with each other's musical experiences (video excerpt: https://youtu.be/HwVBk2Mr-lg). For example, in our qualitative user studies, one audience member stated that, rather than feeling connected with other members in the audience, what was felt was a more one-to-one with performer, and was curious how it felt to actual members who use ASL as a means of communication (Cavdir and Wang 2020).

In addition to providing nonauditory musical experiences, this performance practice delivers the expressive qualities of movement. Felt Sound's

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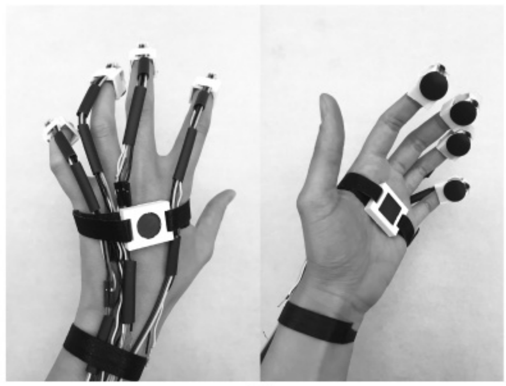
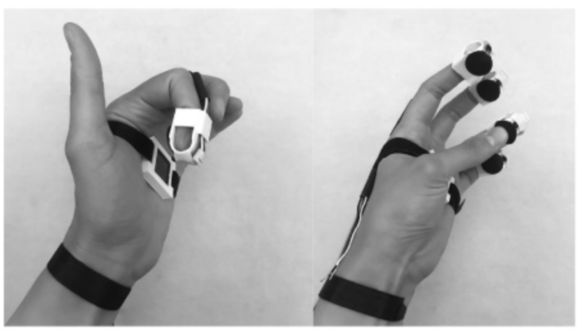
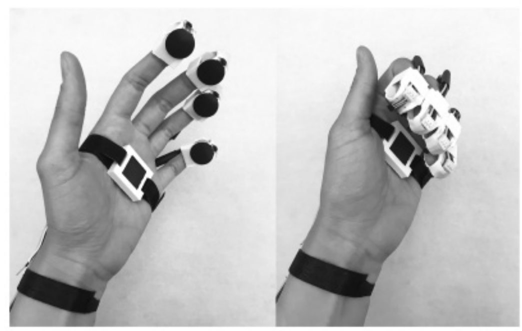
Figure 9. Individual modules allow for different combinations of the sensors, thus gestures. The pairs of images show the fingertip and magnet modules worn on the same hand, front and back (a), the activation of the sensor using one fingertip module (b), and the activation of multiple sensors using four modules (c).



(a)



(b)



(c)

performance highlights the metaphors in the gesture-to-sound mapping that create a visual as well as a kinesthetic feedback channel. Our mapping carries the expressive qualities in a gestural domain whose primary purpose is to communicate. Felt Sound allows the musician to perform the ASL words and their associated signs independent from their overt meaning and narrative; instead it focuses on the metaphors used for such gestures. For example, in the exit questionnaire, one audience member reported thinking that the "discover" gesture (see Table 1) seemed as though the performer were pulling the sound out of her left hand when it was used to add a new sound engine to the composition. ASL signs in Felt Sound, in general, are used as interpretations of these words' inherent meanings. The functionalities of these gestures are not limited to their sole communicative meanings in sign language; they are rather metaphorical, inspired by ASL poetry. Some gestures are more closely related to their meanings, whereas others adapt movement patterns and qualities into the gestural composition. As an example, Felt Sound uses the ASL gesture for "empty" to clear all the sound engines—in a way, to empty the sonic space.

Our approach to the gesture-to-sound mapping problem in DMI design (Wanderley and Depalle 2004) is based on the connection between the meaning of a given gestural vocabulary in a nonmusical domain and the sound design, while still allowing for exploration. This approach becomes more crucial when working with people with hearing impairments, since they might have little access to music education or listening opportunities.

The significance of Felt Sound derives from incorporating a purely communicative gestural vocabulary into music performance. This design method transfers expressive qualities of sign language and also uses their overt meanings as a metaphor in the gesture-to-sound mapping. The composition

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and performance design inherently offers shared musical experiences, discussed in more detail in the Performance Practices section.

Aesthetic Evaluation

We believe that an effective evaluation of MDMI designs requires examining the design, performance, and musical experience as a whole. This aesthetics-based evaluation seeks to understand the quality of the experience and the overall success of the instruments. Our evaluation approach aligns with the artful design principle, "There is an aesthetics to interaction," and the idea that a meaningful assessment of new musical instruments ought to include the music and performance practices that the instruments can afford (Wang 2018, Sec. 5.2). We take an artistic and performance-based approach to evaluate our three case studies through (1) a performance-based assessment and (2) a critical exercise to capture our integrative approach in a set of design principles.

In this type of evaluation, we highlight a strong consideration of both the performers' and the audience's process, since the process becomes crucial for the artistic output. Performance practices for a digital musical instrument serve as a proof for the instrument's potential for creative outcome. We follow a practice-based research approach (Candy and Edmonds 2018; Glăveanu 2010) to assess the instruments and their performance practices within the design process. Circling back to our integrative approach (see the Integrative Approach section), performance practices both emerge from the design process and serve as a design stage. As Candy and Edmonds (2018) emphasize, artifacts (such as performances, compositions, and designs) play an important role in "new understandings about practice" in which "practice and research operate together."

Following Candy and Edmonds, we evaluate the instruments' *capacity to create* by capturing the performance as creative artifacts, developing composition and performance practices, artistically and qualitatively reported through the participants' self-reported experiences and artistic outcomes, and summarizing these experiences in design principles. The artistic outcomes include not only performances but also performance practices, compositions and scores, and implementation documents.

Performance Practices

We explore performance practices with DMIs by prioritizing the first-person experience of both the performer and the audience (Varela and Shear 1999; Höök et al. 2018). The performer's presence is inherently critical when musician–instrument mediation not only supports movement experience but also incorporates the performer's body into the physical interface. Similarly, the audience's presence in the musical experience affects the artistic performance shared between performers and the audience. Performing with a combination of musical gestures and expressive body movements offers a bodily experience that can be communicated with the audience through the physicality of the performance Cavdir and Wang (2022).

We prioritize designing shared performance practices across disciplines such as music, dance, and sign language. For example, Bodyharp incorporates musical gestures and dance movements into the instrument for a performance space that can be shared between musicians and dancers. Armtop adapts conductor's and cospeech gestures for the physical laptop instrument design to offer better transparency in gesture-to-sound mapping for the laptop orchestra audience. Felt Sound combines musical gestures with sign language motions and offers shared musical experiences for the D/HoH and for the hearing participants.

More specifically, the virtue of these performances derives from the instruments' gestural vocabularies. The musical and bodily interactions allow performers and the audience to communicate musical expressions through a shared context. In *Liriope* (a performance with Bodyharp), dancers and musicians reported that the presence of Bodyharp allowed them to communicate with each other, both through its movement patterns and qualities and through their corresponding sonic outcomes. The dancers follow Bodyharp's dance-like

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sound-generating arm gestures while musicians receive sonic cues based on the performer's musical gestures and bodily movements. The instrument's physical affordance allows Bodyharp's player to build a vocabulary of musical and dance gestures and create music through mimicking a dancer's movement.

The dancers in *Liriope* reported that they improvised in response to Bodyharp's dance-like gestures in addition to its music. A dancer with contact improvisation background shared that during her improvisation, she was following the Bodyharp's arm gestures. Similarly, musicians expressed that Bodyharp's performance served as a bridge between traditional musical instruments and dancers. In this performance, we observed that the Bodyharp's performance can benefit from increased transparency in the mapping, based on the audience's comments. Although they appreciated the bodily expression of the instrument and its gestural interaction with dance and musical gestures, they expressed difficulty understanding the gesture-to-sound mapping. To address this concern, instrument in the next prototypes used a physical model of a string instrument as the main sound engine (Cavdir and Dahl 2022).

Armtop's audience reported that the transparency between gestural interaction and sound mapping created an inclusive communication between the performers and the audience. The performer's arm has a sound control function while performing communicative gestures, as though each note is physically being offered and extended from the player to the audience. This gestural performance offered the audience an aesthetically accessible musical experience with the laptop orchestra. This performance practice added an embodied dimension that made visible what would otherwise be mostly indiscernible interactions between the performer and the laptop.

Additionally, the audience shared that they "could finally relax and enjoy the performance without trying to understand what was happening on the stage." Based on their feedback, in the next physical laptop instrument designs we continued to compose more tonal music for laptop orchestra and to design gesture-to-sound mappings that more clearly communicate the action-to-sound correspondence with not only gestures but also forms borrowed from traditional instruments (Cavdir et al. 2019). According to the audience, the bodily expression of the Armtop was still the strongest aspect of the performance and, as a result, these practices could be expanded to performers' instruments, which the designers applied in the next iterations.

Similarly, in Felt Sound, the audience reported a body-to-body connection between the performer and the audience members. One audience member expressed the physical sensations: "I felt like the sounds are not perceived through pinpointed sources, but rather through the entire body. The sounds definitely embraced the bodies within the audience." and "the connection was more one-to-one between the performer and myself." They expressed the effectiveness of the metaphorical representation of the ASL gestures and their sound mapping. One audience member highlighted the fluidity and sonic representation of the ASL gestures as: "I very much like the fluidity of the gestures and the way it looked like you were pulling the sound out of your left hand" (referring to the "discover" gesture, see Table 1).

This performance emphasized the shared listening experiences among people with diverse hearing abilities, exploiting the physicality of both the performance and listening (Cavdir and Wang 2020, 2022). We observed that the gestural interaction and composition based on a communicative gestural vocabulary supported delivering movement qualities through sound. One participant reported that "the felt sound highlighted moments of silence for me more so than traditional sound. I felt light and free in those moments and active in the moments of more intense vibration." Some participants shared their experience with the gestural performance; as one said, "The premise of the piece felt like a physical expression of music through low-frequency sounds. Combining it with gestural elements created a powerful body-to-body connection."

Developing performance practices and exploring the instruments' creative potentials helped us to identify common design themes and to simultaneously utilize them as tools to evaluate these instruments in new contexts (Ramsay and Rockwell

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2012). We discuss the design themes in the following section.

Design Principles

Supporting our aesthetic evaluation, we present principles for designing movement-based digital musical instruments. We evaluate these instruments based on how successfully they capture the following design principles.

Principle 1: Gesture First; Interface Later

Designed based on a gesture-first approach, movement-based instruments focus on musicians' gestural interaction and movement awareness. The physical interface design follows the gestural vocabulary and gestural interaction design. Bodyharp's interface is designed to capture dancers' arm movements as well as musicians' nuanced finger gestures. Similarly, Felt Sound first incorporates ASL gestures, and the hand interface is later designed to capture these gestures.

Principle 2: Take Advantage of Existing Skills, Extended with Body Movements

Musicians develop mastery of nuanced small-scale motor skills whereas the traditional instrumental practice limits the use of body movements. Utilizing both instrumental skills and expressive body movements is one of the core design principles of this research. Armtop shows how to adopt gestural skills from both domains to laptop instrument interface and performance. This approach is not limited to physical interface design, but extends to gesture-to-sound mapping.

Principle 3: Dissolve Boundaries between Body and Instrument

Bodyharp presents the physical and conceptual melding of the musical instrument with the musician's body and body movements. This principle supports designing interfaces that include both the physical interface and the musician's body to form the full instrument. Neither is an augmentation of the other, but both complement each other.

Principle 4: Seek Inclusivity; Design for Shared Performance Context

Borrowing gestures from two distinct domains inherently invites at least two audience or performer groups to share a musical experience together. For example, Felt Sound invites both hearing and hearing-impaired audiences. and Bodyharp invites both musicians and dancers. These performances offer shared experiences for increased accessibility, inclusivity, and collaboration for people with diverse abilities.

Principle 5: Extend the Musician's Kinesphere

An important design principle derives from the need to allow musicians to develop movement awareness using MDMIs. We focus on designing interfaces that extend the musicians' performance space (kinesphere) with body movements.

Conclusion

This article has presented the design framework for movement-based digital musical instruments that extend the gestural vocabulary of musicians, as well as the physical affordance of the interfaces with *borrowed gestures*. We introduce the concept of "borrowing" gestures from musical and nonmusical domains into DMI design and performance. We discuss transferring such gestures' expressive and communicative qualities into music performance through three case studies, including the designs of movement- and body-based instruments and their performance practices. Contributions of this article include: (1) description of an integrative approach that embodies the performer's body as much as their bodily movement in the physical interface, (2) three case studies designed using this approach that attempts to unite two domains of gestural interaction, and (3) a performance-based aesthetic evaluation and a set of design principles. We approach design and performance practices as

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a whole, melding these three areas of contribution. This approach leads to new possibilities for creating performance spaces that are more inclusive.

As we study these research outcomes, we would like to conduct further movement studies with our interfaces. Our design framework creates an interaction domain to capture gestures' movement qualities (style), meanings or intentions (and their associated metaphors), and expressivity. Building upon embodied design and movement-based interaction, our case studies show that by affording gestural interaction between musical and nonmusical domains, the instruments allow performers to carry either domain's expressive and communicative movement qualities. A more in-depth study on the contributing factors as well as higher-level descriptors of borrowed gesture qualities could provide information about the kinesthetic interaction between performers. Future studies will support this practice-based approach with further movement analyses to investigate musical interaction through kinesthetic channels.

These instruments and their design framework are not meant to replace existing design frameworks but rather to build upon three main interlaced approaches and to offer embodied examples in order to address the gap between physical interfaces and nontactile full-body interactions. This aspect of our designs poses some limitations due to the physical boundaries that the instrument-body connection brings. So far, we observe that such boundaries benefit musicians by offering familiar musical mediation. We expect similar experiences for a greater user group beyond musicians (such as dancers or ASL signers), since these interfaces require extending the use of bodily movement in music performance. Similarly, the physicality of the interfaces and the performances need special setups (for example, a subwoofer array for Felt Sound), and there is a need to bring diverse communities together (such as musicians and dancers for Bodyharp, or listeners with and without hearing impairment for Felt Sound). Both requirements challenge the reproducibility of the musical experience.

Through the design of movement-based interfaces with "borrowed" gestural vocabularies, we investigate this unexplored area by asking these research questions: (1) How can we design new musical instruments that embody performers' bodies as well as their body movements in the physical interface?; (2) Which nonmusical expressive and communicative gestures can be transferred to music performance as instrumental gestures?; and (3) How can we design movement-based instruments and their performance practices that afford such a gestural space? Often, the numerous designs of new musical interactions create a duality between body and instrument, encouraging us to seek answers for our understanding of body movement and musical experiences.

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