Dance and Choreography in HCI: A Two-Decade Retrospective

Qiushi Zhou
The University of Melbourne
Melbourne, Australia
qiushiz2@student.unimelb.edu.au

Cheng Cheng Chua
The University of Melbourne
Melbourne, Australia
chuaccheng@gmail.com

Jarrod Knibbe
The University of Melbourne
Melbourne, Australia
jarrod.knibbe@unimelb.edu.au

Jorge Goncalves
The University of Melbourne
Melbourne, Australia
jorge.goncalves@unimelb.edu.au

Eduardo Velloso
The University of Melbourne
Melbourne, Australia
eduardo.velloso@unimelb.edu.au

ABSTRACT

Designing computational support for dance is an emerging area of HCI research, incorporating the cultural, experiential, and embodied characteristics of the third-wave shift. The challenges of recognising the abstract qualities of body movement, and of mediating between the diverse parties involved in the idiosyncratic creative process, present important questions to HCI researchers: how can we effectively integrate computing with dance, to understand and cultivate the felt dimension of creativity, and to aid the dance-making process? In this work, we systematically review the past twenty years of dance literature in HCI. We discuss our findings, propose directions for future HCI works in dance, and distil lessons for related disciplines.

CCS CONCEPTS

• **Human-centered computing → Interaction design theory, concepts and paradigms**; *HCI theory, concepts and models*; • **Applied computing → Performing arts**.

KEYWORDS

dance, choreography, creativity support, movement quality, somaesthetics

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1 INTRODUCTION

> "To understand what I am saying, you have to believe that dance is something other than technique. We forget where the movements come from. They are born from life."
>
> — Pina Bausch [23]

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Dance research in Human-Computer Interaction (HCI) thoroughly embodies the cultural, experiential, and phenomenological characteristics of the third-wave shift [13, 36]. As an interactive experience, the uniqueness of dance lies in its tight coupling with the body as the main interface through which expressive movements are conveyed. The kinaesthetic creativity of the choreographers, the lived experience of the dancers on stage, and the embodied perception of the audience, collectively makes dance an interactive experience [10]. Apart from the complex relationship between the diverse parties involved, the abstract meaning-making process of dance further distinguishes it from the other performing arts that involve performances through explicit semantic means, such as theatre.

Pioneering explorations in HCI dance research have revealed important challenges at the intersection of the two disciplines. Exemplified by the effort in achieving a bodily dialogue between human dancers and machines [28], and the evaluation of the technical, social, and ethical issues in the use of novel choreographic tools [21], the bodily nature of dance expression and the complexity of its creative process present two major challenges for HCI researchers and interaction designers: *How can we use computing to define, understand, and cultivate the felt dimension of creativity realised through body movement? How can we equip choreographic professionals with effective computational aid in the complex, idiosyncratic, and highly diverse process of dance production?* Answering these questions will not only help progress dance-related HCI research, but also contribute towards a better understanding of creativity research in HCI at large. In this work, we systematically review the literature on interactive technologies and HCI theories in dance over the past 20 years, and contribute the knowledge to a better understanding of HCI research in dance and beyond.

The past two decades have seen a surge in the development and accessibility of motion capture technologies, such as reflective marker systems in the early 2000s and the launch of the depth-based Microsoft Kinect series in 2010. Practitioners and researchers interested in dance have eagerly adopted these emergent technologies, which provided unprecedented opportunities for analysing and understanding abstract characteristics of physical movement in dance that were previously unquantifiable, such as movement quality and emotional expressiveness [33]. Better motion capture and computer vision systems have also enabled easier annotation and analysis of dance movements, which consequently changed the creative process of dance. Additionally, artists have attempted to create computationally augmented interactive dance performances, enabling novel experiences such as responsive ambience [43] and collaboration with robotic agents [44]. Accompanying these technological advances was a wave of theoretical propositions with the moving body under the spotlight. Mostly under the influence of the phenomenology of Merleau-Ponty and Heidegger [37, 63], researchers have brought to HCI a shift of focus towards the cognitive merits of the living physical body and its felt experience within its surrounding context [25, 40, 78].

The rapid development of both the technological and the theoretical dimensions have created tension in HCI dance research. In designing computational support for dance, the quantifying nature of algorithms collides with the felt bodily experience while attempting to concurrently recognise and cultivate expressive movement qualities. Additionally, the diversity in the contexts of dance performances makes it difficult to design tools that serve multiple types of performances, or to generalise understandings gained from one performance to another. In light of the challenges identified in the literature, we recognise a need for a holistic understanding of the current state of dance-related research in HCI, for designing better computational support for the creation and the performance of dance, and for identifying promising research directions in the future.

In this work, we present a timely review on 77 publications from the literature of dance in HCI during the past two decades (2000–2020), covering publications from the Special Interest Group on Computer-Human Interaction (SIGCHI) and from the emerging International Conference on Movement and Computing (MOCO). We summarise important themes in the literature, and identify trends in which computing has been appropriated by the HCI dance research community. We discuss the implications of the problems and the opportunities identified in this review with the aim of informing future HCI works on dance and in the context of artistic expression and creativity support. Through our discussion, we propose future directions toward a multimodal understanding of the embodied creativity and expressiveness of dance, and call for wider acknowledgement of the complexities in the social, contextual and lived experience of dance-making.

2 BACKGROUND: DANCE AND EXPRESSIVE BODY MOVEMENT IN HCI

Previous works in dance and HCI have intersected mainly from three perspectives. First, with the theoretical grounding in embodied interaction [25, 40] and the experience from empirical studies of the human body, previous works in dance have experimented novel use of bodily signals in performances, and investigated the idea of kinaesthetic creativity [9, 42, 85]. Second, the extensive use of motion capture and analysis technologies and methods have provided the foundation for the crucial analysis of expressive movement qualities in dance, such as the attempts of capturing and analysing the Laban Movement Qualities with novel technologies [30, 31, 62]. Finally, the designs of computational aid for the process of dance-making have learned from HCI studies of creativity support, to develop systems and tools for annotating dance sequences and for coordinating the communication between different personnel in dance production teams [21, 22, 81]. Following these perspectives, we present the background of HCI dance research in three parts: the body as the instrument, the movement as the vehicle of expression, and the artform itself as a practice.

2.1 Body as the Instrument

In third-wave HCI, the body is approached as a medium that carries all of our perception, experience, and expression within the world in which we are situated, serving as a crucial part of our cognition, and with malleable shape and size [42]. This image of the body is profoundly influenced by phenomenology, as advocated by Heidegger and Merleau-Ponty [37, 63]. Interpretations of these works by HCI researchers have laid the theoretical foundation for interpreting the body in HCI : (1) as situated in the contextual life-world through interaction with tools; (2) as part of our cognitive experience; (3) as actively perceiving the world with directed intention; (4) as dynamically altered in shape and size as perception changes with the spatial and functional relationship between the body and the world [25, 82]. This multifaceted image of the body has been captured by the discipline of dance, which fully exploits the aesthetic, expressive, and creative qualities of the body, and makes it an instrument for artistic creation [12, 58]. Through the moving body, dancers live the experience of the performance on the stage, and are shaped and influenced by that experience at the same time [82]. The experience brings the attention of the dancer not only to the audience and the stage, but also to their own moving bodies. This introspective direction of perception is captured by the idea of somaesthetics, which reflects the generative relationship between the physical body movements and the affective qualities of the experience [40, 41, 79]. From the somatic perspective, HCI researchers must not only consider the aesthetic goals served by the technologies incorporated into dance performances, but must also cater to the felt experience of the performer on stage, for that will also—though implicitly—affect the expressive quality of the performance [39].

At the lower level of the complicated body-instrument is the human sensory-neural system acting as the circuits and switches of the somatic interface. The inherent learning and creative ability of the body is realised with the multimodal sensory system being ready to adapt to choreographed or improvised postures and movement sequences in response to the contextual stimuli, potentially triggered by interactive technologies [58]. Among the sensory channels, kinesthesia and proprioception are the crucial senses to movement. They provide kinaesthetic awareness and kinaesthetic creativity, which help generate novel movement with the body [84].

For the choreographer, the body could be extended by computing. Robotic and algorithmic agents are becoming popular as accompaniment to human dancers and even as the main performer at times. When acting as accompaniment, they are usually present on the stage as interactive visualisations, costumes [48], and mechanical bodies that respond to the human dancer, as either pre-programmed or autonomous agents. Dance makers must consider how to avoid disturbing the lived experience of the human dancer during the performance with computational partners, while encouraging and cultivating their kinaesthetic creativity. The main challenge is how to use the human body (with its neural and sensory characteristics) and computational technology together, as instruments of fundamentally different natures, while minimising the tension between them.

2.2 Movement as the Vehicle of Expression

Body movement is the primary means of expression in dance. Movement has been considered mostly as functional in HCI until the shift of the field towards an increased focus on the expressive and experiential aspects of interaction [31]. While dance benefited from the advanced motion capture technologies that emerged in recent years, it also met the challenge of capturing and defining movement quality. Motion capture technologies show potential in *quantifying* the functional parts of the dance movement by modelling and recognising pre-defined movement sequences [69, 86]. However, *qualifying* the expressiveness of those movements is a much harder challenge for HCI researchers to design computational support for. Facing this challenge, most of the previous works have borrowed from existing frameworks for formalising movement quality.

Among the frameworks used to formalise, categorise, and describe movement quality, is the Laban Movement Analysis (LMA) developed by the movement theorist and dancer Rudolf Laban [87]. The LMA framework has been widely used in dance practices before it was adopted in HCI. The framework benefits from Certified Movement Analysts (CMA) who can provide their expert opinion on the movement quality of performances by observing with trained eyes. Previous works that attempted to model Laban movement qualities have used CMAs to train their algorithms [30, 62]. Movement quality has been used for annotating and analysing performances, and as an interaction modality itself for triggering events during dance performances [2, 3]. However, as a new practice that only emerged in recent years, recognising movement quality through computational methods such as computer vision is still in an exploratory stage [31].

2.3 Dance as a Practice

The new technologies for studying and supporting dance have brought further understanding of the practice and raised more questions to be answered. Technology has always been involved in the performing arts, as the lighting and sound effects of many performances are technology-heavy. Those use cases of technological tools are mostly situated within the specific context of the performance, and usually disappeared afterwards [54]. This presents a challenge for the HCI community to transfer the understanding gained from one performance context to another, especially when the technological intervention was designed without the awareness of the contextual differences. This lack of awareness has further induced conflicts between the expected outcome of the intervention with a computational tool and the unexpected obstacles hidden in the details of the context, such as the seating of the audience [36]. In this work, we illustrate the challenges in detail and discuss opportunities for future HCI dance research towards a better awareness of the importance of context, to design better computational support for dance making.

3 METHODOLOGY

In this systematic review, we aim to summarise and understand current HCI research related to dance, choreography, and expressive body movement. We aim to address the challenges identified at the beginning of this paper by analysing the literature from the following two perspectives: *how technological advances, as exemplified by motion capture and computer vision, have contributed to the recognition and analysis of expressive qualities in the body movement of the dancers; how computing has influenced the creation of dance performances through case studies of technological intervention in HCI dance projects.* By reviewing the literature from these two perspectives, we take lessons from existing works and propose directions for future works. Two researchers, one with a background in computer science and expertise in body-based interaction research and one with a background in psychology and professional experience in dance, led the analysis under the supervision of a team of HCI researchers. We also consulted and received feedback on our results from a professional artist with extensive experience in using novel technologies in theatre practice and interactive installations.

3.1 Sampling

We describe below the sequential and systematic approach that we employed. We first conducted a search in the ACM Digital Library using the following search string:

Title:(danc OR choreograph* OR movement* NOT "eye") AND Abstract: (danc* OR choreograph* OR movement*)*

To identify papers in HCI that were published within the last 20 years, the search filters were set to only show results from SIGCHI, and between the years 2000 and 2020. This publication time frame was selected as we wanted to identify papers relevant to recent technologies being used to support dance and choreography. We included 'movement' in the search string to cover papers on expressive movement qualities, even though 'dance' or 'choreography' were absent in the Title. We also included "NOT 'eye'" in this search string to screen out results related to eye and gaze movements. This search resulted in 323 papers in total. We also conducted a second search to gather papers from the MOCO conference. While papers from this conference were not included in the SIGCHI proceedings, we found that many of them addressed our research questions. This search resulted in 205 papers between the years 2014 and 2019.

The initial dataset from the two searches resulted in 528 papers. We conducted an initial screening by reading through the Title and Abstract sections, and removed irrelevant papers. As we limited our review to papers on dance-related movements, we were only interested in full body movements that were intended to be expressive, voluntary, and performative. As such, we identified and removed papers on movement in HCI that were not related to performing, storytelling, expressiveness, or choreography. This includes papers on movements of individual body parts, such as hand, head, or facial movements, papers on involuntary movement, as well as papers related to crowd or social movements. We then removed duplicates, extended abstracts, workshop papers, and papers that were not peer reviewed. This resulted in a final sample of 77 papers.

3.2 Analysis

We analysed the remaining 77 papers using affinity mapping, to identify themes and categories. We achieved the first round of open coding by reading through and summarising the main keywords for each paper on a digital post-it note in the online collaborative platform *Miro.* In the second stage, we rearranged and clustered the notes into categories according to the keywords. In the third stage, we further analysed those clusters with axial coding using a spreadsheet. We conducted this categorising process twice. Inspired by Latulipe et al's work discussing the effect of temporal integration of interactive technology in dance, we divided the sampled literature into categories as three stages in a dance project: creating, performing, and analysing [54]. Separately, we categorised the papers according to the type of technological intervention involved in their main contributions. Two researchers completed the analysis process separately and compared their results in the end. We present the final two sets of codes used for the categorisation in Table 2 and Table 3 as we describe the results in next sections. The categories are not mutually exclusive, as one paper could belong to more than one categories.

4 TYPES OF CONTRIBUTION

We present the numbers of papers with different types of contributions in Table 1, as well as their distribution over the years in Figure 1. We used the contribution types defined by Wobbrock and Kientz [88]. The vast majority of the papers (45, 58%) contributed artefacts, including new technique such as novel computational models for movement quality recognition [67], new systems consisting interactive costumes [48], and novel digital tools for annotating dance movement [81]. This is followed by empirical papers (18, 23%) comprised of case studies of performances that utilised novel technologies [8], and evaluations of different approaches for recognising movement quality [56]. There were six (8%) papers with methodological contributions that mostly focused on evaluating and discussing different ways of incorporating technology in the creative process of dance production [54]. Five (6%) papers with opinion contributions discussed different aspects of using technology in the practice of dance, including mutually inspiring relationship between dance and technology [36], and issues of using biosensors in artistic practice [66]. The fewest number of papers (3, 4%) contributed datasets, all of which were aimed at the analysis of abstract qualities of movement.

Contribution type	Number of paper	Percentage
Artefact	45	58%
Empirical	18	23%
Methodological	6	8%
Opinion	5	6%
Dataset	3	4%

Table 1: Types of contribution by the sampled papers.

Category	Number	Topic
Creating	**38**	Creation of dance performances.
Choreography	22	The choreographic process of dance, including choreographic development, choreographic learning, and choreographic cleaning.
Stage	19	Stage setup of dance performances, such as visualisation, costuming, and sound effects.
Performing	**25**	The performing of dance.
Interactivity	17	Interactive performances.
Improvisation	10	Improvisation in dance performances.
Analysing	**16**	The analysis of dance.
Modelling	6	Computational modelling of expressive movement qualities.
Observation & Annotation	12	Observing and annotating processes in dance analysis.

Table 2: Stages in the creative process of dance.

5 TECHNOLOGY IN THE CREATIVE PROCESS

In this section, we summarise and highlight the results as categorised by the use of technology in different stages of the creative process of dance. We present the number of papers in each category (not mutually exclusive) in Table 2, and their distribution over time in Figure 2.

5.1 Creating Dance

5.1.1 Choreography. The majority (19) of the papers about the choreographic process were papers with artefact contributions, among which a prominent group contains tools for annotating and sketching body movement to help initiate or modify dance sequences. For instance, Singh et al. designed *The Choreographer's notebook*, which enables the multimodal annotation of rehearsal videos by taking advantage of the portability of the web interface [81]. Carlson et al. presented their design of a mobile tool, *iDanceForms*, which enables choreographers to sketch novel movement sequences using tablets to capture and recognise keyframes of novel movements performed live by a human dancer [18, 20]. For a similar purpose but with a more abstract form, Felice et al. presented their iterative design and evaluation of *Knotation*, a mobile pen-based tool that allows choreographers to sketch their ideas using their own free-form abstract representations, which serves the purpose of sketching movements from scratch as well as documenting the choreographic process [22]. While benefiting from the computational tools, the users have also encountered unexpected problems from the disturbance of the traditional choreographic process by the technological intervention. For instance, the evaluation of *The Choreographer's notebook* has revealed a series of issues induced by the online tool, such as the reduced verbal conversations and the obscured work-life balance as the users were enabled to work during after hours [21].

Apart from tools designed for sketching and annotating choreography, other novel tools emerged that were not intended solely for choreography but deeply impacted the choreographic process during their implementations. These range from practical tools that help with specific parts of the creative process to novel visualisations and costumes. For instance, Molina-Tanco et al. took the approach of enhancing tools which already exist in dance studios. They designed and evaluated the *Delay Mirror*, which records video streams of real-time practice of dancers and projects them with a delay of a few seconds, enabling the dancers to observe and correct their own

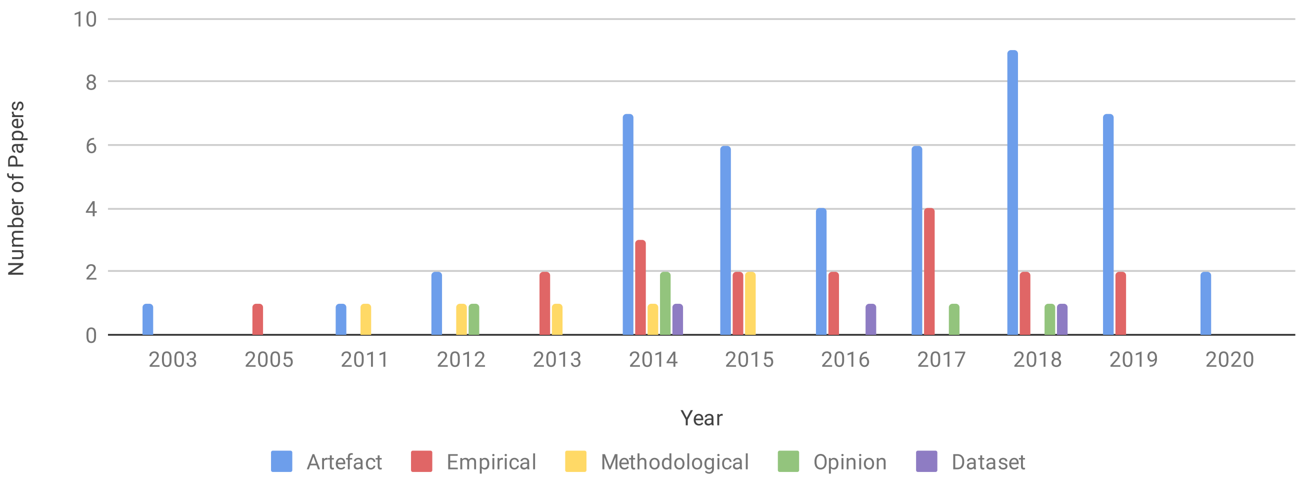

Figure 1: Types of contribution by the sampled papers distributed over time.

movements [64]. Other researchers brought novel technologies into the choreographic process. In *Movement Matters*, Gemeinboeck and Sanders explored the meaning-making capacity of movement in non-anthropomorphic robot in collaboration with human dancers. They found and discussed the choreographic potential sparked by the affective relationship emerged through the interaction [35]. Similar explorations have been made in projects such as *Choreomorphy* and *Dancing with Drones*, where novel choreographic concepts emerged from interaction with drones and interactive visualisations [28, 73].

Instead of contributing tools or methods, other works studied the choreographic process itself, such as the previously mentioned evaluation of *The Choreographer's notebook* [21]. Rivière et al. investigated the process of dancers learning new dance moves, and provided advise for future learning-support technologies [75]. Carlson et al. discussed the use of defamiliarisation, and analysed previous works on choreographic technology through that lens. They envisioned a framework that delineates the relationship between human agency and system agency to direct future works to cultivating embodied creativity in human dancers and choreographers [17].

5.1.2 Stage. Nineteen papers contributed novel designs and evaluations of stage props, all of which had artefact contributions. The props presented in the paper include costumes, visual or acoustic stage effects, and other interactive objects such as robots. Sixteen out of the 19 papers featured interactive stage visual or auditory effects. This large number was expected because multimedia stage effects have been traditionally used in dance production. As a crucial component of most dance performances, music has been explored in research works as an interactive medium. Palacio et al. studied a performance, *Piano&Dancer*, which featured a simple but powerful relationship between a dancer and an electromechanical piano. The dancer controlled the piano with a non-tactile exchange of mechanical energy realised by their physical movement, which consequently moved actuators connected to the piano hammers [70]. Akerly designed an interactive audio system that featured live music adapting to the data from an accelerometer attached on the dancer's limb, to encourage the dancer to discover new ways to interact with the music [2].

The abstract expressive nature of dance requires HCI researchers to design interactive visual effects by reflecting the often poetic element of meaning-making, which leaves space for interpretation. For instance, Brenton et al. found that hardwired mappings between specific postures and the changes in the appearance of visual elements lacked the flexibility required to accommodate free-form idiosyncratic movements from dancers [14]. More works focused on training agent algorithms to react to subtle changes in the qualities of expressive movement performed by the dancers. McCormick et al. proposed a novel machine learning method to train an agent to recognise and respond to short full body movement phrases with projection rendering a virtual avatar and abstract visual patterns. Their method allowed the dancers to reacquaint themselves with the agent's response based on the training movements that they previously performed. This consequently cultivated the relationship between the agent and the dancer [61]. Similarly, Bisig and Palacio trained an agent to interact with dancers through visual projection that simulate a bodily extension of the dancer, moving in a loose correspondence with the dancer's movement and position [10].

Similar to the works with interactive visual effects, some works directly altered the virtual representations of the dancer, aiming to provide a more directly embodied experience with the "virtual costume". For example, El Raheb et al. built *Choreomorphy*, an interactive system that enables dancers to choose from a set of virtual avatars varying in all kinds of visual features, to study how the different appearances of the body representations encourage novel improvised movement from the dancer [73]. In the performance *Encoded*, Johnston brought this "avatar augmentation" to reality using a costume designed with projectors attached on the front and the back of the dancer wearing it. It projected interactive fluid simulation effects on the dancer's body and on the large black backdrop. The visual effects appeared as the extension of the dancer's body, forming an hybrid relationship between the physical and the virtual parts of the

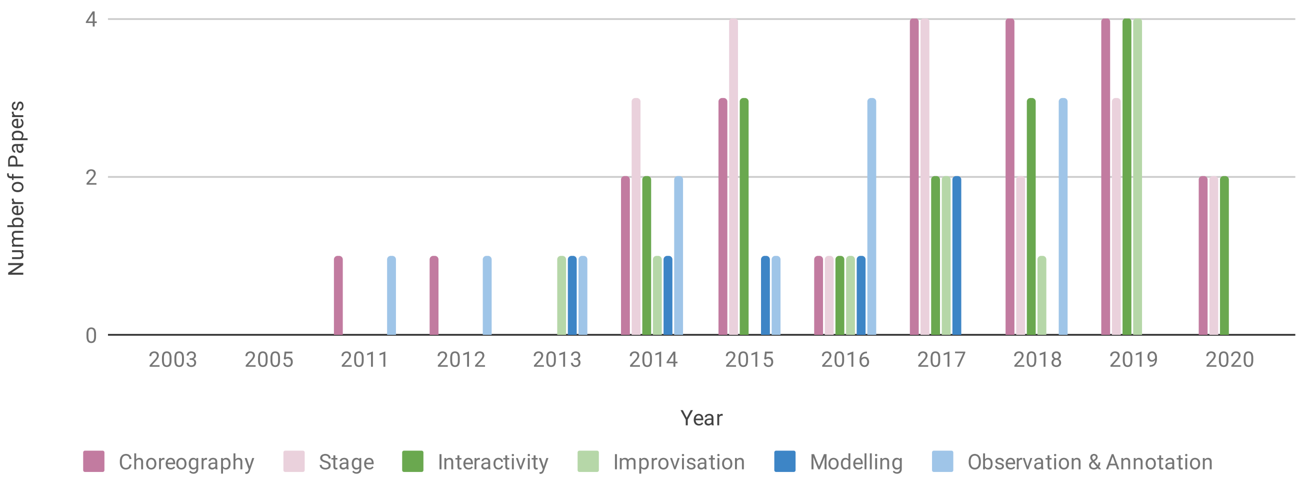

Figure 2: Papers related to different stages in the creative processes of dance distributed over time.

costume [45]. Other works have explored the designs of physical interactive costumes. Karpashevich et al. learned from the Bauhaus movement in the 1920s, and designed interactive costumes that deliberately limited the freedom of the dancer's movement, aiming at sparking novel dance forms. The costume consisted of plastic wires aligned around the dancer's waist to emulate a dress, which also had LEDs that emulated wave effects to accompany the performance [48]. Ladenheim et al. featured mechanical actuators in the design of their costume intended to creating a "feminine cyborg metaphor". The costume has a pair of mechanical wings on the back that opens and closes following a button controlled by the dancer [52].

5.2 Performing Dance

5.2.1 Interactive performance. Many papers focused on the interactivity between human dancers and technology, and addressed the challenge of determining the right amount of mapping and control. The performance *SKIN* featured a basic interactive system where the dancers controlled the playback of the video playing on the background of the stage. An interesting finding in that work is that the dancers perceived the interactive artefacts as partners, characters or members of the ensemble when they observed ambiguous behaviours from the artefacts. Conversely, if the artefacts exhibited clear behaviour patterns, they were perceived only as instruments to control, and ignored by the dancers most of the time [29]. Most works explored the interactivity in dance with the whole body movements of dancers, including the above mentioned works that featured interactive virtual "costumes" for dancers. In their experimental performance, McCormick et al. created an interactive experience between the dancer, their motion-captured avatar, and an agent avatar in abstract form. The two avatars coexist in the space of a stereo projection, where their movement is similar but subtly different, to present a child-like character as if it has the will to "perform" [61].

Previous works have explored physical interactive objects that formed embodied relationships with the dancers on stage, such as robotic agents. Notably, projects on interaction with drones have emerged in recent years. The dance system *Aeroquake* augments a dancer's body movement with sound and the movement from a swarm of drones in real time. Dancers were able to perform improvised foot stomping choreographies transformed into movement across multiple drones [49]. Eriksson et al. incorporated drones in a novel re-creation of the classic opera of *Medea*, in which the drones acted as Medea's children. In that performance, the drones created dramatic tension by reacting to Medea's pushing and polling actions, while achieving an intercorporeality between the human and the drones [28]. Unlike using whole body movement, Van Nort has taken a more "radical" approach and designed an interactive performance around the concept of amplifying the sounds of muscle contractions from the dancers. They captured the sound with electret microphones and transformed it into music that accompanied the dance performance [85].

5.2.2 Improvisation. Among the works on interactive performances, a significant subset were about supporting improvisation in dance using interactive agents. Similar to the interactivity in dance, technological support for improvisation faces the challenge of finding the right amount of the freedom of expression and the training and planning needed to set the stage for it [55]. In *Neural Narratives*, Bisig and Palacio discussed the complexity of designing an interactive visualisation that responds to the dancer's movement to encourage novel movements during improvisation. They argued that a balance must be achieved between the possibility of more open-ended improvisation enabled by real-time adaptation in how the agent responds to the dancer, and the difficulty of integrating such a system with a predefined choreographic structure [10]. Their later work *Piano&Dancer* built on this and integrated an algorithmic layer as an intermediary level between the analysis of the dancing movement from a human dancer and the electromechanic piano controlled by the movement. In this way, the interactive system succeeded as an improvisation partner with autonomous musical agency [70]. Hsueh et al. investigated how to support kinaesthetic creativity with technology to generate movement ideas. They perceived the virtual visualisation agent as a medium for the dancers to "externalise" their internal movement ideas [50]. They proposed that we should enable dancers to engage in active dialogues with the improvisational agents by designing explicitly to cultivate this abstract relationship, which characterises kinaesthetic creativity [42].

Another notable trend is towards improvisation with physical robots. Gemeinboeck and Saunders investigated how movement propels the becoming-body of non-anthropomorphic robots. They demonstrated that the non-anthropomorphic robots such as boxes and tetrahedron prostheses can learn to develop movements that are unique to their own machinic bodies and their relations with the environment. They proposed that machine learning systems can learn human movement qualities as a series of implicit biases, and later use them to generate new improvisation that is unique to the robots [35]. Jochum and Derks conducted an exploratory study to investigate embodied improvisation between human dancers and non-anthropomorphic robots that are free to move on stage. From an embodied perspective, they argued that robots cannot emulate improvisation, because they cannot experience their own movements in the way in which the human performers do. This is reflected in the observed failures of the robots performing on stage with the human dancers. However, they argued that it is precisely this unintentional resistance exhibited from the robots that became a mark of an authentic improvisational performance [44].

5.3 Analysing Dance

5.3.1 Observation and annotation. A series of tools emerged to provide multimodal annotating functions to choreographers. For instance, *Choreographer's Notebook* enables choreographers and dancers to annotate video clips of dance rehearsals remotely and asynchronously with multimodal input, such as textual comments and video demonstrations. The video annotating function enables its users to directly sketch on the video to highlight points of interest, and to see an overview of them along the time scale [81]. Later, the authors reported on results obtained from a few case studies of dance projects that used the tool. They observed and interviewed the production teams on their experience with the tool, and obtained a wealth of insights in how technological intervention can influence the creative process in many subtle ways, as the users adapted their original styles of work to the novel functions and the unexpected failures of the technology [21]. Similarly, other tools such as *Mova* and *BalOnSe* also provide multimodal annotating functions with visualisations of motion capture video data and movement quality features extracted, such as speed and acceleration [4, 26, 27].

Another group of works were dedicated to the observation and analysis of movement qualities in dance, extensively using LMA as the main analysis framework. To understand how movement qualities are perceived, Mentis et al. conducted video analysis sessions with Laban Movement experts and post-performance interviews with audiences. They found that trained experts tend to feel the qualities of the observed movements by recreating those movements by themselves, whereas the amateur audience perceived the movement qualities with a heavier influence from their own experience and interpretations [62]. With the aim of deconstructing the observation process of LMA experts, Fdili Alaoui et al. transcribed and analysed the process of 12 expert-participants observing and annotating videos of movement according to LMA categories. They offered insights such as the benefit of group observation, which can inform future designs of movement-based computational systems [30]. Other works have attempted to define movement qualities without the LMA framework. For instance, Piana et al. created a multimodal repository of movement qualities in dance, in which they focused on three self-defined expressive qualities: *Fluidity, Impulsivity, and Rigidity* [71]. Anjos et al. presented a novel three-dimensional visualisation of movement qualities in dance. They used coloured point cloud videos similar to heat maps to visualise movement qualities such as moving direction and synchronisation between dancers [24].

5.3.2 Modelling and analysing movement qualities. A few attempts have been made to model movement qualities using computational methods for easier analysis of dance movements. For instance, the above-mentioned systems, such as *Mova*, extract basic features such as speed and fluidity from movement recordings, consequently enabling a more intuitive visual access to those movement qualities for easier annotation [4, 71]. Ran et al. explored multitask learning for LMA using a dataset of 550 video clips recorded with a Kinect sensor. They recruited two certified LMA analysts to help train an algorithm to recognise movement qualities, which consequently obtained better performance than single-task methods [74]. To explore how LMA expertise can contribute to the design of computational models of Laban Movement qualities, Fdili Alaoui et al. worked with Certified Laban Movement Analysts (CMAs) to select sensors and to determine features that best define the *Effort* quality in LMA. The subsequent evaluation of their model showed that multimodal data combining positional, dynamic, and physiological information allows for a better characterisation of Laban Efforts [31]. Niewiadomski et al. presented a low-intrusive approach for detecting two movement qualities, Lightness and Fragility, defined in their own framework [15], with the novel use of Inertial Movement Units (IMU) and electromyography (EMG) sensors [67].

5.4 Other Works on the Creative Process

Based on the observation of a series of performances intended to explore the dance-technology relationship, Gonzalez et al. identified unexpected problems hidden in the details along the production cycle. For instance, they found that effective use of motion tracking relies on the seating arrangement that should avoid occlusion of sensors or the audience's viewing angle. This a a practical concern because there is usually limited time to make adjustments after identifying those problems within the tight schedules of dance productions. Additionally, they found that the differences in stage sizes can also limit the distance between the dancers on stage, consequently reducing the consistency and accuracy of motion tracking. Finally, costumes and props introduced at later stages after the technological setup can also degrade or change the tracking, causing overhead in production time and resources [36].

Specifically, Caroll et al. investigated the technological intervention in the dance production process regarding its personnel relationships and the physical space. They found that the complicated chain of technology involved in a dance project can fail at any unexpected point. They found that the introduction of a choreography annotating tool has substantially changed many aspects of the choreographic process. For instance, when the place of choreographic communication changes from the physical rehearsal studio to an online tool that is accessible all the time, the power relationship between the choreographer and the dancers changed. The dancers would fear that their written comment, without contextual information such as tone of voice or facial expressions, might seem offensive. This consequently made them reluctant to share their opinion, hence reifying their submissive roles and hindered free communication of opinions. Additionally, this case study of technological intervention revealed other ethical concerns, such as the extra workload induced by the choreographer posting comments on the tool during after hours, and the dancers feeling observed by the technology experts in the studio [21].

6 THEMES OF TECHNOLOGY IN DANCE

In this section, we present our results from the categorisation (not mutually exclusive) of the important themes of technologies used by HCI works in dance over the past two decades, including *physiological sensing, multisensory perception, movement quality, and agent collaboration* (Table 3). We present the trends of development in those themes over time in Figure 3.

Category	Number	Technologies Used
Physiological Sensing	8	Physiological sensing technologies to probe the status of the dancers while they perform expressive movement.
Multisensory Perception	15	Various media to affect the dancers' perception in different sensory channels during performance.
Movement Quality	28	Recognising, modelling, or analysing movement qualities.
Agent Collaboration	18	Collaborative agents (e.g., robots, visualisations, etc.) that perform with human dancers.

Table 3: Use of technology in the dance project.

6.1 Physiological Sensing

Previous works have attempted to sense physiological signals from the dancers and to use them directly in the performances, with the aim of uncovering their inner felt experience on stage. Bermudez and Ziegler presented an interactive installation, *Pre-Choreographic Movement Kit*, consisted of seven objects aimed at articulating questions around movement tracking and the digitisation of dance and notation [9]. One of the components is the combination of a pulse sensor and a vibration motor, expressing the idea of the transformation of rhythm between the inner body space and the outer choreographic space [85]. The project *[radical] Signals from Life* originated from the idea of directly using the sound of the dancers' body, which is the sound of muscle contraction captured using electret microphones, to generate a musical composition that accompanied the dance performance [85]. Niewiadomski et al. proposed a low-intrusive method of recognising expressive movement qualities. They used two EMG armbands placed on the dancer's forearms, and extracted features from the patterns of the EMG signal to define *Fragility* and *Lightness* in the dancer's movement [67].

6.2 Multisensory Perception

More papers explored the possibility of actively affecting the dancers through their multisensory perception. For instance, the EMG-generated music in *[radical] Signals from Life*, and the piano music transformed from the gesture of the dancer in *Piano&Dancer*, both in turn affect the dancer's performance, either in the form of improvisation or expressive movement qualities. Other uses of the auditory channel include accelerometer-controlled responsive music to encourage embodied flow [2], and EMG-controlled synthesis of field recordings in the performance *Still, moving* to cultivate kinaesthetic awareness [16].

Apart from stage effects, physical costumes can directly alter the dancer's sensory experience, specifically the bodily senses, such as proprioception and kinesthesia. Karpashevich et al.'s re-creation of the wire costumes ideated from the Bauhaus movement changed the dancer's physical body in the most direct way and with the exact intention of evoking "unthinkable" movements. As the title of the paper suggested, the alteration in the dancer's proprioceptive map (i.e. the soma) forced the embodied cognition of the dancer to automatically shift into a new pattern of movement qualities, which is unlikely to be achievable through instructions with other sensory channels. Additionally, the interactive LED component added to the costumes enabled the dancers to "affect back" by controlling the lighting effects, forming a dialogical relationship in the new somatic experience [48]. The efficacy of altering the bodily perceptions of the dancers is evidenced in the emergent use of drones as performance partners, which we elaborate in the following.

6.3 Movement Quality Analysis

Other than directly accessing the bodily input and output channels, the most commonly applied approach of tapping into the expressiveness of dance is through modelling and analysing movement quality. As summarised in section 5.3, movement qualities have been used extensively in previous works to describe the expressiveness of dance movements, mostly under the guidance of the LMA framework. The first challenge in capturing movement quality is how to determine which features of the movement best characterise the intended expressive qualities of the choreography. Although there are a wealth of feature extraction methods designed for general purpose movement interaction in the HCI literature, they are often not designed to reflect expressive qualities, consequently not suitable for using in dance [53].

In their latest work on the recognition of Laban movement qualities, Fdili Alaoui et al. built on their previous work [30] and sought inspiration from CMAs. After learning from the multi-sensory observation process of experts, they designed a multimodal approach for recognising *Effort* with positional, dynamic, and physiological information. They found that *Effort* could be represented using the jerk motions from inertial data and EMG signals. However, despite validating the value of the expert opinions, they still could not recognise

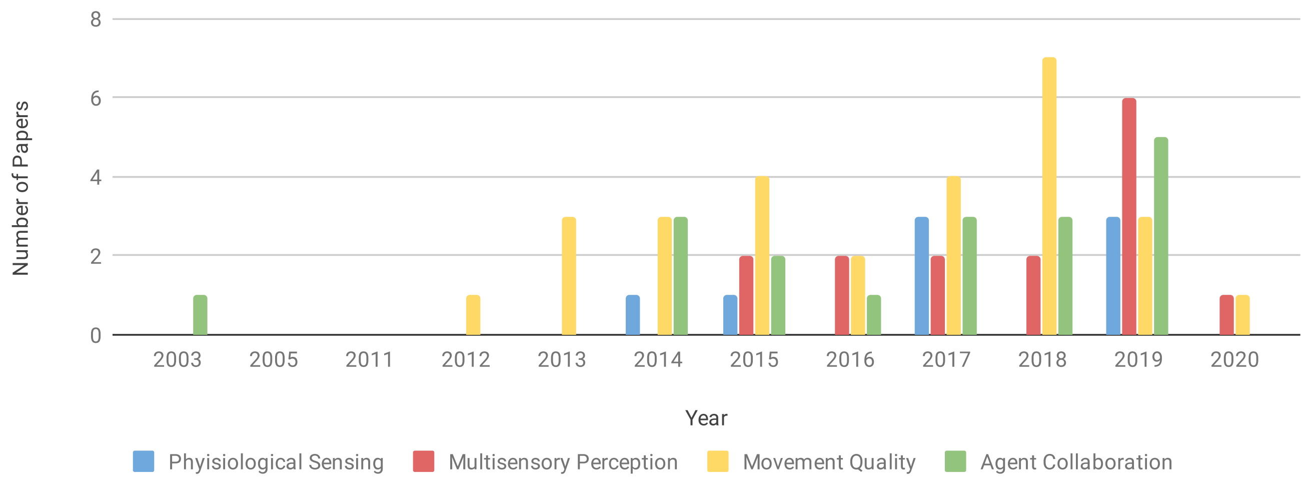

Figure 3: Important themes of technology in dance-related HCI works over the past two decades.

more nuanced effort categories such as *Space Effort*, which represents the spreading/enclosing features of body movement [31]. As the authors reflected, capturing movement quality is challenging because characteristics such as *Space Effort* can only be effectively described by human observers with their embodied perception and kinaesthetic empathy with the dancer. This obscurity faced by computational tools is different from the quantifiable features in the motion capture data or in the physiological data, that the movement quality itself cannot be easily described with concrete definitions, therefore the computable basis is hard to find [77].

6.4 Agent Collaboration

Collaborating with performing agents has been a popular approach taken by dance makers to explore possibilities of novel dance experiences. For instance, interaction with different types of avatars in *Choreomorphy* inspired different types of movements and different emotions in the dancers. This is realised through the different ways in which dancers perceived the avatars, as they embraced the abstract anthropomorphic avatars more like a mirrored-self, but perceived the cartoonistic avatars with specific visual features as other entities that they could puppet [73]. Similarly, the interactive artefacts in *SKIN* were perceived by the dancers as partners when they had their own ambiguous behaviours, but only as instruments to control when they displayed a clear responses [29].

The efficacy of evoking different expressive movement qualities using virtual body visualisations is further evidenced by Hsueh et al.'s work on understanding kinaesthetic creativity in dance. They sought inspiration from the lines of thought in the literature that advocated the "openness for interpretation" [19, 34], and Simondon's argument that technical objects should maintain a "margin indetermination", with which humans are able to form meaningful interrelationships with technology [80]. In their experiment, participants improvised dance movements accompanied by visual representations of their body contours in different styles, and their senses of agency were impeded by too many changing visual elements. This resulted in an inability to form meaningful relationships with the visuals, consequently limiting their creative expression with movement. The authors finally argued that computational support for expressive movement creativity should be designed to encourage the active discovering and appropriating of the indeterminate features in the system by the dancers, through a dialogical correspondence [42].

The similar spirit of cultivating kinaesthetic creativity through collaborative agents is reflected in the emergent use of drones. In the most recent work by Eriksson et al., the non-anthropomorphic nature of the drones were desired by the collaborating dancer. Novel artistic emotional expressions from the dancers were enabled when a balance between machine-like agency and emotionally expressive behaviours was achieved. As the result of the non-human otherness, the dancer somaesthetically attended to the drones, changing her movements to fit with them, and consequently adjusting to a new soma that produced novel artistic expressions through movement [28].

7 DISCUSSION

Our review of the literature has revealed the complexity of incorporating interactive technologies in the creation, performance, and analysis of dance. It demands diligence from designers and researchers to bridge the felt experience of human dancers with reductionist computational models and sensor technologies, while avoiding the trap of oversimplifying their relationship. Further, the complexity and diversity of different dance performances present the challenge of applying generalisable methods and tools learned from dance studies, bringing attention to the diverse contexts of individual performances. Finally, the case studies of technological integration in the creative process of dance have demonstrated the complexity in the iterative process of choreographic development and stage design, expanding across time and among the diverse collaborating parties involved. We discuss the challenges addressed and the opportunities emerged in the literature, and elaborate on how HCI creativity in general could take dance as an example and learn from the experience gained in this field.

7.1 Meaning-Making with the Moving Body

The opening quote from Pina Bausch precisely encapsulates the tension between the two sides of dance: an innate human creative ability and a technique that can be interpreted through segmenting, quantifying and analysing [23]. This tension creates a dilemma that is inevitably faced by HCI researchers while they attempt to translate the knowledge that they gained from quantifying and analysing generic user experiences to dance studios and theatres.

The most prominent difference between dance and the other technological application scenarios is its focus on the abstract meaning-making with the human body. The communication between the choreographer, the dancer, and the audience is achieved through a chain of embodied perceptions, such as kinaesthetic empathy during choreographing and performing, and the appreciation by the audience according to their own emotional and bodily experience [7, 62]. These are ultimately all carried out on stage through the dancer's moving body, which *is* the output of the dance as an artwork [21]. Consequently, for technological interventions to succeed in a dance project, effort must be paid to uncover and deconstruct the relationship between the body and the achieved artistic expression. We identified two emerging novel approaches overall in the sampled literature that delves into this problem (Figure 3). One is the direct measurement of dancers' physiological signals through various sensors (i.e., reading the body), and the other is the cultivation of the dancer's felt multisensory perception (i.e., writing the body).

7.1.1 Reading the Body. We can see that those attempts of hacking the body directly through physiological sensors are mostly still at a premature stage, while the choices of sensors and the interpretation methods of the signals are rather simple. Notably, Naccarato and MacCallum discussed the ethical and aesthetic implications of the appropriation of biomedical sensors in artistic practice. They pointed out that the mapping between the biosignal obtained from sensors and the expressive elements in media representation is a complex one, that is shaped by the hardware, software, context, and the designer of the performance. They gave an example close to the idea of the *Pre-Choreographic Movement Kit*, that the mapping from the heartbeat sensor data to a drumbeat is biased by many factors such as the sampling rate of the sensor, the choice of peak values to sonify, and the quality of the sonification [9, 66].

We suggest that the unreliability and bias in using physiological signals to extract expressive movement quality can be addressed by learning from works on sensing cognitive features in HCI, and by employing multimodal approaches. Although the mapping between any single sensor and expressive quality is likely biased [65], a multimodal approach incorporating the results from different types of sensors could provide a solution that is more reliable and richer in content. Recent advances in the application of sensor technologies in HCI have presented many novel options that could be explored by dance practitioners. For instance, the latest facial recognition methods showed promising results for detecting the attentional state of users through facial cues [6]. This could be further developed to detect the level of focus and mindfulness of the performing dancer, to help indicate some aspects of expressive movement qualities. As another example, thermal imaging has been proved to be an unobtrusive option to remotely monitor users' mental workload [1]. Such methods could be used to reveal the mapping between stage visualisations and the dancer's intensity of mental activity, to externalise the affective elements behind the dance movements.

7.1.2 Writing the Body. Contrary to the approach of directly measuring physiological signals, somatic practices and Somaesthetics emphasise the awareness of the body during movement, which suggests that the quality is evaluated according to felt, not necessarily externally perceivable or measurable aspects of movement [77]. The dancers performing on stage are constantly affected by the visuals, music, costumes, and haptic accessories, which collectively form their lived and felt experience. There already exist a series of works in the currently sampled literature that have explored the opportunities to spark novel expressive movements by altering the dancer's experience through multiple sensory channels. The specific approaches in those works include physical costumes [48], music [2], and virtual avatars [73]. Through adapting to the restrictions of the new costume or to the illusion of the new virtual body, the dancers could experience a new soma, which is accompanied with new expressive movement behaviours. We suggest that future works could extend this trend of research and explore possibilities to provide a richer multisensory experience, which has the potential of intensifying the novel somatic experience in dancers.

7.1.3 Embracing the Abstract. The challenge of recognising expressive movement qualities in physiological and motion capture data raises fundamental questions for designing computational support for dance. Should the expressive qualities of dance be quantified? Should we accept the abstract nature of meaning-making in dance, and look to apply technology elsewhere? To answer those questions, we suggest that the HCI dance research community should be aware of the obscurity in the meaning-making process of dance, but it should not be an obstacle in designing computational support for dance. The "openness for interpretation" [19, 34] of the expressive movement qualities is precisely where the values of the art of dance lies. As we summarised in section 6.4, the abstract nature is also desired by the dancers for their relationships with collaborative performing agents [42]. Instead of trying to achieve accurate mappings between movement qualities and features in motion capture data, future works should explore and investigate the more relaxed relationships between a richer set of multimodal features and the expressive qualities in dance movements. For instance, incorporating multimodal sensing of the physiological and the cognitive signals in the characterisation of expressive movement qualities may yield better results than using motion capture data alone.

7.2 Technology in Dance Production

Much of HCI research into dance has focused on assisting the creative process of dance, as summarised in Section 5. Among the many insights gained from those works, one common conclusion is that dance is a highly complex and idiosyncratic creative process that requires attention to the creative and production contexts. For instance, the temporal effect of technological integration may affect the resulting dance performance in unexpected ways [54]. Even the details such as the timing of encouragement from the choreographer could be felt by the dancers as a change brought by technology to the choreographic process [21]. Apart from communication, earlier adoption of technological tools can also limit the possibilities in subsequent choreographic development process. Similarly, the spatial constraints of physical theatres could also limit the options of applying technological tools [36]. With the awareness that each dance performance is situated in its unique context with many constraints in the time, space, software, and hardware setups, future works should actively design for the ease of adaptation in their methods or tools that account for the unexpectedness in the implementation. Otherwise, designers should think twice before aiming to generalise any technological tools created or used only in specific projects.

7.3 Challenges and Opportunities

We identified major challenges for HCI research works on dance at the beginning of this paper, and subsequently discussed the effort made by the community for addressing them in this section. Reflecting on the progress of that journey so far, we appreciate the amount and the quality of the works, which already cover a wide range of topics in dance, and a diverse set of novel technologies. To better address the challenges and to advance the field in the future, we propose the following directions for future works to explore.

7.3.1 Alternative approaches to the body. Learning from previous works, we should be aware that the direct capture and analysis of movement are not the only means through which we can use computational methods to co-create the bodily experience of the dancers and the expressive movement qualities. As the examples of introducing collaborative agents in the performances successfully evoked novel expressive qualities in the dancers, we propose that future works could learn from this approach and explore alternative ways in which we can apply technology in the complex and abstract process of dance making [28]. In those ways, we could avoid directly dealing with the chasm between the lived and felt human experience and the quantifying computational methods, but to constructively create a technologically aided lived experience with the dancer.

7.3.2 Experimental approaches to choreography and expression. Another promising and potentially more radical approach is to further explore the use of non-anthropomorphic robots as autonomous agents. We have already seen, in the work of Gemeinboeck and Saunders, how non-anthropomorphic robots can develop their own patterns of improvisations with the help of the human dancers [35]. With the Artificial Intelligence technologies being rapidly adopted by various disciplines, it would be exciting to see technologists and dancer makers work more closely together and explore new approaches through which we could gain deeper insights on how this relationship between dance and technology would develop further amid the prevalence of machine learning, and what would the role of the human dancers be in it. The radical adoption of technology in dance or in any form of artistic works will inevitably open unexpected doors and produce disruptive innovations that may appear controversial. However, as William Forsythe commented in his essay *Choreographic Objects*: it serves no cause "to prohibit or constrain this process of terminological migration across fields of arts practice" [32]. More exciting possibilities of technological intervention in dance await future collaboration between dancers, choreographers, and technologists.

7.3.3 Other opportunities in the dance-making process. Previous works on the creative process of dance-making, such as those around the tool *Choreographer's Notebook*, served as great examples of what valuable insights could be gained from the incorporation of novel tools and the evaluations of them [21]. Future works should learn from those works and explore more possibilities of utilising novel technologies out of the context of choreography. For instance, pioneering works in other related disciplines, such as *YouMove*, have used dance as an area of application to present their motor learning interface [5]. HCI dance researchers should embrace the adoptions of similar technologies in different stages of their works, such as teaching and learning (for an extensive survey, see [72]). Additionally, the advance of Augmented Reality (AR) technology technologies, especially in its mobile form, has brought further opportunities for dance makers to explore. For instance, Syiem et al. have investigated the attentional issues with the audience's use of mobile AR in the experience with installations [83]. Whereas briefly touched on by the literature, the experience of the audience in dance performances has been relatively underexplored by HCI researchers. Will the incorporation of mobile AR empower the audience or distract them from the performance? Can novel forms of dance performances be designed for an audience equipped with mobile and augmented lenses? How would remote or virtual performances be perceived differently from traditional performances when physical attendance is inconvenient? Those are important questions to answer and exciting opportunities for future works to explore.

7.4 Lessons for HCI At Large

Dance is a unique field of interaction for HCI researchers to investigate. The amount of diversity in context, people, and the complexity in accessing the bodily felt experiences and the abstract expressive movement quality, collectively make dance a challenging application area to design for. The knowledge gained from the previous works, such as the awareness of the specific contexts in different performance setups can readily inform technological intervention in other performing arts. Further, the literature over the past two decades have not only accumulated experience to inform better future design for dance, but also contributed a wealth of knowledge that benefit broader HCI research in the context of artistic practices and creativity support. The field of performing art has always been inspiring the exploration in emerging novel forms of media [66, 76], and investigations on novel integration of technology in artistic context can help extend the horizon for traditional HCI research [46].

In third-wave HCI research, there is an increasing focus on designing for the felt dimension of the body with the richness in sensations and emotions, such as in the theories of somaesthetic design [68, 82]. Among such works, studies on recognising and characterising user gestures and whole body movements have increased along with the maturing of motion tracking technologies, in application areas such as gestural control and health [38, 51, 89]. While many of the dance-related HCI works also belong to movement research, they offer a unique contribution to the grand understanding of the role that human body movement plays in the interaction with technologies. Above all, the works on embodied cognition and somatics can benefit greatly from dance-related works. One of the goals of somatic design is to access and cultivate the felt experience [82]. With a focus on expressive movement quality, dance is a bridge that tightly connects the observable "outer" behaviour of the body movement with the abstract "inner" processing in the felt dimension [11]. Somatic HCI research can learn from the approaches in dance research that are aimed at understanding and cultivating the affective and emotional expressiveness in the movement of dancers. For instance, the interactive costume [48] and the prosthetic robot [35], as described previously, both alter the somatic experience of the dancers through their own active and creative appropriation of the technological intervention. Those changes are unlikely to be achieved out of the context of dance, and are only likely to be accessible through creative movement [57, 59, 60]. In those cases, while the technologies were appropriated by the dancers and altering their somatic experience, the dancers were at the same time contributing to the technology. The prosthetic robot, and the many previously mentioned interactive agents used in dance performances were trained using the movement of the dancers, and subsequently recreate their own novel movements, all of which could not have been possible without the human input [10, 35, 36, 61].

An element of dance which HCI creativity support research could specifically take lessons from is improvisation. In any performing art, improvisation is an active and sophisticated learning process comprised of complex and interrelated elements and interactions [47]. In dance, the source material of the improvisation is the body and its kinaesthetic creativity. However, cultivating kinaesthetic creativity is difficult due to the delicate relationship formed in the abstract meaning-making process between the human dancers are their performing partners, either robotic agents, interactive visualisations, or other human dancers. Even if we could say that an experienced musician can handle any dissonance in the course of a chord progression, it may not be the case with dance. Unlike music, the improvisational performance of dance involves the engagement of many more sensory channels, the cooperation between more motor functions, and a tighter limit in the freedom of movement that are physically possible. But above all, the technological partner of improvisation must be designed carefully to foster the intercorporeal relationship with the human dancer instead of disturbing it [16, 42]. This awareness of the delicacy in the human-technology relationship for cultivating creativity is a ready lesson that could be learned by many HCI research works in creativity support.

8 CONCLUSION

Over the past two decades, the HCI community has seen the third-wave shift towards the cultural and sensorial aspects of interaction. This shift has been reflected by the growth in the field of creativity-support research, including the subfield of designing computational support for dance. The bodily nature of expression, the abstract meaning making through movement, and the social and technological complexities in the production, collectively present a series of challenges for HCI researchers to design better technological interventions to assist in the creative process of dance. Through this work, we identify the challenges and present a timely review of the HCI literature on dance over the past twenty years. We take stock of the accumulated experience and contribute a systematic understanding of the status quo, and identify future directions to help progress research in this field. Specifically, we propose future works to explore multimodal approaches to understand and affect the bodily sense of dancers in the aid of recognising and cultivating the bodily creativity and expressiveness. We also suggest that the complexities in the social and contextual differences in the highly idiosyncratic creative process of dance should raise awareness from the dance research community, as well as the creativity-support research community at large, to avoid unexpected pitfalls when designing and incorporating technology in those projects. Finally, we illustrated how HCI somatic research can take lessons from the works in dance to design interactions that better understand and cultivate the felt dimension of the embodied experience.

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