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Robots and Dance: A Promising Young Alchemy

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Abstract

Research at the intersection of robots and dance promises to create vehicles for expression that enable new creative pursuits and allow robots to function better, especially in human-facing scenarios. Moving this research beyond fringe spectacle and establishing it as a serious, systematic field—a proper subdiscipline of both robotics and dance—will require answering a key question: How does dance advance the fundamentals of robotics, and vice versa? Focusing on the former, this article offers glimpses of this new field with examples of meaningful contributions to control, robotics, and autonomous systems, such as novel actuator designs, improved sensing systems, salient motion profiles for robots, reproducible experiment designs, and new theories of motion derived from the study of dance. It also poses two grand challenges for the emerging field of choreobotics: developing a robust symbolic system for representing bodily action and establishing rich, repeatable testing environments for human–robot interaction.

1. INTRODUCTION

Roboticists have long dreamed that robots will become harmonious (or, alternatively, antagonistic) counterparts of human beings. Although companies like Amazon, iRobot, SoftBank, and Zebra Technologies are making big bets on new so-called social devices, there has been little success for machines that engage in complex embodied interactions with humans. It is a pragmatic suggestion, then, that a field like dance, which is primarily concerned with arranging bodies in space and time harmoniously (or, alternatively, antagonistically—and everything in between), can make important contributions toward achieving this dream.

This article is a review of progress at the intersection of robotics and dance as framed for an audience interested in control, robotics, and autonomous systems. In it, both robotics and dance are treated as academic fields with clear questions for research-oriented inquiry and urgently needed applications in industry. Although many of these advancements also stand to advance the field of dance (by creating new movement patterns and modes of expression reflective of modern life), the questions and applications in robotics are foregrounded. Moreover, a healthy primer on dance is offered for this audience.

1.1. Alchemy

Imagine it is the year 325, in a world without aspirin, magenta dye, nylon, and the entire field of chemistry. Today, many teenagers learn the basics of ideas and facts that took thousands of years to untangle in the form of the periodic table of the elements (1), which outlines a comprehensive structure of how elements combine to create compounds. This feat of rigor and order gave rise to a true academic field from people who look like goofballs in hindsight: the alchemists, who tried to turn lead into gold. Using the alchemists as an argument for bold experimentation, Baker (2) compared the advances in his relatively recently developed field, linguistics, to those in chemistry, and I do the same in this article, comparing an emerging intersection between robotics and dance to the well-established field of chemistry (see **Figure 1**).

Without any tools or procedures that we would today consider scientific, ancient philosophers imagined that matter would have an indivisible unit. They called this unit an atom, and this name kept everyone dreaming about the possibility of its existence for thousands of years, especially during the Renaissance, when alchemists worked to convert ordinary materials into gold. They never succeeded, but they maintained an interest in a way of working with matter that was crucial to establishing the field of chemistry. A similar idea about movement—a moveme—has been percolating in control, robotics, and autonomous systems for over a quarter of a century (3, 4).

The ancient concept of the atom was picked up—after a couple of millennia of fitful experimentation—by experimentalist John Dalton, who associated the term with the patterns in weight he observed after combining elements chemically. This pattern was related to electron valence structure by Dmitri Mendeleev in a paper that presented a precursor to today's periodic table (5), and the modern field of chemistry was born. The periodic table provided not only a symbolic representation of elements but also the ordered relationships among them, finding a pattern across many previously disparate experiments. As an academic field, the intersection of robotics and dance has delivered nothing like the periodic table of the elements. But it may be in a similar medieval period, somewhere in that long, confusing inflection interval after the dreams of philosophers but before rigorous organization.

Thus, this article presents a pitch for alchemy—for play, exploration, and failure—and highlights the brave pioneers who dare attempt the impossible in today's successful-output-oriented world. It is not gold we are searching for, but machines that move in harmony with human counterparts—that glitter and shine in the presence of human observers. Perhaps the behavior of these machines will come to be symbols for various emotional or aesthetic states, e.g., happy or

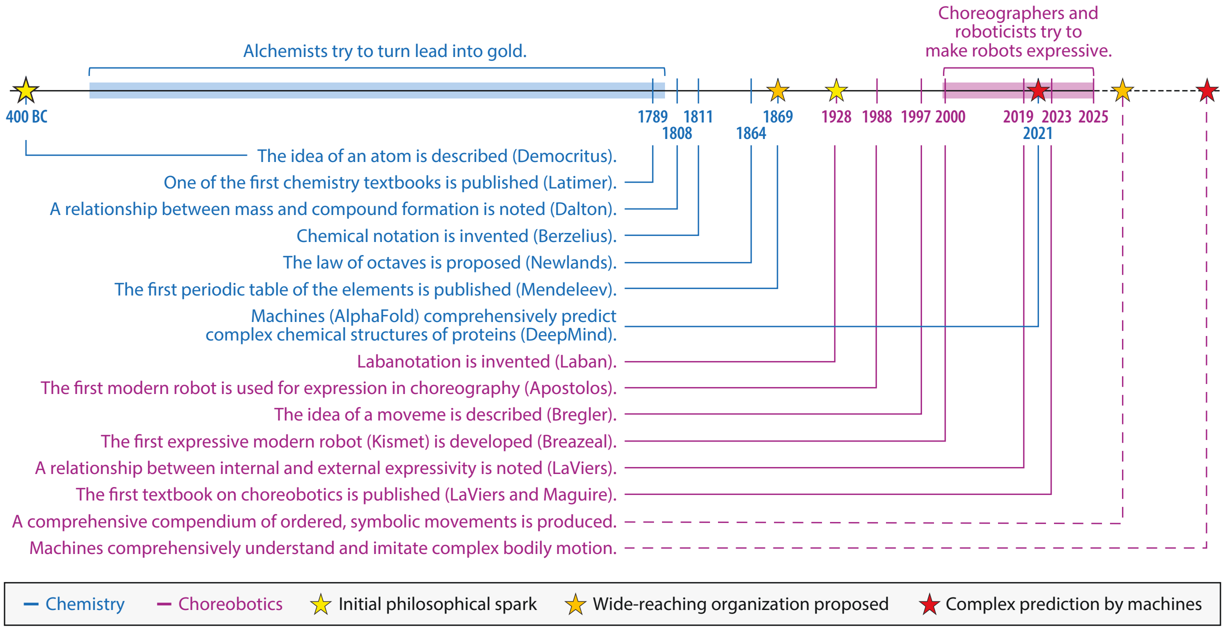

Figure 1

Comparison of key developments in chemistry and choreobotics. It took thousands of years for the field of chemistry to develop—from the conception of the atom to centuries of alchemical exploration to the initial development of the periodic table to predictive computational models. How long will it take choreobotics to develop similar underpinnings?

chic. This article celebrates the value of panning for gold in this frontier, even if we never find it, and suggests directions for deeper veins of ore.

1.2. Outline

The introduction has given some overview as to why such an article would be valuable and a comparative frame through which we will proceed. Section 2 provides a significant primer on dance, distinguishing it as an academic field (as opposed to only a human activity) and hopefully deepening the reader's appreciation for this crucial knowledge base. Once dance has been established as a serious intellectual domain, we will look at how an expressive frame poses new questions (and some answers) for control, robotics, and autonomous systems. Section 3 provides a review of work at the intersection of robotics and dance in the following categories: examining whether robots can actually dance, crafting tools for motion design and art making (including hardware, software, and interface development), studying human behavior through an expressive lens, and evaluating the efficacy of robot motion with the rigor of theatrical production design. Framed by what I suggest as two grand challenges for this intersection (symbolic representation of movement and a revolution in experimental design), Section 4 then attempts to define areas of this field, directions that seem ripe for exploration, and possible theoretical foundations and experimental practices that will illuminate and organize a spirited group of explorers on the fringe of control, robotics, and autonomous systems. Section 5 concludes the article with a vision of our future field.

2. PHILOSOPHERS OF MOVEMENT (A PRIMER ON DANCE)

This article is not concerned with dance as an activity; rather, I pursue dance as an art form, a base of knowledge, and an investigative approach. It is this definition that is the most apt in an academic

HOW DOES ART WORK?

In 2019, I co-taught the course "FAA 110: Exploring Arts and Creativity" at the University of Illinois Urbana-Champaign. One day, when my co-instructor and I were walking around the university's Krannert Art Museum, he asked which piece I would most like to hang in my own home. This is a great question to ask a colleague in an art museum, getting right at the heart of art in an approachable package: Which piece speaks to you right here, right now? I chose a nearby piece by Mark Rothko. My answer was partly personal—I do appreciate the soothing and brilliant swathes of color made iconic by Rothko—but also professional: I wanted my colleague to know that I recognized the prominence of this particular artist. Thus, our discussion of art was more about a social exchange than a decoding of a singular meaning of a particular work. As Elgin (6) wrote about Goodman (7), "the same thing may serve as different symbols by being incorporated into different systems. The same configuration, for example, can serve as an electrocardiogram or as a Hokusai drawing. That being so, Goodman contends, the question we should ask is not 'What is art?' but 'When is art?' Rather than embark on the futile quest for the essential properties that permanently distinguish art works from other objects, we should seek to determine under what circumstances an item of whatever sort functions as a work of art. For the very same item can function aesthetically at some times and not at others" (p. ix).

context and the most urgent in a research pursuit, and it is in this meaning of dance where we will find kindred spirits to the philosophers who dreamed up the concept of an atom. To share a sense of dance as an intellectual pursuit (see also the sidebar titled How Does Art Work?), I will quote philosopher Catherine Elgin and offer insights from dance literature to illustrate her points for an engineering audience. Elgin (8) writes about three important works of art—dances—that give insight into how Western concert dance is more like an ever-evolving search for movement and expression than a static set of moves, steps, or routines:

> *Swan Lake* is beautiful. It is delicate, graceful, enchanting. Martha Graham's *Night Journey* is not. It is riveting, harrowing, horrifying, often ugly. Yvonne Rainer's *Trio A* isn't even that. Being utterly pedestrian, it does not play on the emotions at all. But it is intriguing. Taken together these three dances raise questions: What is dance up to? What does it do and how does it do it? *Night Journey* discredits the thesis that the end of dance is beauty. *Trio A* discredits the thesis that the end is affective engagement. Possibly dance as such has no end. Different works and different genres pursue different ends. But whether or not dance has a telos, questions arise: "What does this particular dance do? How does it do it? And why?" (p. 82)

Swan Lake is a work of classical ballet set to music by Russian composer Pyotr Tchaikovsky that originally premiered in 1877 with choreography by Czech ballet master Julius Reisinger (9). Subsequent choreographers have created alternate steps that follow a similar narrative structure: A handsome prince falls in love with a beautiful maiden who is trapped by an evil sorcerer as a swan; to defeat the sorcerer, the two choose death together.

The style of motion of these productions was that of movement that evolved from court dances formalized primarily in France and Russia after the Renaissance. It is movement of a particular time and place that is a direct ancestor of ballet today (10). The steps of this dance form are highly codified and recognizable motifs in Western culture. The movements leverage outward rotation of the limbs, a lifted presentation of the spine, and particular articulation of the feet and hands. Dancers move with a quality that creates a sense of ethereal weightlessness associated with virtuosic ease of motion, which contrasts the intensely physical jumps, lifts, and turns performed by the dancers. The form includes the use of special shoes that allow dancers to balance on the very distal ends of their toes. Other traditional costuming choices include tight-fitting pants and stiff, short skits (tutus) that emphasize a distinction between the upper and lower bodies. Likewise, traditional sets depict pastoral and romantic settings where the movement is meant to be set.

Swan Lake highlights an important tradition of dance as an art form. Dances were created to accompany musical scores with a narrative structure and theatrical embeddings that created a richer performance. In restagings, the steps performed tend to vary more than the musical scores (in part due to music notation). The narratives included fantastical creatures and magical beings that transformed between earthly and heavenly forms. Themes of royalty, virtue, and betrayal were created through archetypal characters that emerged. This tradition is so well known in Western culture that it is commonly thought to be synonymous with dance itself—that dance is wholly about being graceful, beautiful, or otherwise aesthetically virtuous while performing a set of preordained steps. Elgin's writing complicates this idea, as she presents two more important works of dance that came after *Swan Lake*: *Night Journey* and *Trio A*.

Night Journey is a work by choreographer Martha Graham that premiered in 1947, 70 years after *Swan Lake*. Graham's company refers to the piece as a ballet in its archives (11); however, the style of movement Graham was working in—the steps her dancers took onstage—has little overlap with those in *Swan Lake* or other classical ballets. Graham's goal was to reject the light ethereality of classical ballet in order to express a modern image of her experience: gritty, painful, and hard (12).

Like *Swan Lake*, *Night Journey* used narrative structure, referencing the Greek myth of Oedipus, a king who tragically falls in love with his mother. But, instead of tutus, Graham's dancers wore body-hugging and revealing costumes adorned with graphic, scrolling lines. Some female performers wore long rectangular dresses that stretched across and hid their limbs as they walked, ran, or made deep lunges and squats—a shocking departure from the costumes of classical ballet, where tutus and tights preserved physical space for independent and visible articulation of both legs.

But it was Graham's movement vocabulary that ensured her place in the halls of dance history. In fact, her movement spawned an entirely new eponymous technique. The core idea of this style of motion, as Graham writes in an essay included in Reference 12, is the duality of contraction and release. As such, her dances break away from the almost constantly lifted presentation of the spine in classical ballet, where the sternum is open and upward facing and the shoulders are spread open across the collarbones, the lower abdomen supporting this lift, highlighting trim, thin waists. In Graham's technique, dancers round their spines in deep contractions that bring the sternum facing downward with the pelvis rotating upward, deepening the spine's articulation, creating a jarring and powerful contrast to the postures promoted in classical ballet. This resulted in dances that were loaded with dramatic storytelling that relied on portraying intense affective states of the onstage characters. These works, like the classical ballets before them, create another idea that is so powerful it might be confused as the entire goal of dance: to make movement about or conveying emotion. But Elgin paints a more complex picture by introducing the innovative work of Yvonne Rainer and her fellow postmodern choreographers.

Trio A is a stark departure from the narrative and emotive engagements of *Swan Lake* and *Night Journey*. Rainer's "No Manifesto" (13) outlined her approach to choreography. It stands in direct reference to choreographers before her, including Reisinger and Graham. Eschewing their approaches to dance-making quite directly, she wrote, "NO to spectacle no to virtuosity no to transformations and magic and make-believe. . ." (13, p. 14). This manifesto was anathema to many of the tools and conventions that dances in Rainer's cultural lineage favored. It was again a sharp departure that created wholly different movement, staging, presentation, and, thus, artistic expression.

Dressed plainly in comfortable, loose black pants and a T-shirt, Rainer does not immediately seem to be employing any particular vocabulary or refinement of movement, as in *Swan Lake* or

Night Journey. She seems utterly pedestrian, casual, and unaffected in her movement. She walks, raises an arm, jogs, shifts weight, bends over, folds her arms together and apart—all while maintaining an emotional detachment or indifference to the actions that was radical for her time. Yet, as the piece winds on, a particular expressive state is achieved. Even the setting—it was performed in the famous Judson Memorial Church in New York City to a soundscape of wooden planks being dropped (14)—pointed to the experimental, nontraditional nature of the work (13).

The work is a technical and creative accomplishment. Rainer developed new modes of movement, performance, and presentation—pushing our understanding of how the human body may express itself in space and time. Only 17 years after *Night Journey*, Rainer had yet again innovated in human movement. The vocabulary developed by Rainer and her peers would transcend dance, too. For example, it informs the movement used by actors in their performances, even in popular movies (15). Even political movements of the time (16) are associated with postmodern dance: In shedding so much, choreographers like Rainer helped identify aspects of everyday life where, for example, women were asked to perform their gender, e.g., through actions associated with camp and/or seduction. Their vocabulary informs how I think about robots, and it probably informs how you think about them as well.

The steps and movements used in dance change every day. It is not interesting, in fact, to do the same steps that have been done; instead, artists seek to push and change those steps (or something about their sequencing or presentation) to create something new. This kind of expansion of the known movement palette is what robotics requires as well.

Dance can be seen as an overlap of the broader fields of movement and performance studies. Movement studies, which encompasses movement analysis (e.g., Laban Movement Analysis), is a fundamental resource for fields like physical therapy, meditation, and exercise science. Performance studies, on the other hand, has a more theatrical focus and feeds adjacent fields like music, theater, performance art, and even interactive museum installations. Dance sits at the nexus of these two broader fields, foregrounding the whole physical body of performers, situated inside of performative settings. This is not the only way to describe the field, but it works for my purpose here: to vividly outline the depth and expanse of the field of dance for an audience of engineers. The next subsections briefly highlight three topics from this nexus and share (some) relevant literature in each; for a deeper reference, readers can consult Reference 17.

2.1. Choreography (Writing Movement for an External Audience)

Essays in Reference 12 by influential figures in modern dance reveal variety: It includes works by Isadora Duncan, known for her flowing movement that echoed her sheer wisps of costuming; Loie Fuller, known for her innovations in stage lighting and technology; Martha Graham, known for her dramatic contractions; Merce Cunningham, known for using random chance in his process and performances; Alvin Ailey, known for his seminal piece *Revelations*; Anna Halprin, who helped her spouse, the landscape architect Lawrence Halprin, notate movement to aid in his community-based design process (18); Yvonne Rainer, who studied with Martha Graham, Merce Cunningham, and Anna Halprin before creating her work; Twyla Tharp, who has authored broader texts on creativity based around her choreographic process (19, 20); William Forsythe, who has codified his “improvisational technologies” (21); and Mark Morris, who juxtaposes a traditional appreciation of classical music[1] with modern, playful gestures. These examples of choreographers who have been significant to a particular tradition of Western concert dance give a sense of the vastness of

[1]Morris also provided a great example of how dance need not be set to music with *Behemoth*, a work that is performed in silence.

choreography. Other traditions, entire universes of choreography unto themselves, exist alongside this work, e.g., jerking (22) and Bharatanatyam (23). Choreography is an arena where the artists' movement training, the time and place where they live, the work of prior artists, and the abilities of their dancers' bodies mix to create new traditions in movement (24). It is a place of problem solving, convention creation, and expression through (often) nonverbal movement.

2.2. Somatics (Investigating Internal Bodily Experience)

Dance also houses communities of knowledge centered around physical practice: How do we experience and edit our own bodily movement? This is manifest in how dancers train and how choreographers find physical inspiration for their material. In the movements of *Swan Lake*, dancers exhibit control through a lifted carriage of their skeleton, with a generally upright orientation to gravity. In *Night Journey*, dancers practice a series of contractions and releases of their cores, bending their spines almost like rubber bands, storing and releasing potential energy. In *Trio A*, the approach to stability (and its dual, mobility) is instead informed through a more relaxed tone of muscle that invites skeletal efficiency, e.g., allowing the femur to float more deeply into the hip socket. These examples of physical practice and approach to movement showcase another vein of dance: somatics (25). Systems of somatic practice include the Feldenkrais Method, the Alexander Technique, Laban Movement Analysis, Bartenieff Fundamentals, Body–Mind Centering, and yoga.

2.3. Notation (Representing Movement Symbolically)

A third area of study within the larger field of dance is that of movement notation. For ballets of historical importance, such as *The Afternoon of a Faun* by Vaslav Nijinsky (26), systems of movement notation are our only record of the work. In Reference 17, I argued that the development of movement notation has been hindered by technological development, in particular by video. But representations of movement through symbolic systems (7) have epistemic value beyond their use as archival records (27, 28). Technology can and has helped in this process of "writing dance" (29–31), and new systems for movement analysis are constantly improving our ability to notate it (32–35).

3. ALCHEMISTS EXPERIMENTING WITH MOVEMENT

When Cynthia Breazeal built Kismet (36), she took an important first step away from robots that served a work-oriented function (like the industrial machines of the prior decades) into something that was meant to be sociable and expressive. Her immediate goal was to create a device that would simulate the expression of emotion (though we know from Section 2 that this was not the only goal she might have pursued). She worked toward this goal through the design of vocalization and with an imitation of facial features: The robot had eyes, lips, and ears. But she also launched a whole field of machine designers who would aim to recreate these ideas about expression through movement via improvements in software and hardware across an array of forms. Like the alchemists before and after her, Breazeal was interested in bringing forward a rare, fleeting aspect of her earthly experience and making it more readily available. For medieval alchemists, it was a shiny metal that made people feel good. For Breazeal, it was a machine—and its movement—that would make people feel good. And, while there were experiments in robotics and dance long before Breazeal (who is not a trained dancer, to my knowledge) (e.g., 37), she is the instigator who has created a true and lasting need for the field of dance within robotics.

Did she succeed? While she constructed user studies (more on these in Section 3.4) that supported the claim that the robot expressed different emotions (38), there remained low differentiation among emotional states, e.g., ones that shared high degrees of arousal in Russell's circumplex model (39). In my opinion, she created a fascinating device (more on building these in Section 3.2), which could certainly ape emotion in limited contexts but is fundamentally incapable of resolving enough perceptually distinct physical states of motion to robustly simulate our changing facial expressions (more on humans in Section 3.3). First, I address the question of dancing robots.

3.1. Dancing Robots?

"Does a robot really dance or does it only *appear* to dance?" asked Margo Apostolos (40, p. 549) of her early explorations as a choreographer working with a robot (37). As a dancer and choreographer, Apostolos used these machines to extend her own palette of movement and create new patterns onstage—just like the choreographers discussed in Section 2. In asking, "Can computers create art?" Aaron Hertzmann (41) offered a definitive answer to her question, detailing the ways that technology changes (and creates) art forms but also unilaterally and effectively arguing that art is a social act and that "computers do not create art, people using computers create art" (p. 2). This argument applies to Apostolos's inquiry as well: Robots extend the potential for human dancers—and may, quite convincingly, *appear* to dance—but the true artists are the humans whose intent they translate into action.

Seeking the appearance of avatars (42) or robots dancing (43) is a process that dates to antiquity (44) and has much yet to offer. My doctoral dissertation focused on this idea, developing new tools for sequencing (45) and modulation (46) of movements, collaborating with dancers (47), and subsequently analyzing data with the designed model (48). In shifting from a task-oriented goal, movements must be codified, named, and sequenced and become the goal of the work in and of themselves. This is a shift from task space to configuration space that begins a deeper pipeline into symbolic representation of movement and has many applications, e.g., in education (49), healthcare (50), manufacturing (51, 52), defense (53), entertainment (54, 55), and the arts (56), including generating choreography with computers (57), as, e.g., Analivia Cordeiro (58), Merce Cunningham (59), and engineers (60) have done.

The cultural shifts that occur when creating dancing robots necessitate an awareness of these real theatrical productions (61–65) when designing robots (66). In 2011, the dance company Pilobolus collaborated with Daniela Rus's robotics lab at MIT to create a joint venture combining cutting-edge dance and cutting-edge drones. This was a golden opportunity to conduct research and simultaneously make art; however, the collaboration was criticized in both the dance and robotics communities as being superficial (67). On the other hand, the performance artist Stelarc has used robots throughout his work over decades with many different iterations of use, enabling a deeper exploration that has gained critical acclaim (68). Dance also offers the frame of improvisation for human–robot interaction (HRI), suggesting the possibility of creative extemporaneous relationships between humans and these embodied movement devices (69–72).

These performances serve as incubators for compositional ideas about movement inside and for the dance community—and provide a key opportunity for robotics labs. Formalizing this concept and hoping to offer meaningful outputs in both the dance and robotics communities (and supplement my lab's composition of mostly engineering students), I developed an artist-in-residence program in my lab, which has given berth for two external artists, Catie Cuan (73, 74) and Kate Ladenheim (75), to train my students and employees and consult on research projects (both paid pursuits) while developing their own artistic collaboration (an unpaid pursuit that created opportunities for paid showings in the future). The works were shown in international arts venues, including the DANCE NOW Festival at Joe's Pub at the Public Theater in New York City, USA, and the Performance Arcade in Wellington, New Zealand. Both residencies also produced rich research in robotics, pushing my own understanding of robots further. The work with Cuan developed into designing characters on low-degree-of-freedom platforms (76, 77) and examining

THE MOST POIGNANT ROBOT MOVEMENT I HAVE EVER SEEN

A jarring, jerky march animates the quadruped through a series of natural and unstructured environments: the underbrush of the woods in the fall, then the winter; an icy parking lot, painted lines hidden under thick, mounded sheets of ice. The irritating hum of noisy engines is overwhelming, but the progress of the device is undeniably impressive. (It is the year 2009; I am watching a video posted nearly a year prior.) As I adjust to the alien rhythm of Boston Dynamics' BigDog robot, a human counterpart appears. A man, clad in heavy work boots, enters stage left (the right side of my screen) and lands a merciless kick to the center of the robot, sliding the whole device—which must weight hundreds of pounds—sideways, off its footing. The machine sputters, for a lack of a better term, and the legs that so closely matched the repeating noise of the engines reveal themselves as a separate process from that hum as they slip and slide on the ice out of time with the drone of the engines. It is in this struggle [discussed in Reference 17 as "shaping" (pp. 178–79)] where a sense of amazement, followed by concern, bubbles in my chest. I give a short, relieved exhale when the device regains its footing, rejecting the disturbance and righting itself against the booted man. See, all movement is expressive, sometimes powerfully so, even when it is designed for a functional end.

perceptions of expressivity (78, 79) and control (80, 81). The work with Ladenheim considered feminine representations in robotic design (56) as well as the creative process of making dance with robots (82). Additionally, making art provides more enriching opportunities for outreach with robotics, casting these systems as creative tools, not just functional ones (83).

Working in the capacity of art making can be viewed as the most basic, exploratory research at this intersection of robotics and dance. (It also can refine and investigate our experience of robots created in a more traditional manner—e.g., see the sidebar titled The Most Poignant Robot Movement I Have Ever Seen.) While the immediate practical applications of these works can be unstated and even unforeseen at the time of their presentation (just as with a curiosity-driven researcher in basic science or basic math), the basic capabilities in expression through artificial bodies is best developed in this capacity. For example, researchers in robotics have translated avant-garde participatory robot dance (63) into the broader development of exoskeleton robots (84). This approach was summarized in a piece on the process and methodology that developed in my lab (85).

3.2. Machines as Hammers—and Paintbrushes

Those with an interest in studying dance quantitatively (as in 86, 87) are in luck: Robotics is increasingly interested in human-facing applications and other dynamic contexts but coming up short. This has brought on a heightened awareness of how "creepy" robots can be. My favorite example of this has to be the googly eyes belatedly affixed to Badger Technologies' Marty robot to help grocery store shoppers put up with the large, lumbering stockist aid (88). We might say that Marty was designed with functional goals in mind (as a hammer) but needed expressive goals during its deployment (like a paintbrush).

The quest to choreograph complex robot motion through the lens of function (where stability is the main criterion) has led to many interesting developments. Grizzle's output linearization takes the richness of complex nonlinear systems (useful for imitating complex systems in theory but difficult to control in practice) and renders them simple and controllable (useful for not falling over) (89). Mombaur et al.'s (90) path planning and whole-body musculoskeletal control adheres closely to the spirit of Flash & Hogan's (91) seminal paper on studying human motion and seems to take optimization as far as it can interestingly go. Kingston & Egerstedt (92) developed tools for morphing signals from a high-dimensional body to a low-dimensional one. However, while these methods do get out of the limits of logical specifications, none of them create systems that are as richly expressive as human or animal bodies (93). These new, dynamic contexts require more modularity (94). Switching among distinct motion controllers, as imagined by Brockett (95), stably (96) and optimally (97)—with progress toward leveraging actual natural language in constructing these controllers (98)—has helped produce a more mature viewpoint of movement design: from a simple, functional, stability-oriented view to one that aims to create complex aggregated phrases with rich moments of instability (99). The goal of these efforts is summarized well as "symbolic control" (100).

The boldness with which Petra Gemeinboeck dons a physical artifice in order to choreograph robot motions with her own body (101) and her broader analysis (102) makes the metaphor of using robots as an extension of an artist's body literal and promises a new class of roboticist. Likewise, a coterie of roboticists are using metaphors from choreography or expertise from dancers to control large groups of robots (103, 104), even leading to industrial applications (105) and patents (106). No one has thought more deeply about creative flow and its intersection with physical machines and embodied humans than Alexandra Nilles, who has developed a framework for "live-coding" robots based on her study of improvisation in modern dance and the theoretical underpinning for classes of mobile robot motion, forming clear design specifications from these experiences (107, 108). Kate Sicchio brings a similar ethos from her live-coding and dance backgrounds, teaming up with Patrick Martin, an engineer who is long versed in the challenges of interoperability of controllers and programming architectures (109). Such choreographic design specifications have inspired many control and specification architectures (and I anticipate will inspire many more) (103, 110–112).

Hardware design is also affected by the influence of dance. Umer Huzaifa and I worked with dancer and movement analyst Cat Maguire to develop robots that exhibit a wider range of walking styles (113). Maguire led a workshop on walking, parameterized not by external measures of distal joints, which are well measured by motion capture, but by the subtle movements of the spine, which are not (114). This shift from external measurements to internal somatic strategies required a lot of rolling around on the floor (training in Bartenieff Fundamentals) and also resulted in new ideas about hardware design (115–117). Other have proposed robotics spines (118) and soft machines (119) as apt for collaborations with dance.

3.3. Dancers as Specimen—and Collaborators

When engineers work alongside dancers, the expressive body holds a different deference. I have seen this accomplished in two distinct modes: one as dancers being anonymous human subjects and one as dancers being intellectual collaborators in research. No one has better exemplified how contributions to both dance and robotics can be created in both of these modes than Naomi Leonard's group, which has operated in both. In the former, Leonard collected data from human dancers and, applying similar methods as she has in the study of fish schooling behavior, analyzed the influence of different dancers on the rest of the group—in this case, using automatically tracked position and orientation data from anonymous dancers (120, 121). In the latter mode, she collaborated during the choreographic process of a new piece, aiding the choreographer (Rebecca Lazier) and composer (Dan Trueman) in understanding the role that various decentralized control strategies may have in the work (122), and then (using laboriously hand-annotated data to accurately recognize more complex movement patterns of dancers named in the created work) studied the deployment of these methods (123, 124).[2]

[2]Perhaps I am biased, because Leonard and Lazier were my undergraduate thesis advisers, but I prefer this mode of working considerably. Not only were papers coauthored by artist and engineer teams working as peers,

Using motion capture data from my own body (without acknowledging this source), I explored studying the style of motion (125) and movement segmentation (48). This approach had the advantage that I intimately understood the data sources I was examining, but I also lacked objective researcher distance from the measurements. The approach of studying one's own movement training is also seen in Sommer Gentry's PhD thesis (126), which documented a variety of quantitative analyses of West Coast swing dance. Gentry attempted to dissect rhythmic and haptic interaction structures for coordination of agents—a topic that remains a large and active area of research in robotics. While Sharma et al. (127) used motion capture data from an unnamed dancer trained in Laban Movement Analysis, who used the effort system to "author" motions for drones to exhibit distinct states or affects, Dana Kulić's group named their dancer collaborator (Sarah Jane Burton, who is certified in Laban Movement Analysis) in creating a similar dataset to animate nonanthropomorphic kinetic sculptures (128).

This particular system within dance has widespread use in studying human movement through an expressive lens (48, 129–131) and likewise inspiring systems to generate variation in artificial motion (46, 132–135) and is an especially good opportunity to examine the behaviors of dancers under a structured system, allowing their expertise to contribute as collaborators. Other work using this system has looked at modeling creativity (136, 137), studying the perceptual consistency of the system (138), movement recognition (139), movement generation with Labanotation (140–142), emotion communication (143, 144), and other aerial robot movement design (135, 145).

As with the examples presented in Section 3.1, the success of these projects, with simpler platforms than human or animal bodies, indicates that human perception aids the pursuit of expressive robots more than anything [and our intuition from simple cartoons, dating back to Heider & Simmel's (146) seminal study on apparent behavior, agrees with this]. This tantalizingly suggests that even the simplest robots may be able to create behaviors that represent complex states. For example, Kingston et al. (147) convinced human subjects that goopy green amoebas might look like human movement. In my group, Roshni Kaushik worked with dance artist Ilya Vidrin to develop a metric of imitation based on his preferences for professional performances (148), which went on to drive imitation between humans and low-degree-of-freedom robots (149). We also found that this metric breaks down when applied to new cultural contexts (150).

3.4. Human–Robot Interaction Experiments in the Lab—and Onstage

In Kate Darling's work asking human subjects to smash robots with hammers, some subjects are read a story about the simple device, and some are not. Those given a narrative struggle more to smash (151). What is often taken from this paper is the tantalizing idea that we can create lifelike robots, but what I think is more important is the role of narrative and framing in creating experiences for human subjects. Narrative and framing undermine nearly every HRI experiment in a significant way: All of the results can be easily manipulated with the right (or wrong) presentation. Given that there are few rigorous boundaries on how these setups should be established (many papers fail to provide sufficient detail for reproduction), the field bumbles on using robots that don't fall over or do anything interesting, unless roboticists tell the right story about them.

A popular way to evaluate success in this vein is through the Godspeed Questionnaire (152), which scores motion on traits like likability, animacy [the axes of the plots that supposedly reveal

but the dancers involved are publicly acknowledged through program credits and publications (allowing for greater replication in future studies). But the work won the equivalent of an Oscar—a Bessie—indicating that I am not the only fan!

an uncanny valley (153)], anthropomorphism (154), perceived intelligence, and perceived safety. These ideas have no direct mapping in dance, which suggests an entirely different route for movement evaluation (something situated, personal, and descriptive). Work by Andrea Thomaz and collaborators has formulated novel metrics for being human-like (instead of assuming that this idea is well defined) and centers much of their discussion around imitation. First, the team exploited the many possible ways that a given task may be completed (155). Then, the authors proposed metrics to evaluate how human-like a particular motion is, including measuring the number of times subjects rewatch a video in order to repeat the movement (a genius measure, in my opinion) (156). Ultimately, the team's method for creating human-like movement rested on this notion of imitation writing—"this experiment assumes that a human-like motion should be easier for people to mimic accurately, and awkward, less natural motions should be harder to mimic" (157, p. 1282)—and using trajectory-based measures of similarity (157).

Similarly, Dragan et al. (158) defined the concepts of legibility and readability based on integrative measures of movement trajectories. These ideas assume that movement is meant to be predictable and advertise the intent of the mover, which may be a good idea for robots but is not the case in many examples of human movement (consider the standoff between a goalie and a penalty kicker or the actions of a thief or someone unhappy to see a disliked colleague arrive unexpectedly to a faculty meeting). Yet this limited idea is pervasive in HRI, giving rise to the redundant term expressive motion (159), which aims to describe movement that represents emotion or other complex intents (160). In the isolated environment of a robotics lab, these ideas can produce usable experimental results, but they frequently break down across the kinds of situational and environmental contexts that are so frequently explored in the arts. The field of dance advances a different usage of this term: It demonstrates how all movement profiles can be expressive in the right context, for the right observer, and reveals how the more movement profiles a given body can exhibit, the more expressive that body is.

No one at this intersection has done more than Knight and her group (161–166) to present evidence of the plausibility that robot motion can be tokenized for representative meaning of complex human states, such as emotion, in a variety of real-world contexts. Enabling this success is her work in the performing arts (including dance, theater, and comedy); she has formalized systems for tracking and dealing with errors from robots in a theatrical context (167), demonstrating an unparalleled sophistication and experience with putting robots onstage in front of a live audience—and measuring the results. Likewise, Cuan has given high-profile performances at venues such as the Public Theater, the Smithsonian, National Sawdust, and the TED main stage, with novel robotic systems onstage, which brings weight to the potential for machines to exhibit intriguing, pleasant, and delightful behaviors (74, 168). Another artist–engineer, Alexandra Bacula, is bringing robots into public spaces (166), with the sensibility of a ballet dancer driven by archetypal characters (169). Fellow former RAD Lab member Ishaan Pakrasi is also building evidence that characters and imagined worlds can be built from simple mobile robots (76).

These efforts have groundbreaking practical applications. For example, Lena Ting's group (50, 170) uses dance-framed robots for rehabilitation. By embedding simple devices inside a partner-dancing context, their work shows that instead of applying mechanically significant disturbances to improve gait, small forces can be communicative inside this frame (171), which is part of a larger effort to use dance in rehabilitation (172).

Using the stage to reformulate HRI experiments opens up new conventions and tools for reporting on and understanding the implication of user study framing, with formulations already suggested by my group (78), Jochum & Herath (173), and Troughton (174). Theaters offer controlled environments where the lighting, sets, and costume designs are regularly attributed and well understood; theater professionals create routinely repeatable conditions for performance; and audience flow is commonplace (and comfortable for participants). What's more, working inside the ethos of performance provides a more realistic set of expectations around robot demonstrations (that is, working once in an experiment is a long way from working routinely in practice).

In this vein, my group has shown how representative labels supported by subject pools in one context break down in another. For walking gaits created by animators from motion capture data, emotive labels such as happy and sad break down across contexts, while gender labels hold up slightly better (175). We have also explored our own character-oriented styles of motion in distinct contexts (176, 177) and gaits for a planar walker in different environments (178). Such studies are relatively rare, to my knowledge, but are aimed at formalizing context and situation variance for perception of motion. Based on our studies, I am sure that prominent results like those from Badler and colleagues (179), Dragan and colleagues (158, 160), and Knight & Simmons (132) would not hold up through this kind of theatrical inquest.

4. TOWARD A NEW FIELD (COMPARING CHEMISTRY AND CHOREOBOTICS)

In the quest to turn lead into gold, it took two millennia to find empirical evidence for the atom. The organization of different types of atoms with respect to one another and principles for how they combine to create compounds then came together relatively quickly—only a few decades later, Mendeleev debuted the periodic table. In the quest to turn robots into harmonious, expressive human counterparts, at least two grand challenges remain: developing symbolic relationships between our experience and machine behavior and creating more robust, human-facing testing environments, which account for context and result in more success deploying systems in the real world. Take the example of self-driving cars: These machines are unable to interpret the meaning of counterpart actions [of both vehicles and pedestrians (180)], and though the vehicles demonstrate success in testing, they are endangering public safety (181).

With this framing challenge, and amid specialized publication venues, growing conference opportunities, and high-profile events, there is a sense that we are moving toward a new field. We are calling it choreobotics. We have a concept of an indivisible unit of movement (although it is only decades, not millennia, old), and we have theories about how longer phrases of movement become meaningful for people (from studies in psychology, dance, and HRI). But these ideas are not coherent: Our indivisible units of movement (movemes or motion primitives) are short, quantitative, and universal, while our theories of meaning making are contextual, qualitative, and personal. We have intriguing and fascinating examples of machine movement, but we have no rigorous system for making them and limited ability to deploy and test them. We need a new guiding framework—a periodic table—to advance into a true field. What are the columns and rows of this periodic table? What are the topics that form the foundations of this field?

I think some initial answers may be found in the relatively recently established field of linguistics. Linguistics is the study of symbolic notation for the bodily action of vocalization (language) (182). It has around 30 different subfields (183), including origins of language, field linguistics, phonology, morphology, syntax, semantics, pragmatics, and translation. Each of these (and the many more subfields of linguistics and computer science that have produced technologies that deal with language, from cuneiform tablets to the keyboard to text-to-speech systems to generative AI) offers a possible template for how much work there can be at the intersection of robotics and dance—work that lives as much in studios and on stages as it does in laboratories, as illustrated in **Figure 2**. Here, then, are some suggested foundational areas for choreobotics, framed by a comparison to chemistry.

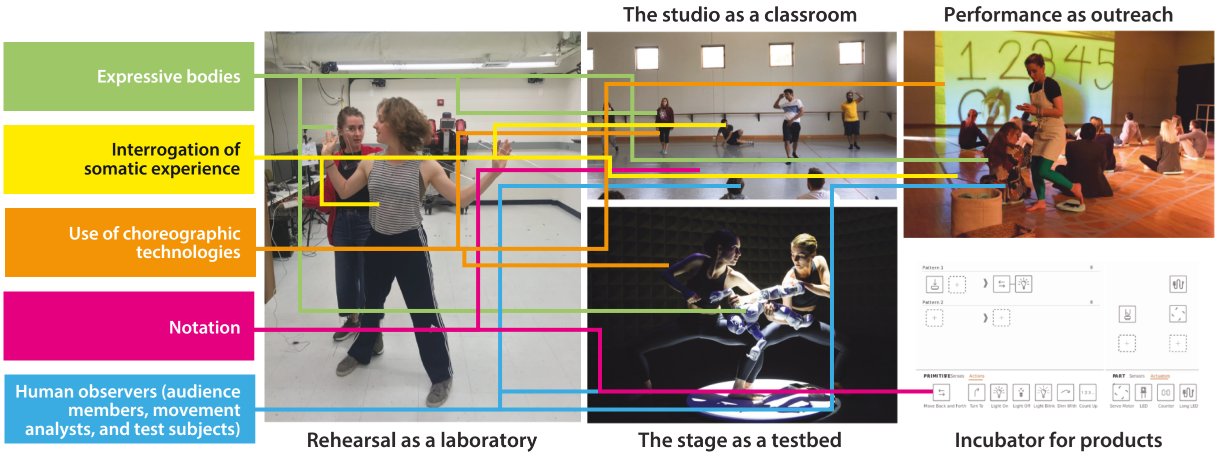

Figure 2

Features of a life cycle of art making, commercialization, education, outreach, and research at the intersection of robotics and dance. Photos feature RAD Lab artists-in-residence Catie Cuan ("the stage as a testbed") and Kate Ladenheim ("rehearsal as laboratory") and were provided by Yi-Chun Wu ("the stage as a testbed"), Natalie Fiol ("performance as outreach"), RAD Lab members ("rehearsal as a laboratory" and "the studio as a classroom"), and the RAD Lab startup spin-off AE Machines ("incubator for products").

4.1. Platforms (Matter and Bodies)

The advances in the manipulation of matter brought by chemistry have proved a fertile space for building all sorts of objects large and small [e.g., proteins (184)]. The expressivity of human language is evident through the way that a finite set of words can be combined and recombined into endless paragraphs, sentences, and utterances. Likewise, the many theatrical successes of choreographers for robots, like Margo Apostolos, Huang Yi, Merritt Moore, Petra Gemeinboeck, Stelarc, Madeline Gannon, Blanca Li, Elizabeth Streb, Catie Cuan, Kate Ladenheim, Ilya Vidrin, Susan Marshall, and Monica Thomas, suggest that robot bodies are expressive, fertile media as well.

How do we understand this phenomenon quantitatively? The minimum jerk model suggests that human movement is solving a basic optimization problem (91). Fitts's law, another classic model, took an information-theoretic approach, using Claude Shannon's work in communications to develop predictive models for trajectories and end points of human movement (particularly across a human–computer interface) (185) that develop measures of throughput (bits/s) across a range of devices (186). These models have helped advance an understanding of a moving body through a functional lens. But what makes one body more expressive than another? As I describe in Reference 187, we should think about these devices, in the context of expression, as information sources, where bits, or Shannon entropy, can distinguish why robot motion is still (mostly) so opaque to human counterparts. Comparing the number of static postures described by the anatomy of a variety of robots and animals, I offer an expression-focused alternative to other models, which use displacement to determine information content (188), and establish a measure of expressivity for robotics that is consistent with how the term is used in other disciplines (e.g., computer science, genetics, and dance) and reveals how inexpressive our current platforms are. Expanding their capabilities may be as simple as adding well-designed dynamic indicator lights or as complex as using soft materials (see, e.g., the sidebar titled My Favorite Robot to Dance With) (189).

MY FAVORITE ROBOT TO DANCE WITH

It's yellow, it's squishy, and it's difficult to resist dancing with it. I don't think anyone has done it better than Marek Michalowski and collaborators did when building the interactive Keepon robot (190). The inclusion of beat detection and rhythmic imitation meant the system would be responsive even if users were off the beat (191). The squishy body of Keepon dresses up the relatively simple linear actuators inside, offering a more complex, softer shape than most robots to date. Instead of rigid blocks rotating precisely in space, Keepon squishes. Maybe because people are mostly made of water or maybe because we just like squishy things, this feels right. Finally, the design of each action and the variety across repeated up-and-down pumping provide a beautiful imitation of the bouncing of our spine. My favorite thing about this motion design, though? It serves as a wonderful reminder that you don't need arms, legs, or music to dance.

4.2. Dyadic Interactions (Bonds and Body Language)

How do we know if an expression was successful—if we have been understood by a counterpart? How do we share that we understood? Perhaps we do so through imitation. Psychologists have measured this phenomenon in humans, describing and probing symmetry breaking and formation in dyadic interactions (192, 193). Moreover, parents have experienced this with infants: How do you know if the baby heard you? You wait for an imitation. How do you let it know that you heard it? You make the same sound back.

We have developed robust tools for determining whether a system can be stabilized, e.g., the Lyapunov stability criterion (194). Although systems are often most interesting when they employ instability and nonlinearity, tests for stability provide an important foundational underpinning for robotics. Just as stability is a baseline requirement for successfully producing movement on an artificial system, I predict that a measure of imitation will form a test for the possibility of successful communication. Such is the approach employed by Simmons & Knight (195), who showed that mimicking robots elicit a greater range of behaviors—and thus engagement—from interactants. Just as bringing a system to rest is rarely the goal of modern robotics, solely mimicking a human's action—in a parrot-like way, say—will be unlikely to produce the desired interactions between humans and machines, but formalizing tests for our ability to do so will become an important foundation of robotics. Likewise, I think we will find analogs between energy and entropy, information and mass, and even expression and force. Working through this alternate way to view movement—as a source of information and variation rather than a repeatable trajectory of mass—requires foundations in dance that will transform robotics.

4.3. Indivisible Units (Atoms and Movemes) and Their Combinations (Compounds and Movements)

Although comprehensive models for simple animal movement have been established (196), identification and classification of smaller snippets of human movement from measurement systems like two-dimensional video (197), mouse data (198), and three-dimensional motion capture (199) are ongoing challenges common to computer vision, robotics, and dance. Most of this work is driven by empiricism (which is tricky when ground-truth labels depend on finicky human perception), but some are philosophical, probing lived experience for models that identified movements from actions and activities and so on (200). More complex behavior, especially for animated bodies, is generated through motion graphs (201), and style of motion has also been modeled (202).

Researchers in computer vision have coined a term for indivisible snippets of human movements, calling these snippets movemes (3) in order to relate the idea to phonemes in linguistics.

Oxford Languages defines a phoneme as "any of the perceptually distinct units of sound in a specified language that distinguish one word from another" (**https://www.google.com/search?q=define+phoneme**.) But the engineer who coined the term defaulted to an external, quantitative definition of the idea. In the many attempts to define a moveme, usages in control, robotics, and autonomous systems typically fail to emphasize the idea of perception. Several adhere to the original definition of a second-order linear system that approximates a region of significant movement (3, 198), a parameter in an expectation–maximization problem (200), bases that facilitate translation between 2D image data and 3D movement models (203), and even an unconscious aspect of our neuromuscular systems (204). In the study of animal behavior, ethology, where Perona and colleagues have motivated the discipline of computational ethology, the emphasis of human perception is present in the definition and use of the term, defined in that context as "the simplest meaningful pattern associated with a behavior" (4, p. 27). Linguists produce the underlying phonetic elements (phonemes) through a concept called minimal pairs. By creating words that sound almost exactly the same (but aren't), linguists identify perceptually salient sounds. It should be similar, then, with movement. Instead of defining movemes through mathematics, they must be defined through experience.

Comparing motion programs to snippets (or sounds) of words has been inspirational in the community of researchers trying to compose longer behaviors from simpler movements. One example is Topping's dissertation (205), which uses the idea of a syllable (figure 4.1, p. 71). From a dynamical systems perspective, this is a very hard problem. Branicky's counterexample (206) shows the fundamental issue with such switched systems: Even if each individual mode is stable, switching between modes at the wrong moment can produce an overall unstable system. That is, just because a robotic system can hop, skip, wave, and jump doesn't mean it should (or could) do all four in sequence. In a functional framework, Topping asks, Are these movements stable? In an expressive framework, we must also seek a rigorous mapping but instead ask, Do these movements make sense?

4.4. Notation (Chemical Formula and Movement Scores)

Generative AI tools, like OpenAI's ChatGPT, only work because we have the symbolic system of writing, developed by ancient humans in a long, iterative, laborious process. ChatGPT works great when training corpora, queries, and responses are all in this shared symbolic stream: The user types a symbolic query, and the algorithm uses its huge corpus of data (text, video, and images) labeled in this same symbolic stream to then reply in this symbolic stream or media format. The internet is full of images, videos, and long streams of text that have been generated by humans. The algorithm creates an internal representation of that material (which is nonsensical to us) and then uses that representation to generate (mostly) sensible replies. No such widely used system of labeling or data corpus exists for bodily movement (not to mention that consistent correspondences to human bodies and machine bodies are still an open problem). Therefore, embodied agents are not prepared to use generative AI, and increased research (both scientific and embodied) is needed on developing this symbol system.

Consider the International Phonetic Alphabet (207), a common system (of many) used by dictionaries to provide word pronunciations. This system is rooted in the morphology of the mouth and was created through obsessive study of its movement. This system allows for detailed notation of human movement to translate to more abstract concepts like words (which can be pronounced in different dialects and even with different body parts, e.g., in American Sign Language). The body can make many more shapes and dynamic actions than the vocal cords alone, so we will likely need elaborate computational tools to aid in the discovery of useful movement notation (17; C. Maguire, S.H. Yoo, A. Bacula & A. LaViers, manuscript in review), but I expect this area of work will need to develop many movement taxonomies (e.g., 208–210). Moreover, this advance would help dance artists protect their own intellectual merit (211).

4.5. Testbeds (Laboratories and Studios/Rehearsals/Stages)

Just as chemists have toiled in laboratories and linguists traveled the globe studying languages in the field, the field of dance has a long, physical lineage of practice in studios and on stages, and of moments when audiences clapped, gasped, sighed, and cried (or didn't). The sense of whether a particular work—and performance of it—worked is established and reestablished with every live performance and every unique audience. Likewise, all HRI experiments take place on a stage. HRI studies are created from a very specific, ephemeral alchemy of the researchers, their lab, their recruited subjects, and the presentation of stimuli and queries. Yet, whereas lighting designers in theaters are acknowledged in the credits of every dance performance, I have never once read an HRI paper where the details of the lighting conditions were available.

Papers that purport to create emotional expression in robots will be better understood as papers attempting to create symbolic relationships between robot behavior and human interactants. And these relationships are relative. Just as motion is only accurately recorded with respect to a particular reference frame, we need to develop a system of reference frames that resolves the multiplicity and variability of meaning for each observer. These frames are likely better viewed as contextual than planetary: environment, situation, culture, and so on.

4.6. Foundations (the Periodic Table and the BESST System)

One of my favorite video series on the internet is Jimmy Fallon's on the history of (or evolution of) dance, in which he performs alongside another famous entertainer. There is real knowledge embedded in these entertaining videos. For one, they present a taxonomy of different dance styles. For another, they offer an example of two distinct bodies doing the same thing despite significant physical differences between them. Under what conditions is this exercise successful? When do two bodies stop doing the same thing? When has a particular presentation changed how a robot is perceived? Why are some imitations successful and others aren't? How do bodily postural and gestural shifts supplement the far-better-understood movements associated with vocalization (and facial expression) to support communication and expression? How do we write down the essence of an observed example of bodily movement? What is the relationship between observed movement and real physical phenomena? How many different things can our bodies do, and how many can they perceive? These are questions that should be keeping you up at night.

The periodic table unified chemists around an experimental exploration of matter, and choreobotics will be developed when the kind of internal, somatic investigations and external, choreographic presentations happening on a regular basis in dance studios begin occurring more frequently alongside the measurement, modeling, and movement systems of robotics labs, e.g., motion capture suits, Euler–Lagrange equations, and humanoids. The best system I know to grow this experimentation into a symbolic, ordered system—one that captures the experience of being a moving human inside a systematic taxonomy—is the Body, Effort, Shape, Space, and Time components of movement, comprising the BESST System, which has recently been documented in a textbook for engineers (17).

5. CONCLUSION

This article began with imagining the past—1,700 years ago, before chemistry existed as a field. Now, let us imagine a possible future. It is the year 2325, and we are at the IEEE International Conference on Robotics and Automation. Many elements of the event are the same as they are today: Industrial companies and academic research labs bring physical demos of their latest devices and software systems; researchers present new foundational advances on the subject of robotics in parallel paper tracks, divided by topic area; and developing, fringe areas of work are explored in workshops and tutorials before and after the main conference. But a new class of material (choreobotics) and a new kind of conference attendee have emerged: the kinesiologist, the physical therapist, and the dancer—people who make their work in studio spaces, in bodily motion perception and creation, in making meaning with moving bodies. These attendees will come because of multiple paper tracks that leverage knowledge from the performing arts and somatic practices within the study and development of robots (which are now commonplace in human-facing contexts). That is, dance is now widely recognized as a foundational field of knowledge for robotics, and the expressive human body has taken root as a site for research in robotics.[3]

SUMMARY POINTS

1. Dance is an academic field that offers a framework for understanding the complexity and malleability of bodily movement and the process of expression.
2. Grand challenge 1: Robotics lacks a system for symbolic representation, classification, and control of movement. A truly abstract symbolic system of notation is needed to understand the color wheel of bodily movement patterns and how its components combine to, contextually, create expressions in movement.
3. Grand challenge 2: Human–robot interaction experiments take place on an often unacknowledged stage. The notion that movement belies intent (including legibility and the expression of emotion solely through any given movement profile) is a mirage born of ignoring this frame. Meaning (expression) is created through a complex alchemy of body (source), observer, and context. Greater expressivity (in both generation and interpretation of movement) is accomplished through a broadened movement palette.

FUTURE ISSUES

1. Viewing dance as a lexicon of moves—or merely an activity—limits the intellectual power of this rich academic field (and broad scope of professional practice). Instead, it should be formally recognized as a foundational underpinning of the field of robotics in programs for research and education.
2. Robotics is missing foundational theory to govern expression. Entropic models of movement and principles of dance must be incorporated alongside the already prevalent energetic models of movement and principles of psychology. Symbolic description of movement can only be achieved through personal, situated, bodily investigation.
3. Robotics, especially human–robot interaction, is missing grounding practice to govern experimental design. Understanding measurements of human interactions with machines requires better acknowledgment and documentation of the (often performative) framing of experiments and the training of experimenters (including anonymous human subjects with specialized training).

[3] And, wouldn't you know, it *is* possible to turn lead into gold after all (212).

DISCLOSURE STATEMENT

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LITERATURE CITED

1. Gordin MD. 2018. *A Well-Ordered Thing: Dmitrii Mendeleev and the Shadow of the Periodic Table*. Princeton, NJ: Princeton Univ. Press
2. Baker MC. 2008. *The Atoms of Language: The Mind's Hidden Rules of Grammar*. New York: Basic Books
3. **Bregler C. 1997. Learning and recognizing human dynamics in video sequences. In *Proceedings of IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pp. 568–74. Piscataway, NJ: IEEE**
4. Anderson DJ, Perona P. 2014. Toward a science of computational ethology. *Neuron* 84(1):18–31
5. Mendeleev D. 1869. The dependence between the properties of the atomic weights of the elements. *J. Russ. Chem. Soc.* 1:60–77
6. Elgin CZ, ed. 1997. *The Philosophy of Nelson Goodman: Selected Essays*, Vol. 3: *Nelson Goodman's Philosophy of Art*. New York: Garland
7. Goodman N. 1976. *Languages of Art*. Indianapolis, IN: Hackett
8. Elgin C. 2010. Exemplification et la danse. In *Philosophie de la Danse*, ed. J Beauquel, R Pouivet, pp. 81–98. Rennes, Fr.: Presses Univ. Rennes
9. Lee C. 2002. *Ballet in Western Culture: A History of Its Origins and Evolution*. New York: Routledge
10. Warren GW, Cook S. 1989. *Classical Ballet Technique*. Gainesville: Univ. Press Fla.
11. Martha Graham Cent. Contemp. Dance. 2024. Night Journey (1947). *Martha Graham Company Online Repertory Archive*. **https://marthagraham.org/portfolio-items/night-journey-1947**
12. Brown JM, Mindlin N, Woodford CH, eds. 1998. *The Vision of Modern Dance: In the Words of Its Creators*. Hightstown, NJ: Princeton Book Co. 2nd ed.
13. Lambert-Beatty C. 2011. *Being Watched: Yvonne Rainer and the 1960s*. Cambridge, MA: MIT Press
14. Banes S. 1987. *Terpsichore in Sneakers: Post-Modern Dance*. Middletown, CT: Wesleyan Univ. Press
15. Kourlas G. 2019. "Joker": a dance critic reviews Joaquin Phoenix's moves. *New York Times*, Oct. 11. **https://www.nytimes.com/2019/10/11/arts/dance/joaquin-phoenix-dancing-joker.html**
16. Copeland R. 1993. Dance, feminism, and the critique of the visual. In *Dance, Gender and Culture*, ed. H Thomas, pp. 139–50. London: Palgrave Macmillan
17. **LaViers A, Maguire C. 2023. *Making Meaning with Machines: Somatic Strategies, Choreographic Technologies, and Notational Abstractions Through a Laban/Bartenieff Lens*. Cambridge, MA: MIT Press**
18. Halprin L. 1970. *The RSVP Cycles: Creative Processes in the Human Environment*. New York: George Braziller
19. Tharp T. 2009. *The Creative Habit: Learn It and Use It for Life*. New York: Simon & Schuster
20. Tharp T. 2009. *The Collaborative Habit: Life Lessons for Working Together*. New York: Simon & Schuster
21. Ziegler C. 2016. William Forsythe's improvisation technologies and beyond: a short design history of digital dance transmission projects on CD-ROM and DVD-ROM, 1994–2011. In *Transmission in Motion: The Technologizing of Dance*, ed. M Bleeker, pp. 41–51. New York: Routledge

3. Introduced the idea of a moveme—an indivisible snippet of human movement.

17. A reference on choreography, somatics, and notation for engineers (or a textbook on choreobotics).

22. Trebay G. 2009. Hip-hop's new steps. *New York Times*, Nov. 20. **https://www.nytimes.com/2009/11/22/fashion/22jerking.html**
23. Puri R. 2004. Bharatanatyam performed: a typical recital. *Vis. Anthropol.* 17(1):45–68
24. Dils A, Albright AC. 2001. *Moving History/Dancing Cultures: A Dance History Reader*. Middleton, CT: Wesleyan Univ. Press
25. Hanna T. 1986. What is somatics? *Somat. Mag. J. Bodily Arts Sci.* 5(4):4–8
26. Guest AH, Jeschke C. 1991. *Nijinsky's* Faune *Restored: A Study of Vaslav Nijinsky's 1915 Dance Score* L'Après-Midi d'un Faune *and His Dance Notation System Revealed, Translated into Labanotation and Annotated*. Philadelphia: Gordan & Breach
27. Fügedi J. 2003. Movement cognition and dance notation. *Stud. Musicol. Acad. Sci. Hung.* 44(3–4):393–410
28. Fukushima R. 2016. *Why Labanotation remains*. Dance Dep. Best Stud. Pap. 12, Loyola Marymount Univ., Los Angeles. **https://digitalcommons.lmu.edu/dance_students/12**
29. Groves R, Shaw NZ, DeLahunta S. 2007. Talking about scores: William Forsythe's vision for a new form of "dance literature." In *Knowledge in Motion: Perspectives of Artistic and Scientific Research in Dance*, ed. S Gehm, P Husemann, K von Wilcke, pp. 91–100. Piscataway, NJ: Transaction
30. Karreman L. 2013. The dance without the dancer: writing dance in digital scores. *Perform. Res.* 18(5):120–28
31. Shaw NZ. 2016. Synchronous objects: What else might this dance look like? In *Transmission in Motion: The Technologizing of Dance*, ed. M Bleeker, pp. 99–107. New York: Routledge
32. Fdili Alaoui S, Schiphorst T, Cuykendall S, Carlson K, Studd K, Bradley K. 2015. Strategies for embodied design: the value and challenges of observing movement. In *Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition*, pp. 121–30. New York: ACM
33. Studd K, Cox L. 2019. *Everybody Is a Body*. Indianapolis, IN: Dog Ear
34. Wahl C. 2019. *Laban/Bartenieff Movement Studies: Contemporary Applications*. Champaign, IL: Hum. Kinet.
35. LaViers A, Maguire C. 2022. The BESST System: explicating a new component of time in Laban/Bartenieff movement studies through work with robots. In *Proceedings of the 8th International Conference on Movement and Computing*, art. 40. New York: ACM
36. Breazeal C. 2004. *Designing Sociable Robots*. Cambridge, MA: MIT Press
37. Apostolos MK. 1988. A comparison of the artistic aspects of various industrial robots. In *Proceedings of the 1st International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems*, Vol. 1, pp. 548–52. New York: ACM
38. Breazeal C. 2001. Emotive qualities in robot speech. In *Proceedings of the 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems: Expanding the Societal Role of Robotics in the Next Millennium*, Vol. 3, pp. 1388–94. Piscataway, NJ: IEEE
39. Russell JA. 1980. A circumplex model of affect. *J. Pers. Soc. Psychol.* 39(6):1161–78
40. Apostolos MK. 1991. Robot choreography: the paradox of robot motion. *Leonardo* 24(5):549–52
41. Hertzmann A. 2018. Can computers create art? *Arts* 7(2):18
42. Matarić MJ, Zordan VB, Williamson MM. 1999. Making complex articulated agents dance. *Auton. Agents Multi-Agent Syst.* 2:23–43
43. Aucouturier JJ, Ikeuchi K, Hirukawa H, Nakaoka S, Shiratori T, et al. 2008. Cheek to chip: dancing robots and AI's future. *IEEE Intell. Syst.* 23(2):74–84
44. Truitt ER. 2015. *Medieval Robots: Mechanism, Magic, Nature, and Art*. Philadelphia: Univ. Pa. Press
45. LaViers A, Chen Y, Belta C, Egerstedt M. 2011. Automatic sequencing of ballet poses. *IEEE Robot. Autom. Mag.* 18(3):87–95
46. LaViers A, Egerstedt M. 2012. Style based robotic motion. In *2012 American Control Conference*, pp. 4327–32. Piscataway, NJ: IEEE
47. LaViers A, Teague L, Egerstedt M. 2014. Style-based robotic motion in contemporary dance performance. In *Controls and Art: Inquiries at the Intersection of the Subjective and the Objective*, ed. A LaViers, M Egerstedt, pp. 205–29. Cham, Switz.: Springer
48. LaViers A, Egerstedt M. 2014. Style-based abstractions for human motion classification. In *2014 ACM/IEEE International Conference on Cyber-Physical Systems*, pp. 84–91. Piscataway, NJ: IEEE

49. Sullivan A, Bers MU. 2018. Dancing robots: integrating art, music, and robotics in Singapore's early childhood centers. *Int. J. Technol. Des. Educ.* 28:325–46
50. Chen TL, Bhattacharjee T, Beer JM, Ting LH, Hackney ME, et al. 2017. Older adults' acceptance of a robot for partner dance-based exercise. *PLOS ONE* 12(10):e0182736
51. Kaushik R, Mishra AK, LaViers A. 2020. Feasible stylized motion: robotic manipulator imitation of a human demonstration with collision avoidance and style parameters in increasingly cluttered environments. In *Proceedings of the 7th International Conference on Movement and Computing*, art. 40. New York: ACM
52. **Bacula A, Mercer J, Berger J, Adams J, Knight H. 2023. Integrating robot manufacturer perspectives into legible factory robot light communications. *ACM Trans. Hum.-Robot Interact.* 12(1):13**

52. Shows how choreobotics has the potential to transform the factory floor.

53. Sher AJ, Huzaifa U, Li J, Jain V, Zurawski A, LaViers A. 2019. An embodied, platform-invariant architecture for connecting high-level spatial commands to platform articulation. *Robot. Auton. Syst.* 119:263–77
54. Michalowski MP, Sabanovic S, Kozima H. 2007. A dancing robot for rhythmic social interaction. In *Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction*, pp. 89–96. New York: ACM
55. Jochum EA, Murphey T. 2014. Programming play: puppets, robots, and engineering. In *The Routledge Companion to Puppetry and Material Performance*, ed. DN Posner, C Orenstein, J Bell, pp. 308–21. London: Routledge
56. Ladenheim K, McNish R, Rizvi W, LaViers A. 2020. Live dance performance investigating the feminine cyborg metaphor with a motion-activated wearable robot. In *2020 15th ACM/IEEE International Conference on Human-Robot Interaction*, pp. 243–51. Piscataway, NJ: IEEE
57. Sagasti F. 2019. Information technology and the arts: the evolution of computer choreography during the last half century. *Dance Chron.* 42(1):1–52
58. Cordeiro A. 1977. The programming choreographer. *Comput. Graph. Art Mag.* 2(1):27–31
59. Schiphorst T. 1993. *A case study of Merce Cunningham's use of the LifeForms computer choreographic system in the making of* Trackers. MA Thesis, Simon Fraser Univ., Burnaby, Can.
60. Bradley E, Stuart J. 1998. Using chaos to generate choreographic variations. In *Proceedings of the 4th Experimental Chaos Conference*, ed. WL Ditto, LM Pecora, S Vohra, ML Spano, pp. 451–56. Singapore: World Sci.
61. Kourlas G. 2015. In "ROBOT," Blanca Li uses machines to celebrate the body. *New York Times*, June 8. **https://www.nytimes.com/2015/06/09/arts/dance/in-robot-blanca-li-uses-machines-to-celebrate-the-body.html**
62. Toenjes J, Beck K, Reimer MA, Mott E. 2016. Dancing with mobile devices: the LAIT application system in performance and educational settings. *J. Dance Educ.* 16(3):81–89
63. Demers LP. 2019. *Up-close experiences with robots*. Paper presented at the International Symposium on Computational Media Art, Hong Kong, Jan. 4–7
64. Lansky CP. 2020. How quantum physicist ballerina Merritt Moore learned to dance with a robot (plus, her newest film). *Dance Magazine*, Nov. 17. **https://www.dancemagazine.com/how-quantum-physicist-ballerina-merritt-moore-learned-to-dance-with-a-robot-plus-her-newest-film**
65. Lin Y. 2020. Choreographing digital performance in twenty-first century Taiwan. In *Corporeal Politics: Dancing East Asia*, ed. K Mazur, E Wilcox, pp. 301–16. Ann Arbor: Univ. Mich. Press
66. Mullis E. 2023. How to dance, robot? *AI Soc.* **https://doi.org/10.1007/s00146-023-01819-6**
67. Kourlas G. 2011. Dance review: alone with Schubert and 2 flying M.I.T. robots. *New York Times*, July 20. **https://archive.nytimes.com/query.nytimes.com/gst/fullpage-9C02EEDD123CF933A15754C0A9679D8B63.html**
68. Dayal G. 2012. For extreme artist Stelarc, body mods hint at humans' possible future. *Gizmodo*, May 21. **https://gizmodo.com/for-extreme-artist-stelarc-body-mods-hint-at-humans-p-5912041**
69. Jochum E, Derks J. 2019. Tonight we improvise! Real-time tracking for human-robot improvisational dance. In *Proceedings of the 6th International Conference on Movement and Computing*, art. 7. New York: ACM

70. Thörn O, Knudsen P, Saffiotti A. 2020. Human-robot artistic co-creation: a study in improvised robot dance. In *2020 29th IEEE International Conference on Robot and Human Interactive Communication*, pp. 845–50. Piscataway, NJ: IEEE
71. Troughton IA, Baraka K, Hindriks K, Bleeker M. 2022. Robotic improvisers: rule-based improvisation and emergent behaviour in HRI. In *2022 17th ACM/IEEE International Conference on Human-Robot Interaction*, pp. 561–69. Piscataway, NJ: IEEE
72. Trajkova M, Long D, Deshpande M, Knowlton A, Magerko B. 2024. Exploring collaborative movement improvisation towards the design of LuminAI—a co-creative AI dance partner. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, art. 890. New York: ACM
73. Cuan C, Pakrasi I, LaViers A. 2018. Time to compile: an interactive art installation. In *Proceedings of the Sixteenth Biennial Symposium on Arts and Technology*, pp. 19–24. New London: Ammerman Cent. Arts Technol., Conn. Coll.
74. Cuan C, Pakrasi I, LaViers A. 2018. Time to compile. In *Proceedings of the 5th International Conference on Movement and Computing*, art. 53. New York: ACM
75. Ladenheim K, LaViers A. 2020. Babyface. In *Proceedings of the 7th International Conference on Movement and Computing*, art. 34. New York: ACM
76. Pakrasi I, Chakraborty N, LaViers A. 2018. A design methodology for abstracting character archetypes onto robotic systems. In *Proceedings of the 5th International Conference on Movement and Computing*, art. 24. New York: ACM
77. Pakrasi I, Chakraborty N, Cuan C, Berl E, Rizvi W, LaViers A. 2018. Dancing droids: an expressive layer for mobile robots developed within choreographic practice. In *Social Robotics: 10th International Conference, ICSR 2018*, ed. S Ge, J-J Cabibihan, MA Salichs, E Broadbent, H He, et al., pp. 410–20. Cham, Switz.: Springer
78. Cuan C, Pakrasi I, Berl E, LaViers A. 2018. Curtain and time to compile: a demonstration of an experimental testbed for human-robot interaction. In *2018 27th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 255–61. Piscataway, NJ: IEEE
79. Cuan C, Berl E, LaViers A. 2019. Measuring human perceptions of expressivity in natural and artificial systems through the live performance piece time to compile. *Paladyn J. Behav. Robot.* 10(1):364–79
80. Cuan C, Pakrasi I, LaViers A. 2018. Perception of control in artificial and human systems: a study of embodied performance interactions. In *Social Robotics: 10th International Conference, ICSR 2018*, ed. S Ge, J-J Cabibihan, MA Salichs, E Broadbent, H He, et al., pp. 503–12. Cham, Switz.: Springer
81. Cuan C, Berl E, LaViers A. 2019. Time to compile: a performance installation as human-robot interaction study examining self-evaluation and perceived control. *Paladyn J. Behav. Robot.* 10(1):267–85
82. Ladenheim K, LaViers A. 2021. Babyface: performance and installation art exploring the feminine ideal in gendered machines. *Front. Robot. AI* 8:576664
83. LaViers A. 2022. First encounters with robots through embodied observation, imagined narrative and choreography. In *Materializing Digital Futures: Touch, Movement, Sound and Vision*, ed. T Cinque, JB Vincent, pp. 169–86. New York: Bloomsbury
84. Jochum E, Demers LP, Vorn B, Vlachos E, McIlvenny P, Raudaskoski P. 2018. Becoming cyborg: interdisciplinary approaches for exoskeleton research. In *Politics of the Machines—Art and After*. London: Br. Comput. Soc. **https://doi.org/10.14236/ewic/EVAC18.40**
85. LaViers A, Cuan C, Maguire C, Bradley K, Brooks Mata K, et al. 2018. Choreographic and somatic approaches for the development of expressive robotic systems. *Arts* 7(2):11
86. Bench H, Elswit K. 2022. "So. . .will you be looking at dance?" Data-led dance history and the edges of movement computing. In *Proceedings of the 8th International Conference on Movement and Computing*, art. 10. New York: ACM
87. **Baker B, Liu T, Matelsky J, Parodi F, Mensh B, et al. 2024. Computational kinematics of dance: distinguishing hip hop genres. *Front. Robot. AI* 11:1295308**
88. King K. 2020. The robot in aisle five isn't stalking you. No, really. *Wall Street Journal*, Feb. 21. **https://www.wsj.com/articles/the-robot-in-aisle-five-isnt-stalking-you-no-really-11582302075**
89. Westervelt ER, Grizzle JW, Chevallereau C, Choi JH, Morris B. 2007. *Feedback Control of Dynamic Bipedal Robot Locomotion*. Boca Raton, FL: CRC

87. An example of how quantitative, curiosity-driven investigation of dance will help develop the foundational underpinnings of choreobotics.

90. Mombaur K, Truong A, Laumond JP. 2010. From human to humanoid locomotion—an inverse optimal control approach. *Auton. Robots* 28:369–83
91. Flash T, Hogan N. 1985. The coordination of arm movements: an experimentally confirmed mathematical model. *J. Neurosci.* 5(7):1688–703
92. Kingston P, Egerstedt M. 2011. Time and output warping of control systems: comparing and imitating motions. *Automatica* 47(8):1580–88
93. LaViers A. 2019. Make robot motions natural. *Nature* 565(7740):422–24
94. Koditschek DE. 2021. What is robotics? Why do we need it and how can we get it? *Annu. Rev. Control Robot. Auton. Syst.* 4:1–33
95. Brockett R. 1990. Formal languages for motion description and map making. *Robotics* 41:181–91
96. Ames AD, Coogan S, Egerstedt M, Notomista G, Sreenath K, Tabuada P. 2019. Control barrier functions: theory and applications. In *2019 18th European Control Conference*, pp. 3420–31. Piscataway, NJ: IEEE
97. Belta C, Sadraddini S. 2019. Formal methods for control synthesis: an optimization perspective. *Annu. Rev. Control Robot. Auton. Syst.* 2:115–40
98. Lignos C, Raman V, Finucane C, Marcus M, Kress-Gazit H. 2015. Provably correct reactive control from natural language. *Auton. Robots* 38:89–105
99. Cathcart C, Santos M, Park S, Leonard NE. 2023. Proactive opinion-driven robot navigation around human movers. In *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4052–58. Piscataway, NJ: IEEE
100. Belta C, Bicchi A, Egerstedt M, Frazzoli E, Klavins E, Pappas GJ. 2007. Symbolic planning and control of robot motion. *IEEE Robot. Autom. Mag.* 14(1):61–70
101. Saunders R, Gemeinboeck P. 2018. Performative body mapping for designing expressive robots. In *Proceedings of the 9th International Conference on Computational Creativity*, ed. F Pachet, A Jordanous, C León, pp. 280–87. Coimbra, Port.: Assoc. Comput. Creat.
102. Gemeinboeck P. 2021. The aesthetics of encounter: a relational-performative design approach to human-robot interaction. *Front. Robot. AI* 7:577900
103. St-Onge D, Côté-Allard U, Glette K, Gosselin B, Beltrame G. 2019. Engaging with robotic swarms: commands from expressive motion. *ACM Trans. Hum.-Robot Interact.* 8(2):11
104. Santos M, Egerstedt M. 2021. From motions to emotions: Can the fundamental emotions be expressed in a robot swarm? *Int. J. Soc. Robot.* 13(4):751–64
105. Cuan C, Fisher E, Okamura A, Engbersen T. 2024. Music mode: transforming robot movement into music increases likability and perceived intelligence. *ACM Trans. Hum.-Robot Interact.* **https://doi.org/10.1145/3686811**
106. Cuan C, Lee TW, Francis AG Jr., Toshev A, Pirk S. 2024. *Robot navigation in dependence on gesture(s) of human(s) in environment with robot*. US Patent Appl. 18/240,124
107. Nilles AQ, Beckman M, Gladish C, LaViers A. 2018. Improv: live coding for robot motion design. In *Proceedings of the 5th International Conference on Movement and Computing*, art. 43. New York: ACM
108. Nilles AQ. 2020. *Designing boundary interactions for simple mobile robots*. PhD Thesis, Univ. Ill. Urbana-Champaign, Champaign
109. Martin P, Sicchio K, Dietzel C, Olivo A. 2022. Towards a framework for dancing beyond demonstration. In *Proceedings of the 8th International Conference on Movement and Computing*, art. 6. New York: ACM
110. Schoellig AP, Siegel H, Augugliaro F, D'Andrea R. 2014. So you think you can dance? Rhythmic flight performances with quadrocopters. In *Controls and Art: Inquiries at the Intersection of the Subjective and the Objective*, ed. A LaViers, M Egerstedt, pp. 73–105. Cham, Switz.: Springer
111. LaViers A, Bai L, Bashiri M, Heddy G, Sheng Y. 2016. Abstractions for design-by-humans of heterogeneous behaviors. *Dance Notations and Robot Motion*, ed. JP Laumond, N Abe, pp. 237–62. Cham, Switz.: Springer
112. Bushman A, Asselmeier M, Won J, LaViers A. 2020. Toward human-like teleoperated robot motion: performance and perception of a choreography-inspired method in static and dynamic tasks for rapid pose selection of articulated robots. In *2020 IEEE International Conference on Robotics and Automation*, pp. 10219–25. Piscataway, NJ: IEEE

113. Huzaifa U, Maguire C, LaViers A. 2020. Toward an expressive bipedal robot: variable gait synthesis and validation in a planar model. *Int. J. Soc. Robot.* 12(1):129–41
114. Crosbie J, Vachalathiti R, Smith R. 1997. Patterns of spinal motion during walking. *Gait Posture* 5(1):6–12
115. Huzaifa U, Bernier C, Calhoun Z, Heddy G, Kohout C, et al. 2016. Embodied movement strategies for development of a core-located actuation walker. In *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics*, pp. 176–81. Piscataway, NJ: IEEE
116. Huzaifa U, Fuller C, Schultz J, LaViers A. 2019. Toward a bipedal robot with variable gait styles: sagittal forces analysis in a planar simulation and a prototype ball-tray mechanism. In *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2266–72. Piscataway, NJ: IEEE
117. Fuller C, Huzaifa U, LaViers A, Schultz J. 2020. Core-centered actuation for biped locomotion of humanoid robots. In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3481–87. Piscataway, NJ: IEEE
118. Corness G, Carlson K. 2019. Embodied intention: robot spinal initiation to indicate directionality. In *Proceedings of the 6th International Conference on Movement and Computing*, art. 6. New York: ACM
119. Allen d'Ávila Silveira C, Kilic Afsar O, Fdili Alaoui S. 2022. Wearable choreographer: designing soft-robotics for dance practice. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference*, pp. 1581–96. New York: ACM
120. Leonard NE, Young GF, Hochgraf K, Swain DT, Trippe A, et al. 2012. In the dance studio: analysis of human flocking. In *2012 American Control Conference*, pp. 4333–38. Piscataway, NJ: IEEE
121. Leonard NE, Young GF, Hochgraf K, Swain DT, Trippe A, et al. 2014. In the dance studio: an art and engineering exploration of human flocking. In *Controls and Art: Inquiries at the Intersection of the Subjective and the Objective*, ed. A LaViers, M Egerstedt, pp. 27–49. Cham, Switz.: Springer
122. Lazier R, Trueman D. 2016. *There Might Be Others*. Brooklyn, NY: Oper. Syst.

122. A reference full of movement and musical scores that externalize a complex creative process.

123. Özcimder K, Dey B, Lazier RJ, Trueman D, Leonard NE. 2016. Investigating group behavior in dance: an evolutionary dynamics approach. In *2016 American Control Conference*, pp. 6465–70. Piscataway, NJ: IEEE
124. Özcimder K, Dey B, Franci A, Lazier R, Trueman D, Leonard NE. 2019. Social decision-making driven by artistic explore–exploit tension. *Interdiscip. Sci. Rev.* 44(1):55–81
125. LaViers A. 2009. *Learning the primary colors of dance*. Sr. Thesis, Princeton Univ., Princeton, NJ
126. Gentry SE. 2005. *Dancing cheek to cheek: haptic communication between partner dancers and swing as a finite state machine*. PhD Thesis, Mass. Inst. Technol., Cambridge, MA
127. Sharma M, Hildebrandt D, Newman G, Young JE, Eskicioglu R. 2013. Communicating affect via flight path exploring use of the Laban effort system for designing affective locomotion paths. In *2013 8th ACM/IEEE International Conference on Human-Robot Interaction*, pp. 293–300. Piscataway, NJ: IEEE
128. Burton SJ, Samadani AA, Gorbet R, Kulić D. 2016. Laban Movement Analysis and affective movement generation for robots and other near-living creatures. *Dance Notations and Robot Motion*, ed. JP Laumond, N Abe, pp. 25–48. Cham, Switz.: Springer
129. Chi D, Costa M, Zhao L, Badler N. 2000. The EMOTE model for effort and shape. In *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques*, pp. 173–82. New York: ACM
130. Williams G, Bregler C, Hackney P, Rosenthal S, McDowall I, Smolskiy K. 2008. *Body signature recognition*. Tech. Rep. NYU-TR-2008-915, New York Univ., New York
131. Fdili Alaoui S, Françoise J, Schiphorst T, Studd K, Bevilacqua F. 2017. Seeing, sensing and recognizing Laban movement qualities. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 4009–20. New York: ACM
132. Knight H, Simmons R. 2014. Expressive motion with X, Y and theta: Laban effort features for mobile robots. In *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*, pp. 267–73. Piscataway, NJ: IEEE
133. Knight H, Simmons R. 2015. Layering Laban effort features on robot task motions. In *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction Extended Abstracts*, pp. 135–36. New York: ACM
134. Knight H, Simmons R. 2016. Laban head-motions convey robot state: a call for robot body language. In *2016 IEEE International Conference on Robotics and Automation*, pp. 2881–88. Piscataway, NJ: IEEE

134. An influential paper that exemplifies a popular approach to designing and validating expressive robotic systems.

135. Cui H, Maguire C, LaViers A. 2019. Laban-inspired task-constrained variable motion generation on expressive aerial robots. *Robotics* 8(2):24
136. Nahrstedt K, Bajcsy R, Wymore L, Sheppard RM, Mezur K. 2008. Computational model of human creativity in dance choreography. In *AAAI Spring Symposium: Creative Intelligent Systems*, pp. 53–60. Palo Alto, CA: AAAI Press
137. Kumar M, Long D, Magerko B. 2020. Creativity metrics for a lead-and-follow dynamic in an improvisational dance agent. In *Proceedings of the 11th International Conference on Computational Creativity*, ed. FA Cardoso, P Machado, T Veal, JM Cunha, pp. 276–83. Coimbra, Port.: Assoc. Comput. Creat.
138. Kim HJ, Neff M, Lee SH. 2022. The perceptual consistency and association of the LMA effort elements. *ACM Trans. Appl. Percept.* 19(1):1
139. Ajili I, Mallem M, Didier JY. 2019. Human motions and emotions recognition inspired by LMA qualities. *Vis. Comput.* 35(10):1411–26
140. Badler NI, Phillips CB, Webber BL. 1993. *Simulating Humans: Computer Graphics Animation and Control*. Oxford, UK: Oxford Univ. Press
141. Salaris P, Abe N, Laumond JP. 2017. Robot choreography: the use of the kinetography Laban system to notate robot action and motion. *IEEE Robot. Autom. Mag.* 24(3):30–40
142. Abe N, Laumond JP, Salaris P, Levillain F. 2017. On the use of dance notation systems to generate movements in humanoid robots: the utility of Laban notation in robotics. *Soc. Sci. Inform.* 56(2):328–44
143. Lourens T, Van Berkel R, Barakova E. 2010. Communicating emotions and mental states to robots in a real time parallel framework using Laban movement analysis. *Robot. Auton. Syst.* 58(12):1256–65
144. Masuda M, Kato S, Itoh H. 2010. A Laban-based approach to emotional motion rendering for human-robot interaction. In *Entertainment Computing—ICEC 2010*, ed. HS Yang, R Malaka, J Hoshino, JH Han, pp. 372–80. Berlin: Springer
145. Bacula A, LaViers A. 2018. Character design and validation on aerial robotic platforms using Laban Movement Analysis. In *Social Robotics: 10th International Conference, ICSR 2018*, ed. S Ge, J-J Cabibihan, MA Salichs, E Broadbent, H He, et al., pp. 202–12. Cham, Switz.: Springer
146. Heider F, Simmel M. 1944. An experimental study of apparent behavior. *Am. J. Psychol.* 57(2):243–59
147. Kingston P, von Hinezmeyer J, Egerstedt M. 2014. Metric preference learning with applications to motion imitation. In *Controls and Art: Inquiries at the Intersection of the Subjective and the Objective*, ed. A LaViers, M Egerstedt, pp. 1–26. Cham, Switz.: Springer
148. Kaushik R, Vidrin I, LaViers A. 2018. Quantifying coordination in human dyads via a measure of verticality. In *Proceedings of the 5th International Conference on Movement and Computing*, art. 19. New York: ACM
149. Kaushik R, LaViers A. 2019. Imitation of human motion by low degree-of-freedom simulated robots and human preference for mappings driven by spinal, arm, and leg activity. *Int. J. Soc. Robot.* 11(5):765–82
150. Kaushik R, LaViers A. 2019. Using verticality to classify motion: analysis of two Indian classical dance styles. In *Annual Convention of the Society for the Study of Artificial Intelligence and the Simulation of Behaviour (AISB 2019)*, pp. 91–92. Red Hook, NY: Curran
151. Darling K, Nandy P, Breazeal C. 2015. Empathic concern and the effect of stories in human-robot interaction. In *2015 24th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 770–75. Piscataway, NJ: IEEE
152. Bartneck C. 2023. Godspeed Questionnaire Series: translations and usage. In *International Handbook of Behavioral Health Assessment*, ed. CU Krägeloh, M Alyami, ON Medvedev. Cham, Switz.: Springer. **https://doi.org/10.1007/978-3-030-89738-3_24-1**
153. Mori M, MacDorman KF, Kageki N. 2012. The uncanny valley. *IEEE Robot. Autom. Mag.* 19(2):98–100
154. Kulić D, Venture G, Yamane K, Demircan E, Mizuuchi I, Mombaur K. 2016. Anthropomorphic movement analysis and synthesis: a survey of methods and applications. *IEEE Trans. Robot.* 32(4):776–95
155. Gielniak MJ, Liu CK, Thomaz AL. 2011. Task-aware variations in robot motion. In *2011 IEEE International Conference on Robotics and Automation*, pp. 3921–27. Piscataway, NJ: IEEE
156. Gielniak MJ, Thomaz AL. 2011. Spatiotemporal correspondence as a metric for human-like robot motion. In *Proceedings of the 6th International Conference on Human-Robot Interaction*, pp. 77–84. New York: ACM

157. An important investigation on the open question of how to experimentally validate so-called human-like motion.

168. Presents a new paradigm for dance artists working in choreobotics.

175. Demonstrates the crucial role of context in human perception of motion (and the illusiveness of "happy" movement).

157. Gielniak MJ, Liu CK, Thomaz AL. 2013. Generating human-like motion for robots. *Int. J. Robot. Res.* 32(11):1275–301

158. Dragan AD, Lee KC, Srinivasa SS. 2013. Legibility and predictability of robot motion. In *2013 8th ACM/IEEE International Conference on Human-Robot Interaction*, pp. 301–8. Piscataway, NJ: IEEE

159. Venture G, Kulić D. 2019. Robot expressive motions: a survey of generation and evaluation methods. *ACM Trans. Hum.-Robot Interact.* 8(4):20

160. Zhou A, Dragan AD. 2018. Cost functions for robot motion style. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3632–39. Piscataway, NJ: IEEE

161. Knight H. 2011. Eight lessons learned about non-verbal interactions through robot theater. In *Social Robotics: Third International Conference, ICSR 2011*, ed. B Mutlu, C Barneck, J Ham, V Evers, T Handa, pp. 42–51. Berlin: Springer

162. Knight H, Veloso M, Simmons R. 2015. Taking candy from a robot: speed features and candy accessibility predict human response. In *2015 24th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 355–62. Piscataway, NJ: IEEE

163. Fallatah A, Chun B, Balali S, Knight H. 2020. "Would you please buy me a coffee?" How microcultures impact people's helpful actions toward robots. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*, pp. 939–50. New York: ACM

164. Berger J, Bacula A, Knight H. 2021. Exploring communicatory gestures for simple multi-robot systems. In *Social Robotics: 13th International Conference, ICSR 2021*, ed. H Li, SS Ge, Y Wu, A Wykowska, H He, et al., pp. 819–23. Cham, Switz.: Springer

165. Sanchez L, Crocker D, Oo TM, Knight H. 2024. Robotic gestures, human moods: investigating affective responses in public interaction. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*, pp. 935–39. New York: ACM

166. Bacula A, Knight H. 2024. Dancing with robots at a science museum: Coherent motions got more people to dance, incoherent sends weaker signal. In *Proceedings of the 2024 International Symposium on Technological Advances in Human-Robot Interaction*, pp. 83–91. New York: ACM

167. Fallatah A, Urann J, Knight H. 2019. The robot show must go on: effective responses to robot failures. In *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 325–32. Piscataway, NJ: IEEE

168. Cuan C. 2021. OUTPUT: choreographed and reconfigured human and industrial robot bodies across artistic modalities. *Front. Robot. AI* 7:576790

169. Bacula A, LaViers A. 2021. Character synthesis of ballet archetypes on robots using Laban Movement Analysis: comparison between a humanoid and an aerial robot platform with lay and expert observation. *Int. J. Soc. Robot.* 13(5):1047–62

170. Chen TL, Bhattacharjee T, McKay JL, Borinski JE, Hackney ME, et al. 2015. Evaluation by expert dancers of a robot that performs partnered stepping via haptic interaction. *PLOS ONE* 10(5):e0125179

171. Wu M, Hackney ME, Ting LH. 2024. Low-force human–human hand interactions induce gait changes through sensorimotor engagement instead of direct mechanical effects. *Sci. Rep.* 14(1):3614

172. Hackney ME, Earhart GM. 2009. Effects of dance on movement control in Parkinson's disease: a comparison of Argentine tango and American ballroom. *J. Rehabil. Med.* 41(6):475–81

173. Jochum E, Herath D. 2016. Robot choreography: performance paradigms for experimental HRI setups. In *What Social Robots Can and Should Do*, ed. J Seibt, M Nøorskov, SS Andersen, pp. 86–88. Amsterdam: IOS

174. Troughton IA. 2022. Affective movement in robotic art: alternatives to the "interiority paradigm" in social robotics. *Body Space Technol.* 21(1). **https://doi.org/10.16995/bst.7963**

175. Heimerdinger M, LaViers A. 2019. Modeling the interactions of context and style on affect in motion perception: stylized gaits across multiple environmental contexts. *Int. J. Soc. Robot.* 11:495–513

176. Rizvi W, Pakrasi I, LaViers A. 2019. Influence of variable environments and character-specific design on perception of virtual robots with affective labels. In *Social Robotics: 11th International Conference, ICSR 2019*, ed. MA Salichs, SS Ge, EI Barakova, J-J Cabibihan, AR Wagner, et al., pp. 256–66. Cham, Switz.: Springer

177. Berl E, Pakrasi I, LaViers A. 2019. Creating context through performance: perception of the "dancing droid" robotic platform in variable valence interactions in distinct office environments. In *Social Robotics: 11th International Conference, ICSR 2019*, ed. MA Salichs, SS Ge, EI Barakova, J-J Cabibihan, AR Wagner, et al., pp. 288–98. Cham, Switz.: Springer
178. Lambert J, Huzaifa U, Rizvi W, LaViers A. 2019. A comparison of descriptive and emotive labels to explain human perception of gait styles on a compass walker in variable contexts. In *2019 28th IEEE International Conference on Robot and Human Interactive Communication*. Piscataway, NJ: IEEE. **https://doi.org/10.1109/RO-MAN46459.2019.8956361**
179. Durupinar F, Wang K, Nenkova A, Badler N. 2016. An environment for transforming game character animations based on nationality and profession personality stereotypes. In *Proceedings of the Twelfth AAAI Conference on Artificial Intelligence and Interactive Digital Entertainment*, pp. 155–61. Palo Alto, CA: AAAI Press
180. Afolabi O, Driggs-Campbell K, Dong R, Kochenderfer MJ, Sastry SS. 2018. People as sensors: imputing maps from human actions. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2342–48. Piscataway, NJ: IEEE
181. Wang J, Zhang L, Huang Y, Zhao J. 2020. Safety of autonomous vehicles. *J. Adv. Transp.* 2020:8867757
182. LaViers A. 2024. What does it mean? On platform-invariant "body-language" dictionaries. In *Cultural Technologies: Robots and Artificial Intelligence in the Performing Arts*. London: Routledge. In press
183. Aronoff M, Rees-Miller J. 2020. *The Handbook of Linguistics*. Hoboken, NJ: Wiley & Sons
184. Jumper J, Evans R, Pritzel A, Green T, Figurnov M, et al. 2021. Highly accurate protein structure prediction with alphafold. *Nature* 596(7873):583–89
185. Goldberg K, Faridani S, Alterovitz R. 2014. Two large open-access datasets for Fitts' law of human motion and a succinct derivation of the square-root variant. *IEEE Trans. Hum.-Mach. Syst.* 45(1):62–73
186. MacKenzie IS. 2018. Fitts' law. In *The Wiley Handbook of Human Computer Interaction*, ed. KL Norman, J Kirakowski, pp. 347–70. Hoboken, NJ: Wiley & Sons
187. LaViers A. 2019. Counts of mechanical, external configurations compared to computational, internal configurations in natural and artificial systems. *PLOS ONE* 14(5):e0215671
188. Ofli F, Chaudhry R, Kurillo G, Vidal R, Bajcsy R. 2014. Sequence of the most informative joints (SMIJ): a new representation for human skeletal action recognition. *J. Vis. Commun. Image Represent.* 25(1):24–38
189. Baraka K, Veloso MM. 2018. Mobile service robot state revealing through expressive lights: formalism, design, and evaluation. *Int. J. Soc. Robot.* 10:65–92
190. Kozima H, Michalowski MP, Nakagawa C. 2009. Keepon: a playful robot for research, therapy, and entertainment. *Int. J. Soc. Robot.* 1:3–18
191. Michalowski MP, Simmons R, Kozima H. 2009. Rhythmic attention in child-robot dance play. In *RO-MAN 2009: The 18th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 816–21. Piscataway, NJ: IEEE
192. Boker SM, Rotondo JL. 2002. Symmetry building and symmetry breaking in synchronized movement. In *Mirror Neurons and the Evolution of Brain and Language*, ed. MI Stamenov, V Gallese, pp. 163–71. Amsterdam: John Benjamins
193. Ashenfelter KT, Boker SM, Waddell JR, Vitanov N. 2009. Spatiotemporal symmetry and multifractal structure of head movements during dyadic conversation. *J. Exp. Psychol. Hum. Percept. Perform.* 35(4):1072–91
194. Khansari-Zadeh SM, Billard A. 2014. Learning control Lyapunov function to ensure stability of dynamical system-based robot reaching motions. *Robot. Auton. Syst.* 62(6):752–65
195. Simmons R, Knight H. 2017. Keep on dancing: effects of expressive motion mimicry. In *2017 26th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 720–27. Piscataway, NJ: IEEE
196. **Costa AC, Ahamed T, Jordan D, Stephens GJ. 2024. A Markovian dynamics for *Caenorhabditis elegans* behavior across scales. *PNAS* 121(32):e2318805121**
197. Bregler C, Malik J. 1998. Tracking people with twists and exponential maps. In *Proceedings of the 1998 IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pp. 8–15. Piscataway, NJ: IEEE
198. Del Vecchio D, Murray RM, Perona P. 2003. Decomposition of human motion into dynamics-based primitives with application to drawing tasks. *Automatica* 39(12):2085–98

196. Provides the most complete model of animal motion to date, which relies on rich (100 degrees of freedom) posture representation.

199. Joo H, Liu H, Tan L, Gui L, Nabbe B, et al. 2015. Panoptic studio: a massively multiview system for social motion capture. In *2015 IEEE International Conference on Computer Vision*, pp. 3334–42. Piscataway, NJ: IEEE
200. Fanti C. 2008. *Towards automatic discovery of human movemes*. PhD Thesis, Calif. Inst. Technol., Pasadena
201. Kovar L, Gleicher M, Pighin F. 2023. Motion graphs. In *Seminal Graphics Papers: Pushing the Boundaries*, Vol. 2, pp. 723–32. New York: ACM
202. Brand M, Hertzmann A. 2000. Style machines. In *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques*, pp. 183–92. New York: ACM
203. Ronchi MR, Kim JS, Yue Y. 2016. A rotation invariant latent factor model for moveme discovery from static poses. In *2016 IEEE 16th International Conference on Data Mining*, pp. 1179–84. Piscataway, NJ: IEEE
204. Flad M, Trautmann C, Diehm G, Hohmann S. 2013. Experimental validation of a driver steering model based on switching of driver specific primitives. In *2013 IEEE International Conference on Systems, Man, and Cybernetics*, pp. 214–20. Piscataway, NJ: IEEE
205. Topping TT. 2023. *Compositional methods for agile quadrupedal behaviors*. PhD Thesis, Univ. Pa., Philadelphia
206. Branicky MS. 1995. *Studies in hybrid systems: modeling, analysis, and control*. PhD Thesis, Mass. Inst. Technol., Cambridge, MA
207. Int. Phon. Assoc. 1999. *Handbook of the International Phonetic Association: A Guide to the Use of the International Phonetic Alphabet*. Cambridge, UK: Cambridge Univ. Press
208. Cutkosky MR, Howe RD. 1990. Human grasp choice and robotic grasp analysis. In *Dextrous Robot Hands*, ed. ST Venkataraman, T Iberall, pp. 5–31. New York: Springer
209. McNeill D. 1992. *Hand and Mind: What Gestures Reveal About Thought*. Chicago: Univ. Chicago Press
210. Liu J, Feng F, Nakamura YC, Pollard NS. 2014. A taxonomy of everyday grasps in action. In *2014 IEEE-RAS International Conference on Humanoid Robots*, pp. 573–80. Piscataway, NJ: IEEE
211. Milzoff R. 2020. Inside "Single Ladies" choreographer Jaquel Knight's quest to copyright his dances. *Billboard Magazine*, Nov. 5. **https://www.billboard.com/music/music-news/jaquel-knight-beyonce-megan-thee-stallion-billboard-cover-story-interview-2020-9477613**
212. Matson J. 2014. Fact or fiction? Lead can be turned into gold. *Scientific American*, Jan. 31. **https://www.scientificamerican.com/article/fact-or-fiction-lead-can-be-turned-into-gold**