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Performers' Use of Space and Body in Movement Interaction with A Movement-based Digital Musical Instrument

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ABSTRACT

Movement-based musical interfaces support performers' music and movement expressions by drawing from expertise and creative practices of both disciplines. In this work, we qualitatively and quantitatively analyze the movement interaction of participants with Bodyharp, a movement-based musical instrument. This wearable instrument offers musical affordances that allow performers to extend beyond small gestural spaces. Its wearable design encourages the performers to move while creating music and to express while using their bodies. Data was collected from twenty participants' interactions, reflections, and compositions with Bodyharp. Video recordings of the experiment were annotated and qualitatively analyzed to reveal which performed gestures directly contribute to sound production and modification and which gestures accompany these musical actions. For a subset of participants, Musical Gestures Toolbox was used to further quantify the gestures. Using the Laban Movement Analysis framework, we observed participants' use of space and body in their interaction with a movement-based musical instrument and how their backgrounds in music or movement (based on participants' self-reported experiences) influenced the interaction. Our results offer design practices for creating new interactions at the intersection of music and dance.

CCS CONCEPTS

• **Human-centered computing → User interface design**; *Sound-based input / output*; *Gestural input*; • **Applied computing → Sound and music computing**; • **Hardware → Sound-based input / output**.

KEYWORDS

movement-based interaction, digital musical instrument design, dance practice, embodied interaction, human-centered design

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1 INTRODUCTION

Whereas traditional acoustic musical instruments were mainly designed to focus on the constraints of the sound-generating structures (e.g. the vibrating air column in a wind instrument or vibrating string in a string instrument), the interaction with digital musical instruments (DMI) allows for more freedom in movement and performance space. An instrument that allows both small-scale nuanced gestures and large-scale expressive body movements enables performers to musically interact in these two gestural spaces and allows them to leverage their backgrounds in music, movement, or both. Earlier work has studied computationally extracting and characterizing gestures, both in music performance [37] and portrayals of emotion [13]. In this paper, we use a combination of qualitative and quantitative approaches to investigate musicians' and movers' interaction with a movement-based musical instrument within the frameworks of *Laban Movement Analysis* [21].

Schacher [33] explains three conventional research approaches to movement and computing in creative applications and discusses a fourth approach that combines methods and deploys the key elements from these other approaches. The author explains the advantage of using this approach is that the researchers can construct and control "the full adaptive loop between artistic intention, human movement, machinic response, and human perception", emphasizing "the impact and significance of the human in the loop."[33] We believe that the best approach to our research lies at the juxtaposition of practicing, observing, articulating, and measuring body movement and movement expression in the specific context of music-making.

We expect that users' backgrounds in music interaction and previous experiences with musical instruments influence how participants use their body movements with a movement-based instrument, an instrument that provides both musical and non-musical gestural interaction. The overall goal of this work is to explore how such gestures can be characterized in DMI interaction and how movement practice contributes to exploring new affordances in musical interaction. Observing and analyzing variances in participants' interaction and how participants with different artistic backgrounds share the dual gestural vocabulary reveal new insights to the correlation between movement and musical expressions. We combine qualitative and quantitative movement analysis methods to study how participants' experiences reflect in their movement interaction in terms of body and space use. We strive to combine these approaches by placing this work at the center of Schacher's model of movement and computing research [33]. Specifically, the research questions we focus on in this paper are:

- How do participants' artistic backgrounds and experiences influence their musical and movement interactions?

- Do movement backgrounds and experiences influence the performer's kinesphere?

The paper is organized as follows: In Section 2, we provide an overview of the related work on gestural interaction in music and movement analysis frameworks. The interface design and implementation, user study design, and participant selection processes are detailed in Section 3 and 4. We report the results of the movement analysis and our observations, drawing from frameworks (such as Laban Movement Analysis, LMA) and analysis computed using the Musical Gestures toolbox [1] in Section 5. We discuss the results and observations, comparing the interaction of two subgroups: *Movers* and *Musicians* in Section 6.

2 RELATED RESEARCH

2.1 Movement-based Interaction

Movement-based interaction introduces an approach that focuses more on the interaction of the moving body as an integral part and less on the interface [24]. Our approach reflects several key concepts of movement-based interaction frameworks: the development of movement practice and vocabulary, first-person and lived experience of movement, and the aesthetics of kinesthetic experiences [25].

Several researchers have studied first-person and lived experiences of movement interaction. Many of these recent design and research frameworks are dedicated to *role of the body and bodily movement.* However, as Moen emphasizes, "... we still lack the tools, knowledge, and vocabulary to discuss the movement and the experience of movement" [31]. To extend her argument, this section emphasizes that we need not only the tools to experience movement but also the interaction modalities to reveal the motivation and drive to move in response to music that is not often visible to the observer or even to the performer.

Such tools that enable movement-based experience are not only beneficial for performers but also necessary for designers who design for the mover (dancer, musician, or simply the user of the movement-based interaction). In order to design for human movement, designers need to develop a sensibility of movement not just in theory but also in practice. Hummels et al. describe the movement-based design as "doing and experiencing while designing" [16]. Similarly, movement-based interaction design translates to music to encourage musicians to develop a movement awareness and offer them, as well as the designers, instruments to practice bodily movement. Loke and Robertson provide the "moving and making strange" framework, that approaches the moving body as a design material and a design sensibility [26]. They develop a design perspective based on "the central role of the body and movement in lived cognition." [26] The authors present activities combining the perspectives of observer and machine. Similarly, Larssen, Robertson, and Edwards study tangible and intangible interactions to evaluate "the feel dimension" of movement-based interaction [23].

Other researchers have focused on soma-based design and aesthetics of the interaction [15]. Similar to movement-based interaction design, somaesthetics focus on the instrumentality of the body [30] and extend this framework with the social, emotional, and aesthetic aspects and design considerations. Similar to Sheets-Johnstone's work on the "primacy of movement" [35], somaesthetics prioritizes our bodies and human movement and approaches them as tools to understand human perception and understanding. Höök supports the union of the body and mind and compares this unison to the aesthetics of interaction. She states that "aesthetics comes not from the individual parts of the system we are designing, but from the whole" [14]. This emphasis on aesthetics and how to evaluate it as a whole is crucial to discriminate aesthetic movements of some from any other movement or experiences. Based on Dewey [10] and Shusterman's [36] theories, soma-based design explains this difference with the distinction of intentions. Somaesthetics movement derives from inner attitudes and intentions of the mover beyond habitual movements, encouraging (1) rediscovery of movements that we already know [1] and (2) expansion of our existing repertory of movements. Additionally, the soma-based design uses the designer's lived body as a resource in the design process to highlight the first-person approach [14]. These studies contributed to different aspects of movement-based interaction and soma-based design. However, their applications for DMI design and practice that leverage movement practice and integrate choreography techniques into musical interaction are still underexplored.

2.2 Musical Gestures

In music performance, some gestures carry a functionality that is necessary to produce sound or modify the sound while some gestures can be accompanying, communicative, or performative that indirectly affect or have no influence on the sound. Defining these gestures still remains a challenge, especially for new musical instruments and interactions. Schacher et al. map the different terminologies and put the definition of gestures in relation to the composer, performer, and audience [34]. Jensenius et al. [18] categorize gestures into three functions: communication, control, and metaphor. This approach develops into a framework to study musical gestures, mainly through their functional aspects: sound-producing, sound-facilitating, sound-accompanying, and communicative [18].

Camurri et al. [5] and Cadoz and Wanderley [4] introduce different perspectives on studying musical gestures. Camurri et al. explain the term expressive gestures as gestures that convey information about affect and emotion. Cadoz [3] discusses instrumental gestures that are actively and intentionally performed to produce sound for both excitations of instruments or modification of the sound generation. Delalande refers to these gestures as effective gestures [18]. Jensenius et al. define such gestures with excitatory actions (e.g., hitting, stroking, bowing, or plucking) as sound-producing gestures [18].

Sound-facilitating gestures are defined as gestures that support the production or modification of sound [8] whereas sound-accompanying gestures are gestures 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 while Wanderley and Wanderley and Depalle define them as non-obvious or ancillary gestures [40, 41]. Although these definitions dissociate gesture from

[1] https://www.uio.no/ritmo/english/research/labs/fourms/software/musicalgesturestoolbox/

sound generation or modification, sound-facilitating gestures influence output sound contrary to sound-accompanying gestures. For example, Wanderley discusses how clarinetists' non-obvious gestures can contribute to sound quality such as clarinetists' changes in posture that might not necessarily be intentional but affect the sound produced by changing the musician's vocal cords [40]. On the other hand, musicians perform sound-accompanying gestures for solely expressive intentions or to follow the music. These gestures are not involved in sound production or modification.

The last category of gestures, communicative gestures, shares similarities with gestures defined by linguists such as co-speech gestures or sign language gestures [19, 28]. Although the immediate interaction using communicative gestures occurs between co-performers or performers and the audience, some researchers extend communicative gestures to composers' intentions in the piece. Jensenius's framework [18] excludes expressive gestures, partly due to expressive gestures' unclear or complex functionality. They carry aspects of both communicative and sound-accompanying gestures, in some cases even sound-facilitating. Dahl and Friberg studied performers' expressive movement and these movements' relationship to emotional expressions [9]. As much as these gestures aim to communicate musical ideas to co-performers or interact with the audience, they can also originate from the performer's interpretations of the musical piece and expressions of emotional intent.

Music literature overall lacks a consistent use of the terms, *movement* and *gesture*. Although they are sometimes used interchangeably, both terms formulate 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 paper, 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. The study uses *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/acoustic instrumental practice and new musical interactions.

2.3 Laban Movement Analysis

Laban Movement Analysis (LMA) characterizes human movement and offers a system to embody, observe, articulate, and communicate movement patterns and qualities departing from the concepts of Body, Effort, Space, and Shape (BESS) [21]. LMA was initially used to notate dance movement, observe and categorize more functional body movements, and understand the body's relation to the economy of effort [20]. This framework is broken into the four BESS categories: *Body* category focuses on what parts of the body are involved in the movement and how they relate to each other during movement. *Effort* category describes the qualities of movement which reveals the inner intentions behind the movement and what kind of energy we employ performing that movement. *Shape* category analyzes how body changes shape during movement from the body's forms, qualities, and flow support to its relation to the environment. *Space* category describes and notates where in space the movement progresses, how the movement relates to the kinesphere, and how geometrically the movement is observed.

Due to its rigorous language to analyze not only expressive but also functional movements, this framework provides a strong foundation for movement computing. Researchers have adapted LMA's theory of effort into their qualitative and quantitative methods to analyze movement and develop computational descriptors [22]. Alaoui et al.[11] and Mentis and Johansson [29] study how Laban movement qualities can be used to observe movement interaction. In Alaoui et al. [12], the authors provide tools and strategies for observing movement and using these observations in designing for movement.

To analyze movement, HCI researchers largely adapt LMA's effort qualities (e.g. [29]) but rarely include the other three LMA categories (body, space, shape). Larboulette and Gibet develop a computation framework by expanding these four categories with additional descriptors such as *movement activity*, *expansiveness/spatial extension*, and *movement dynamics/energy/power* [22]. Bernandet et. al. conduct a detailed review to assess reliability of the LMA system [2] as a whole. To our knowledge, little research in the recent literature has expanded beyond Effort in the application of LMA techniques, including Body, Space, and Shape categories, to design and assess movement-based *physical interfaces* for music in comparing the influence of participant's artistic backgrounds on the interaction.

2.4 Framing of the Present Work

Our study centres around Bodyharp, a movement-based musical instrument that allow performers to move while creating music with their bodies and to extend their performance space beyond small scale gestural spaces (Figure 1). We use LMA to observe performers' movement patterns and musical and non-musical gestures. Additionally, LMA allows us to compare and contrast these movement patterns between participants with different movement expertise, taking the participants' interpersonal differences into account. We depart from the qualitative annotation of movements and gestures and complement our annotation with automated video analysis. Due to the interaction modality of Bodyharp, combining dance and music qualities, we categorize expressive or dance-like body movements under musical gestures if they contribute to sound generation. Conversely, non-musical gestures are defined as the gestures or body movements that participants perform while playing the Bodyharp, but the they do not directly or indirectly contribute to sound production or modification (e.g. air gestures with the free arm).

Because the Bodyharp is flexible in shape and size, we analyze how performers respond to its dynamic shape with their bodies' shape qualities. Additionally, we focus on participants' varying space use from kinesphere to spatial intention, specifically comparing the effects of different artistic backgrounds on this spatial interaction. Our hypothesis is that the participants with music backgrounds would perform gestures with different uses of LMA's *Space* and *Body* categories compared to the participants with movement backgrounds.

Figure 1: Bodyharp consists of two wearable interfaces (attachment to the performer's arm and a hand controller) and a main instrument body.

3 DESIGN AND IMPLEMENTATION

3.1 Gesture-based Approach to Sound Mapping

The gesture-based approach integrates the performer's body into the physical interface and the body movement into the sound design; more specifically, sound mapping is based on the gestural vocabulary and the instrument affordances. This iterative design process approaches the sound mapping by first defining a set of gestures and movement patterns; in other words, gestures come first and the instrument design is adapted to the gestural vocabulary. After building this correspondence between the body movement and sonic affordances, the musical interface is designed to capture the performer's body as an extension of the musical instrument. Finally, we develop performance practices by combining composition and choreography.

The combination of instrumental practice and extended embodied techniques reflects to the sound mapping. The nuanced, smaller scale musical gestures are mapped to string instrument sounds whereas the larger body movements are mapped to sound effects that are outside the instrumental practice. The interface suggests a string interaction with its plucking gestures and string sound model, and this interaction is simultaneously extended by the instrument's affordances beyond a traditional gestural vocabulary. Following this framework, the performer starts interacting with the Bodyharp by plucking or stretching the strings and continues by controlling the parameters with finger gestures. The sound excitation starts by playing individual strings and is followed by adding sound effects created by larger arm movements. The hand controller allows the performer to control the parameters of these sound effects. Similarly, larger body movements, either captured by the strings or by the accelerometer, change these parameters while simultaneously extending the musician's performance space. These movements provide more freedom in space and expression, indirectly controlling but influencing the music.

3.2 Interface Design

Our approach to Bodyharp's design employs the design consideration that derives from simultaneously capturing aforementioned dual gestural vocabulary. We approach this concept by coupling the performer's gestures with a wearable interface at these two levels of body movements, contributing to kinesthetic and visual aspects of the performance. The larger scale movements exude a dance-like quality that invites embodied skills and somatic expressions to be transferred into music performance. Smaller-scale gestures offer nuanced controls over musical events that are captured by more tactile sensors. This interaction focuses on finger or hand gestures in a smaller periphery. Figure 1 presents some of the nuanced gestures and different sizes that the instrument's and performer's bodies create. The first image shows how Bodyharp can be played closer to the instrument's main body and the other two images illustrate how it is played standing up.

Bodyharp consists of an instrument body and wearable parts including a hand controller and an attachment to the performer's arm that connects the strings to the arm. Figure 1 presents the Bodyharp's six 3D printed interface components, showing (1) the wearable hand controller enclosure with tactile sensors, pressure sensitive resistors, an accelerometer, and a Teensy[2] controller, (2) the wearable arm-string attachment piece, and (3) the instrument body enclosing the string-pulley system. The connection between the instrument and the wearable parts completes the interface by integrating the performer's body, thus the instrument cannot be considered without its performer [6]. This system offers new embodied ways of designing musical instruments and considers the instrument and the body as extensions of each other [6, 7, 27, 32]. Cavdir et al. provide an overview of similar body-based, movement-based, and harp-inspired instruments and gestural controllers in the preceding research [7].

3.3 Sound Design and Mapping

Bodyharp's sound mapping was implemented in Chuck audio programming language[3] to receive and process the sensor data, control string physical models, and record the audio output of participants' performance.

The sound-mapping related to small-scale gestures use the data from plucking strings, interaction with the tactile sensors such as push buttons and sliders, and pressure sensors (FSRs):

- The three push buttons control the chord progressions in three scales, allowing the instrument span over a nine pitches in one scale, twenty-seven in total. In one scale setting, the length of the strings divide the pitch class into three chords. The shortest height maps to the lower frequency chords and the notes raise to higher frequencies with increasing length.

[2] https://www.pjrc.com/teensy/
[3] https://chuck.cs.princeton.edu/

- The pressure sensor, positioned under the thumb, controls the quality of the filter. Dabbing interaction on the sensor creates a pulsating effect on the sound similar to vibrato and tremolo.
- One slider controls the gain and the other one controls the note duration by changing the time constant of the string model.
- The square pressure sensor, positioned on the back of the hand controller, increases the drive of the filter. While overdriving the filter and distorting the waveform, the pressure and touch data detected by the FSR creates a feedback effect with a short delay line.

The string model is excited only by the string interaction. The change of the string displacement in x-y axis beyond a certain threshold triggers the string model and excited the sound. Once the sound is played, nuanced gestures provides expression with musical features and various sound effects. The large-scale gestures are detected by the string excitement and the accelerometer. These movements are mapped to more indirect control of sound effects. For example, stretching the strings beyond plucking range plays a long-duration note, extending the attack and decay time of the ADSR filter.

4 EXPERIMENT

4.1 Study Design

This two-part study was conducted to first lead the participants to learn, explore, and create with the instrument and its affordances and later collect their self-reported experiences through a questionnaire and semi-structured interview. The first part of the study allowed participants to develop their own movement/gestural vocabulary while learning and exploring the instrument. In the second part of the study, precomposed themes were individually discussed in semi-structured interviews. In addition to participants' self-reported experiences, the study collected their musical compositions as an artistic outcome. This practice-based method encouraged participants to (1) more intentionally approach music-making through body movement, (2) build movement awareness of their movement interaction in order to replicate the sonic and physical gestures, and (3) utilize improvisation in music composition and movement choreography beyond exploratory practices. This interaction leverages music and dance expertise and reveals the behavior patterns resulting from participants' backgrounds, artistic experiences, and approaches to creation.

4.2 Participants

Following the IRB approval for non-medical human subject studies, a total of twenty participants were recruited from local artists and authorized in-person researchers from Stanford University. The participants were invited via email and were provided with the information sheet and oral consent from when they arrived for the study. The participants reported their background in music, movement, or both at varying degrees of experience (from informal practice to professional levels, see Table 1). The listed experiences are based on what the participants reported, indicating an on-going practice. Because no musical or movement experience was required, these reported experiences range from self-practice and amateur training to professional training. Thirteen of the 20 participants, of which two were professional dancers, reported dance/movement experience. Nineteen of the 20 participants had music and/or composition performance experience. Some participants had both types of experience. For example, twelve participants practiced both dance/movement and music in their artistic practices. Although no music and movement experience was required for the study, the participants all had multidisciplinary artistic practices.

Table 1: Participant Demographics and inclusion in subgroups for analysis.

P	Age	Music	Movement	Dominant	Subgroup
1	35-40	1	35	Movement	Mover
2	50-55	2	15	Movement	NI
3	25-30	10	5	Music	NI
4	25-30	5	16	Movement	Mover
5	45-50	41	6	Music	Musician
6	30-35	27	0	Movement	Musician
7	70-75	-	-	-	NI
8	65-70	30	0	Music	NI
9	20-25	20	22	Music and Movement	Mover
10	-	-	-	Music	NI
11	45-50	30	30	Movement	Mover
12	30-35	10	11	Music and Movement	NI
13	20-25	14	0	Music	NI
14	20-25	22	12	Music and Movement	Musician
15	25-30	25	1	Music	NI
16	20-25	15	3	Music and Movement	Musician
17	35-40	30	0	Music	Musician
18	20-25	20	3	Music	NI
19	20-25	18	6	Music and Movement	NI
20	35-40	26	0	Music	NI

For the quantitative analysis, a subset of participants were selected. The sixth column in Table 1 presents whether the participants were included in the analysis subgroups as *Movers* (dominant movement backgrounds and practice), *Musicians* (dominant music backgrounds), or not included *NI*.

4.3 Setup

A video camera was positioned directly in front of the stage where the instrument was fixed to the ground and the user interacted in a limited area defined by the instrument's string length. The audio was internally recorded using the Chuck programming language [4] and externally recorded using a Zoom audio recorder positioned next to the camera.

4.4 Procedure

The six-step study asked participants to learn the instrument through guided exploration and create artistic outcomes. The instrument was introduced in a standing pose while participants were encouraged to change levels and explore their performance space. We

[4] https://chuck.cs.princeton.edu/

led the participants in creating artistic artifacts, collected feedback through questionnaires, and held a semi-structure interview with selected themes and questions. The first four steps encouraged participants to learn the gesture-to-sound mapping and develop a movement vocabulary by exploring: (1) the instrument with no sound feedback, (2) the string interface and its corresponding sounds using larger body gestures, (3) the hand controller, plucking strings, and the sonic response using nuanced gestures, and (4) a combination of both gestural domains. The final two steps asked participants to create an artistic performance with and without the instrument: by (5) composing a short musical statement based on the movement patterns and gestures they explored, and (6) performing a free movement improvisation in response to their composition. They reflected on their first-person experience with these creative processes (composition and choreography) through the completion of an exit questionnaire and a semi-structured interview, elaborating on three key topics: (1) the instrument's affordance on movement and sound interaction, (2) gestural vocabulary they developed during the study, and (3) their body-instrument connection. The preconceived themes were developed based on core research considerations, experiences gathered during the project, Bodyharp's earlier prototype, and study design. The procedure was led following the individual elements from data collections to creative outcomes and performance.

4.5 Data Analysis

Based on the dominant practice reported in the exit questionnaire, participants were organised into two subgroups: *Movers* and *Musicians*. A subset of four movers and five musicians were then selected for further analysis. This subset was based on each participant's gestural vocabulary, if this vocabulary included both unique and shared gestures, and if these gestures were clearly articulated.The vocabulary was based on audio and video documentation of the experiment's composition stage, Step 5. In the current study, we limited our analysis to this stage for two reasons: (1) less exploratory, more structured session in Step 5 more clearly demonstrated each participant's frequently performed gestures and (2) this step also allowed us to observe which gestures and affordances were integrated into composition and choreography and how participants expanded these affordances and navigated through the interface's limitations. The gestures in Step 5 recordings were reviewed to be categorized according to the gestures' functionality, use by subgroups, and relation to the body and space. Based on the gesture categories, a subset of participants was formed for further analysis. Briefly, the analysis followed these steps:

1. Identify Pattern – We watched the videos and identified which gestural patterns the users frequently performed. We categorized the most commonly performed movement patterns and gestures unique to some participants.
2. Transcription and Annotation – We selected data to transcribe and annotate. We identified subgroups of participants who used one or more shared gestures more clearly than the rest of the larger group and performed unique gestures that expanded Bodyharp's gestural vocabulary.
3. Analyze Movements – We created a data set of shared and unique gestures of each participant from the selected subgroup. These video segments were analyzed using the Musical Gestures toolbox.
4. Collaboratively Review – We discussed video segments in collaborative data sessions with other researchers, isolating specific gestures and investigating individual LMA qualities and quantity of motion.

The movement patterns and gestures with Bodyharp were analyzed based on LMA's BESS framework, *Body*, *Effort*, *Space*, and *Shape* [21], in an observational analysis starting with us identifying the structural and physical characteristics of the participants' bodies while they were moving with the interface. The body category was particularly suitable for our dual gestural approach. By identifying which body part was moving, we were able to categorize such movement patterns into a gestural spectrum from small-scale, nuanced gestures to large-scale, expressive movements. When the duration, start, and end times were challenging to identify from the videos, the musical response supported the gesture annotation. Additionally, the *body* category allowed us to draw the relationship between the body parts that play the instrument and extract the gesture motifs and sequences relative to body organization and connectivity.

We observed the shape category of Bodyharp's gestures, specifically to analyze how participants interact with the arm attachment. Their interaction with the wearable part changed from arc-like to spoke-like arm movements. Similarly, this category revealed changing shape qualities, dynamically following and modifying the instrument's shape.

The instrument provided participants with more flexibility in extending musical kinesphere than traditional instrumental practice. We analyzed the space category of how participants explored different levels of performance space (e.g., different instrument shape and heights), how frequently change their use of space (e.g., level change), and how dynamically they modified their kinesphere (e.g., holding poses or performing standing up vs on the floor).

Participants' common and unique gestures were annotated with time frames. To understand how commonly and differently *Movers* and *Musicians* interact with Bodyharp, we computed the averaged number of times they performed the most commonly used gestures and movement patterns. We also analyzed these gestures in the video excerpts using the Centroid of Motion (CoM), Quantity of Motion (QoM), and motion history features of the Musical Gestures Toolbox [17].

5 RESULTS AND OBSERVATIONS

5.1 Gestural Vocabulary

During gesture annotation and categorization, we were able to analyze participants' movement interaction at three gestural categories: individual gestures (shared and unique gestures), gesture motifs, and gesture sequences (see Table 2). This categorization allowed us to compose not only an extended gestural vocabulary for Bodyharp, but also choreographic vocabulary of sequential gestures. Individual gestures were identified based on commonly and uniquely performed gestures, either revisited during the study or performed for a period of time. Some participants combined two or

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Table 2: Sample Vocabulary of Gestural Categories, Body Positions, and Movement States

Category	Examples
Individual Gestures (shared)	Plucking, Stretching, Arm Rotations, etc.
Individual Gestures (unique)	Shaking, Up-and-Down, Body-Half, Listening, etc.
Positions and States	Standing, Crouched, On the Floor, Level Change, etc.
Gesture Motifs	Stretching and Wrist Movement; Up-and-Down and Hold; Arm Rotation, Hold, and Listening, etc.
Gesture Sequence (e.g., P1)	Plucking, Stretching and Wrist Movement, Framing Body/Stretching with Body, [...], Level Change, Plucking and Wrist Movement

more gestures, repeated within the same time frame. These gestures were categorized into gesture motifs. Finally, we annotated the full sequence of gestures performed in Step 5. These gesture motifs were performed in different positions and states such as standing, crouched, on the floor, level change, and others. We observed participants performing some of the shared gestures in more than one state (e.g., plucking standing up vs plucking in crouched position).

Several gestures were shared across participants, including plucking strings, stretching strings, tactile sensor interaction, rotating and circulating their arms, and various movements to engage with their performance space. Many participants also played the instrument with unique gestures to their performances. For example, 'Mover' P1 played the strings by shaking her arm close to the instrument along the direction of the instrument's slots. Similarly, 'Musician' P5 created a clapping gesture to trigger touch sensors, and 'Musician' P6 performed up-and-down gesture and holding certain postures, combining string interaction with the tactile sensors.

The experiment led participants to develop their own gestural vocabulary while they explored how to create music with the instrument. We defined these gestures based on how intentionally and frequently they were repeated and performed in the composition stage to avoid accidental performing/identification. With this approach, we also observed how the explored gestures were learned and integrated into composition/choreography. If the gestures were repeated within the same time frame, we grouped these gestures into gesture motifs. The gesture motifs were computed as one when comparing the averaged number of the times that gestures were used in (Figure 2). They were computed separately if these gestures or gesture motifs were revisited after another gesture or motif. For example, Figure 5 shows P06's *up-and-down* gesture motif where she combines this vertical up and down movement with holding a standing pose where she touches the square pressure sensor and triggers the overdrive of the distortion filter. The repetition of this gestural pattern is clearly observed in the QoM graph (bottom panel in Figure 5). Although other participants also performed a similar gesture, P06's up-and-down movement was unique to her performance since this same motif was revisited multiple times and clearly articulated. In general, the shared gestures among participants of all backgrounds presented significant interpersonal differences. The core affordances and the sound outcome of the instrument supported our analysis in identifying such commonly used gestures.

Following participants' space and body use, we counted the occurrence of types of shared gestures. Figure 2(a) shows the sound-producing and -modifying gestures that were fundamental in interacting with the instrument. We observed that some participants stretched and extended the strings not only with their fingers and hands (*Stretching (nuanced)*) but also by engaging with them using their feet, arms, or other parts of the body (*Stretching (extended)*). This interaction was practically unique to the participants with movement backgrounds. The same interaction can be seen when participants use tactile sensors, specifically the square FSR sensor. While the majority of the musicians used the touch sensor with their fingers (*Tactile (nuanced)*), several *Movers* interacted by touching the sensor at different locations on the body (*Tactile (extended)*). Figure 2(a)) presents how frequently *Movers* and *Musicians* performed the body- and instrument-related shared gestures.

Figure 2(b) shows the gestures associated with space use in relation to the instrument and performers' kinesphere. The participants performed in different poses such as standing, crouched, or on the floor (sitting or lying). These shared space-related gestures were analyzed in relation to participants' use of space including more dynamic gestures such as up-and down-gesture which included multiple level changes. Almost all participants explored different vertical levels and dimensions of the instrument. In their use of space, musicians showed a tendency to vertically change their position such as up and down movement and hold poses such as standing or crouched while *Movers* extended the affordance of the instrument with a larger kinesphere such as playing lying down on the floor or rotating around the instrument as a sound accompanying gesture without effecting the sound.

5.2 Quantity of Motion

We computed the centroid of the motion (CoM) and quantity of motion (QoM) [17] for four selected gestures: *Stretching (nuanced)*, *Tactile (extended)*, *Crouched*, and *Up-and-Down.* Our analysis subset

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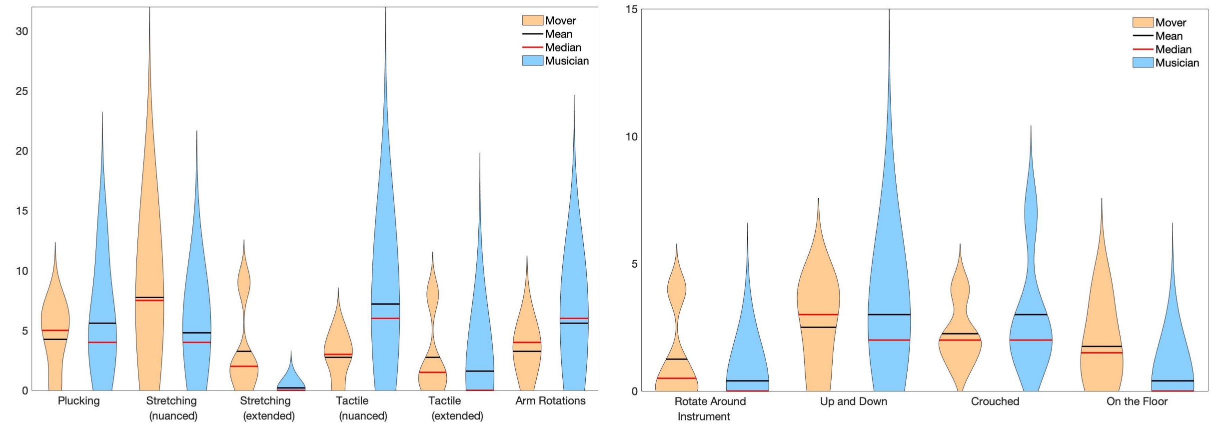

(a) Violin plots for the distribution of six commonly performed gestures among *Movers* and *Musicians*.

(b) Violin plots for the distribution of gestures relating to space use among *Movers* and *Musicians*.

Figure 2: Repetition of shared and spatial gestures, comparing *Movers* (orange) and *Musicians* (blue). (a) displays six commonly performed gestures for both groups (top). (b) The use of space for participants in both groups (bottom)

of gestures represented the shared body-related gestures, unique body-related gestures, shared space-related gestures, unique space-related gestures respectively. CoM graph presents the spatial displacement of motion over the period of the gesture. This descriptor allows us to compare the direction and area of motion of both the same gesture among two subgroups and the same gesture's different versions among one participant's multiple tries. Figure 3 shows 10 seconds excerpts of P16's four different performance instances of the same *Stretching (nuanced)* gesture. Although the QoM profiles considerably vary, the periodic pattern can be observed among all four versions. This pattern also reflects many personal qualities about P16's movement where he performs one larger stretching gesture with one hand and one or two smaller ones following the first one, grouped into one gesture motif. A similar periodicity can be observed in P6's unique up-and-down gesture in Figure 5.

QoM also provided a descriptor to compare the quantity of different body parts' movement. For example, Figure 4 shows the motion history and the CoM and QoM graphs. The large arm and string stretch with the *Stretching (extended)* gesture shows a larger period with larger value of QoM between seconds 5 and 15 while

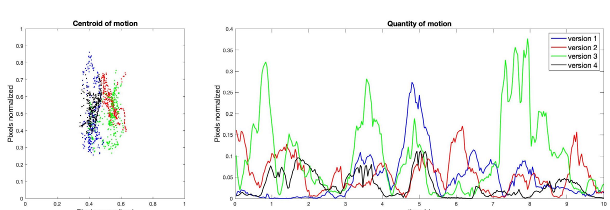

Figure 3: Like many participants, P16 performed the same *Stretching (nuanced)* gesture in several different ways and for varying durations. This figure presents 10 seconds of four different instances that P16 performed this gesture during Step 5.

the wrist movement shows a smaller period with less QoM value. Based on the CoM distribution, we can observe the directionality of the movement, e.g., horizontally wide movement in Figure 4 and vertically aligned movement in Figure 5.

6 DISCUSSION

In designing the Bodyharp and its experiment, our motivation was to study how participants can perform with musical and non-musical gestures in movement-based music-making. We hypothesized that the participants could reflect their expertise in music, movement, or both on the performance with Bodyharp while expanding the existing musical and non-musical gestural vocabularies. Based on our observations of their interaction, we also investigated their use of *Body* and *Space*, drawing from LMA frameworks.

6.1 Mover vs Musician

Based on Bodyharp's interaction affordances, we focused on two main groups of artistic practice: music and movement. Because Bodyharp combines gestures borrowed from instrumental and movement practices, we recruited participants with music, composition, or performance and dance, contact improvisation, or other movement practices. Even in the analyzed subset, many participants had experience with more than one artistic practice, and their multidisciplinary practices reflected in their interaction. For example, we observed some participants with more dominant practice in music who interacted with Bodyharp more similarly to the *Movers* subgroup in terms of the expansiveness of the gesture and body and space use. Comparing the distribution of the shared gestures in Figure 2(a) and 2(b), we observed similarities and differences in three main areas: (1) in learning the instrument, (2) expanding its affordances, and (3) creating musical phrases.

We observed the most significant differences in how participants approached exploring the instrument, with *Movers* typically being more explorative in their interaction. The experiment tasks asked participants to learn and create musical statements with the Bodyharp, regardless of their artistic background. All participants were in a "musician" role, except for Stage 6 where they improvised to their composition from Stage 5 with their movements. However, their approach and learning practice differed. From the early steps in the experiment, *Movers* interacted with the instrument using full-body movement. They used their bodies more frequently without concern for what sounds the instrument might create. For example, they used the strings to frame their bodies in different shapes and used their arms, feet, torso to stretch the strings and apply pressure to the force-sensitive resistors. When learning the instrument, *Musicians* performed gestures more aligned with instrumental practice such as plucking and tactile (nuanced) gestures. We observed that they leveraged their music background in nuanced interactions and in forming musical compositions, focusing more on understanding the sound mapping in detail and repeating musical phrases.

Both subgroups performed with shared musical gestures (plucking, stretching with hands and fingers, tactile sensor interaction, and arm rotations) as shown in Figure 2. Not all participants explored and integrated all shared gestures into their vocabulary. Almost all musicians played the instrument based on how it was presented in the experiment steps (Step 2.1,2.2, and 3). However, *Movers* extended this set of affordances by performing shared gestures in different body positions and movements states (e.g., plucking strings when lying on the floor or stretching strings with their feet) or by finding alternative ways to trigger tactile sensors (touching the square FSR sensor on their bodies). We observed that this exploration was closely related to their prior artistic practice, but the integration of gestures into their gestural vocabularies was influenced by the sound feedback. When participants in both subgroups understood the gesture-to-sound mapping, they started to perform that gesture more frequently.

When composing with the instrument, background in music composition and dance choreography played an important role. We noticed that participants who had experience in composition within the *Musicians* subgroup (P6) and in choreography within the *Movers* subgroup (P1, P4, P11) performed better while creating short musical statements during Step 5. They were able to repeat gesture motifs and sequences, combine different gestures, and use the gain control to isolate their musical gestures. The shared characteristics in their composition/choreography are having a clear start and end of the musical statement, performing with level change in their movement, combining different gestures to form gesture motifs, and performing both nuanced gestures and larger movements that leads to controlling sound effects and exciting the instrument with body movements. We believe that participants' experience of being different actors in the relational schema (Figure 1 in [34]) helped. For example, P6's interaction presented in Figure 5 shows the combination of three movements: (1) when she was leaning down and opening her arms, she triggered the strings, (2) when she was standing up, she increased the pitches of the chord, and (3) when she was holding her pose while pressing the FSR sensor, she increased the feedback sound effect. This combination also exemplifies exciting the instrument with body movements (c.f. "sound-producing") and controlling sound effects with nuanced gestures (c.f. "sound-facilitating" or "sound-modifying"). Similarly, the full gesture motif was repeated twice in her gesture sequence and the up-and-down gesture was repeated multiple times in the motif (as seen in the QoM in Figure 5). Future work can investigate whether recurrence maps [37] or Periodic Quantity of Motion [39] can be applied for further quantification.

While analyzing *Movers* and *Musicians* interaction with musical and non-musical gestures, their categorization benefited from using the musical information from performed gestures. For example, the pose holds in P6's up-and-down gesture (low QoM moments in Figure 5) are the instances where she triggered the feedback sound effect that continues to echo for a longer duration. Without listening to the musical response, these instances could not be grouped into the same gesture motif. Similarly, the gesture motifs and sequences provided musical scores for Bodyharp in line with earlier work on the cross-modal perception of musical structure in performance [38].

6.2 Use of *Body* and *Space*

Two main differences in *Movers*' and *Musicians*' approaches to performance with Bodyharp derive from the two groups' use of *Body* and *Space*. Engaging with these two LMA qualities also expanded Bodyharp's musical gestures from more conventional instrumental interaction.

We observed the change in the Body category in participant interaction with strings and the tactile sensors using different parts of their body. The functionality of the square FSR sensor was not explained to the participants, but they were encouraged to freely explore how to engage with it. Although not all movers used this tactile interaction, those who did engage with played the sensor with their arms, head, chest, legs, and/or knees. Only two musicians in the subgroup played this sensor using their arms or knees; other musicians preferred to play it with their fingers and hands. Among the *Movers* subgroup, only one participant did not interact with this sensor at all; all other movers played it primarily with their bodies (see *Tactile (extended)* as seen in Figure 2(a)). The movers' interaction with their bodies through this sensor showed a choreographic character accompanied by non-musical movements. On the other hand, musicians performed this extended tactile gesture for more practical reasons, e.g., their free hand was plucking or stretching the strings.

A similar interaction that draws performers' attention to both the instrument-body connection and the shape relationship was seen in *Stretching (extended)* gesture, the gesture that stretches one or more strings with body parts other than hands or fingers. Similar to *Tactile (extended)*, this extended gesture was also more frequently performed by movers. Only one musician performed this gesture among all participants with dominant practices in music. In addition to the body use, stretching demonstrated how performers engaged with their performance space or kinesphere. With both stretching gestures, movers used the strings to create different shapes that the instrument and performer's body form together. This interaction expanded the performance space. We observed that both the gesture and its position influenced performers' use of space. Figure 4 and Figure 5 show P1's stretching gesture, P6's up-and-down gesture, and their CoM and QoM values. The variance in CoM demonstrates the performance space that constrained the gestures. P1 expanded her kinesphere to the side while stretching the strings with her

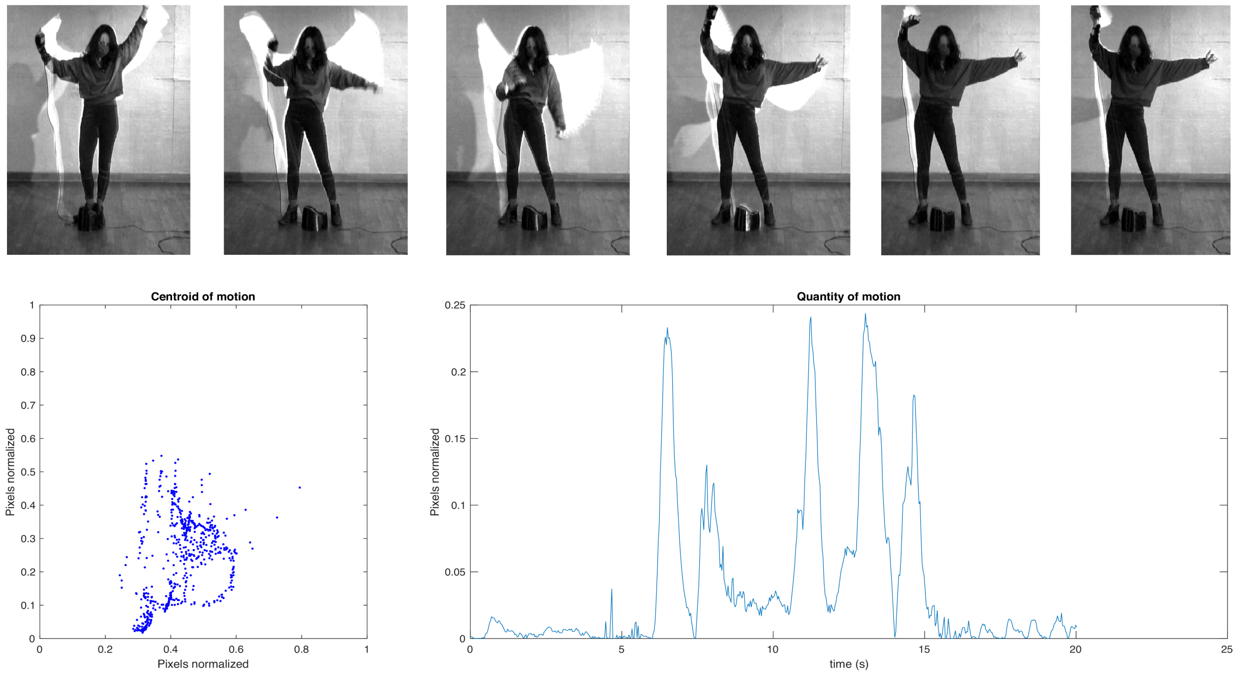

Figure 4: P1's nuanced stretching gesture combined with wrist movement and their correspnding CoM and QoM. During this gesture motif, P1 temporarily holds poses, framing her body with the extended strings.

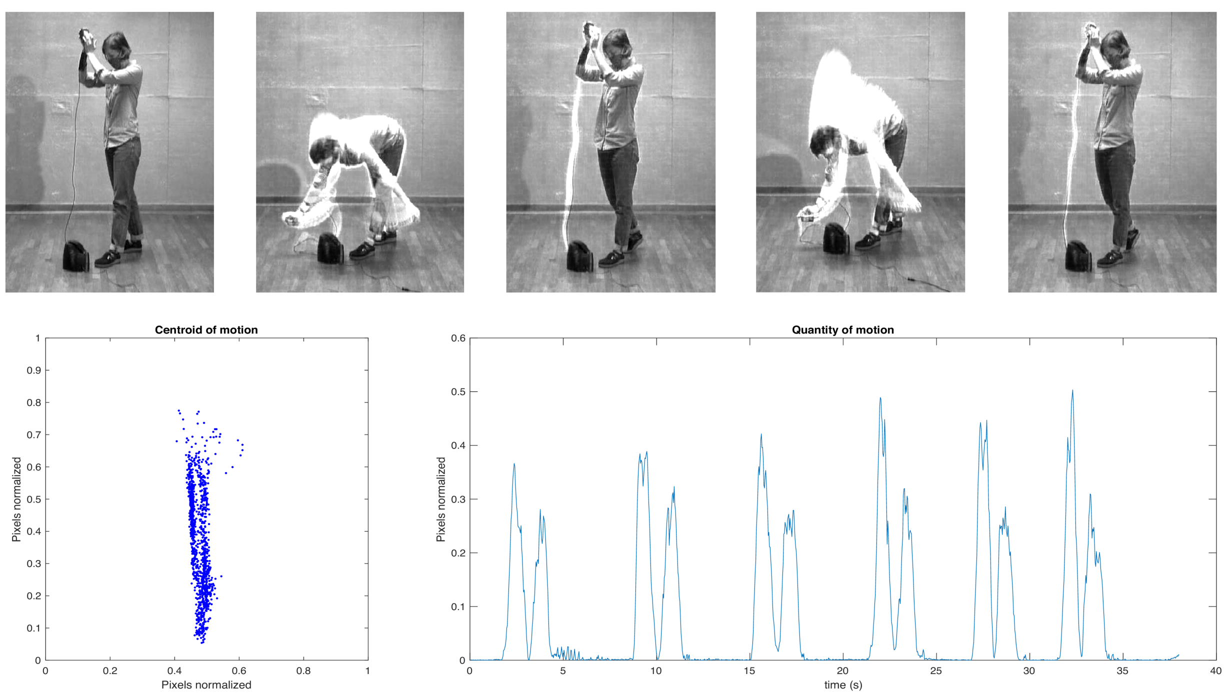

Figure 5: P6's up-and-down gesture and its corresponding CoM and QoM. This gesture motif includes up-and-down gesture, level change, tactile (nuanced) gesture, and position hold, repeated a few times.

fingers while P6 used her arm to stretch the strings and moved in the vertical axis.

Another extended space use was performed by rotating around the instrument, changing the strings' height by moving to the sides, and playing the instrument while lying on the floor. Although the level change was frequently performed in the transition between standing and couched positions, few participants played the instrument while lying on the floor. This position changed the sound excitation since extending the strings at a large angle prevented them from being triggered by many arm movements, allowing the strings to be individually played more easily than when in the standing position.

7 CONCLUSION

In this paper, we study how participants' artistic backgrounds and experiences reflect in their interaction with a movement-based digital musical instrument. To reveal some of the underlying correlations between music and movement interaction and practices, we combine qualitative and quantitative movement analysis methods and focus on participants' use of *Body* and *Space*, drawing from Laban Movement Analysis. We discuss our design approach, detail the instrument and sound design, and explain the experiment procedure and data analysis. Based on the movement interaction and data, we identified shared and unique musical gestures, we annotated individual gestures, gesture motifs, and gesture sequences, and we analyzed gestural interaction of the participants with different backgrounds in relation to body and space use. We used the Musical Gesture Toolbox to compute Centroid of Motion (CoM), Quantity of Motion (QoM), and the motion history. Results from these analyses showed both some anticipated differences in how participants with movement and music backgrounds perform the same gestures with different qualities and features and some commonalities that followed Bodyharp's affordances and extended its existing gestural vocabulary. Moving forward, we will extend our analysis with motion capture data and evaluate Effort qualities by focusing on a subset of musical gestures and participants. Additionally, we will further investigate how music informs the identification of gestures in movement-based musical interaction.

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The first author was the main responsible researcher for the study (designed the instrument, organized the study, collected the data, and performed analysis). The second author assisted in the selection of relevant literature and data analysis. Both authors participated in writing and approved of the final manuscript.

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