The Implications of Technology-Augmented Handbalancing in Training and Performance

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Abstract

This thesis examines the circus discipline of handbalancing (also known as handstanding or inversions) and explores the addition of interactive technology with the goal of enhancing pedagogy, performance, and the relationship between. Circus arts have technical and interaction needs that are similar to other performance domains and would similarly benefit from the application of human-computer interaction (HCI) and engineering techniques. The validity and richness of incorporating digital technologies into a once-analog domain has been amply demonstrated in fields such as music, dance, and theatre. However, the especially strong relationship between pedagogy and performance makes circus arts unique. When training a skill for a circus discipline, the ultimate goal is performance in an artistic setting, which may not be the case for related movement domains such as yoga or gymnastics. While performance is also the goal for disciplines such as theatre and dance, circus arts remain distinct considering the bulk of training takes place in a gymnasium-like setting in order to master the impressive skills later displayed on stage.

Traditional handbalancing training involves either active participation from a spotter to help correct form, or amateur self-recording and analysis of video playback. While valuable, these tools lack objective data. This thesis introduces Haptics-Assisted iNversions Device (HAND), a measurement and feedback tool to help handbalancers self-correct in real-time. HAND leverages technology that can capture and analyze weight distribution differences between hands within fractions of a second to provide real-time haptic feedback. Key elements of the design include wireless hardware, discreet feedback, and the potential for handbalancers to not have to rely on spotters while training. The initial implementation makes use of an algorithm that finds an approximate center of pressure of the hands, calculates an appropriate correction vector, and triggers a corresponding vibration through an eccentric rotating mass (ERM) on the back of the handbalancer's hands, to indicate a posture correction. A preliminary study examining the viability of the device is described, and results indicate that professional circus artists confirm the validity of HAND's corrections, see potential in future development of the device, and would like to try it again in the future.

Next, this thesis introduces commensalisTECH symBIOsis (HAND⋆*CS*), a performance framework for HAND, which allows the artist to intentionally shift their weight to trigger musical events in real-time while displaying a simple interpretation of muscle activation data on cus-

tom surface electromyography (sEMG)-embedded sleeves. Using the same data processing as HAND, HAND⋆*CS* uses a performer's pressure distribution as input for an interactive musical interface. Key elements of the interface allow generation and manipulation of sonic materials, giving the performer more agency and dynamic control of the performance space. This initial version of HAND⋆*CS* is exhibited in a demo video, and the performer indicates her enjoyment in being able to influence the performance space. HAND⋆*CS* and other technology-assisted devices may be used during performances, and could result in changes in what productions offer to viewers, such as more integrated performances, whether choreographed, improvised, or somewhere in-between. Furthermore, by using the performer's own metrics as input for reactive displays within the performance space, the audience may gain a greater appreciation beyond purely the performer's movements.

With further development, HAND and HAND⋆*CS* can be expanded to encompass a larger pedagogical and expressive range. For example, future integration of technologies such as machine learning (ML) could expand the symbiotic potential of HAND⋆*CS* with the performer, similar to Sonami and *Spring Spyre*. As it stands, the link between pedagogy and performance in circus arts is emphasized through the design of HAND and HAND⋆*CS*, and the ease of switching between the two. Furthermore, HAND and HAND⋆*CS* demonstrate the viability of integrating technology into circus beyond careful choreography or post-performance processing of recordings.

Résumé Scientifique

Cette thèse explore la discipline circassienne de l'équilibre sur les mains (aussi appelée handstand ou inversions) et examine l'intégration de technologies interactives pour enrichir la pédagogie, améliorer les performances et renforcer les liens entre les deux. Les arts du cirque ont des besoins techniques et interactifs similaires à ceux d'autres domaines du spectacle et bénéficieraient également de l'application de l'interaction homme-machine (HCI) et des techniques d'ingénierie. La validité et les avantages de l'intégration des technologies numériques dans un domaine autrefois analogique ont été amplement démontrées dans des domaines tels que la musique, la danse et le théâtre. Cependant, la relation particulièrement forte entre pédagogie et performance rend les arts du cirque uniques. Lorsqu'on développe une habileté pour une discipline du cirque, le but ultime est la performance dans un cadre artistique, ce qui peut ne pas être le cas pour des domaines du mouvement connexes comme le yoga ou la gymnastique. Bien que la performance soit également l'objectif de disciplines telles que le théâtre et la danse, les arts du cirque restent distincts puisque l'essentiel de l'apprentissage se déroule dans un environnement semblable à un gymnase afin de maîtriser les compétences impressionnantes démontrées plus tard sur scène.

L'entraînement traditionnel à l'équilibre sur mains implique soit la participation active d'un observateur pour aider à corriger la forme, soit un auto-enregistrement amateur et une analyse de la lecture vidéo. Bien que précieux, ces outils manquent de données objectives. Cette thèse présente le Haptics-Assisted iNversions Device (HAND), un outil de mesure et de feedback pour aider les équilibristes à s'auto-corriger en temps réel. HAND exploite une technologie capable de capturer et d'analyser les différences de répartition du poids entre les deux mains en quelques fractions de seconde pour fournir un retour haptique en temps réel. Les éléments clés de la conception incluent le matériel sans fil, un retour discret et la possibilité pour les équilibristes de main de ne pas avoir à compter sur des observateurs pendant leur entraînement. La mise en œuvre initiale utilise un algorithme qui trouve un centre approximatif de pression des mains, calcule un vecteur de correction approprié et déclenche une vibration correspondante à travers une masse rotative excentrique (ERM) sur le dos des mains de l'équilibreur manuel, pour indiquer une correction de la posture. Une étude préliminaire examinant la viabilité du dispositif est décrite et les résultats indiquent que les artistes de cirque professionnels confirment la validité des corrections de HAND, voient le potentiel du développement futur du

dispositif et aimeraient le réessayer à l'avenir.

Ensuite, cette thèse présente commensalisTECH symBIOsis (HAND⋆*CS*), un cadre de performance pour HAND, qui permet à l'artiste de déplacer intentionnellement son poids pour déclencher des événements musicaux en temps réel tout en affichant une interprétation simple des données d'activation musculaire sur une surface personnalisée utilisant des manchons personnalisés intégrés à l'électromyographie (sEMG). Utilisant le même traitement de données que HAND, HAND⋆*CS* utilise la distribution de pression d'un artiste comme entrée pour une interface musicale interactive. Les éléments clés de l'interface permettent la génération et la manipulation de matériaux sonores, donnant à l'interprète plus de liberté et de contrôle dynamique sur l'espace de performance. Cette version initiale de HAND⋆*CS* est exposée dans une vidéo de démonstration, et l'interprète indique son plaisir à pouvoir influencer l'espace de performance. HAND⋆*CS* et d'autres dispositifs assistés par la technologie peuvent être utilisés pendant les représentations et pourraient entraîner des changements dans ce que les productions offrent aux spectateurs, comme des performances plus intégrées, qu'elles soient chorégraphiées, improvisées ou quelque part entre les deux. De plus, en utilisant les propres mesures de l'artiste comme entrée pour les affichages réactifs dans l'espace de performance, le public peut acquérir une meilleure appréciation au-delà des seuls mouvements de l'artiste.

Avec un développement ultérieur, HAND et HAND⋆*CS* peuvent être étendus pour englober une gamme pédagogique et expressive plus large. Par exemple, l'intégration future de technologies telles que l'apprentissage automatique (ML) pourrait étendre le potentiel symbiotique de HAND⋆*CS* avec l'interprète, à l'instar de Sonami et *Spring Spyre*. Dans l'état actuel des choses, le lien entre pédagogie et performance dans les arts du cirque est souligné à travers la conception de HAND et HAND⋆*CS*, et la facilité de basculer entre les deux. De plus, HAND et HAND⋆*CS* démontrent la viabilité de l'intégration de la technologie dans le cirque au-delà d'une chorégraphie minutieuse ou du traitement post-performance des enregistrements.

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Contributions

This thesis revisits Licklider's philosophy and applies it to the performing arts, a discipline where artificially created expression does not thrive without human taste-making and curation [1]–[3]. Furthermore, this thesis contributes to the idea of using technology to augment circus arts using the example of a pedagogy-performance device for handstands. This device can be used to provide real-time posture feedback during handbalancing training. Once the handstand is mastered, the device can be use within a performance context. By inverting the original concept of correcting pressure imbalance, the user can intentionally shift weight or flex muscles to trigger sound, light, or other events or cues, for example to modulate the musical score in real time.

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Acronyms

AI artificial intelligence.

BT balance training.

CNS central nervous system.

COMS center of mass stabilization.

COPS center of pressure stabilization.

DMI digital musical instrument.

EMG electromyography.

ERM eccentric rotating mass.

HAND Haptics-Assisted iNversions Device.

HAND⋆*CS* commensalisTECH symBIOsis.

HaXD haptic experience design.

HCI human-computer interaction.

HTM high-threshold mechanoreceptor.

IMS interactive music system.

IMU inertial measurement unit.

IxD interaction design.

LRA linear resonant actuator.

LTM low-threshold mechanoreceptor.

ML machine learning.

PC Pacinian.

PIMD “profound intellectual and multiple disabilities”.

PMLD “profound and multiple learning disabilities”.

RA rapid-adapting.

RAKS Remote electroAcoustic Kinesthetic Sensing.

SA1 slow-adapting type 1.

SA2 slow-adapting type 2.

sEMG surface electromyography.

SID sonic interaction design.

VR virtual reality.

“We didn’t reinvent the circus. We repackaged it in a much more modern way.”
– Guy Laliberté

Chapter 1

Introduction: Revisiting Man-Computer Symbiosis

1.1 Philosophy and motivation

Plato once defined “man” as a “featherless biped” to which Diogenes presented him with a plucked chicken, declaring “Here is Plato’s man”... or so the story goes [4, p. 85]. Defining circus can feel just as futile, as any discipline can be circus given enough skill and spectacle. However, modern circus disciplines can classically be broken down into three general categories: aerial apparatuses, ground apparatuses, and object manipulation. Artists typically either grow up within the circus community, or transition to circus from related disciplines such as dance or gymnastics.

While the barrier of entry to circus is low, the skill ceiling continues to rise. Even the most “basic” of skills expected of a professional circus performer — three-object juggling, handsprings, walkovers, splits, handstand holds — require years of hard work and dedication to master. Traditionally, these skills are taught piecemeal, using techniques borrowed from other more regulated disciplines such as gymnastics. Furthermore, most equipment is also borrowed from other specialties, including gymnastics, yoga, wrestling, rock climbing, and even construction. Circus may still have the association with transient productions performed within a temporary canopy, but the popularity of companies such as Cirque du Soleil have proven that circus, just like any other performing art, deserves to have research and innovations dedicated

specifically to it.

1.1.1 J. C. R. Licklider's man-computer symbiosis

In 1960, long before computers became integral to everyday life, Licklider proposed the concept of man-computer symbiosis [5]. In this theory, humans can benefit from the aid of technology in places where humans would otherwise have difficulties. Instead of computers taking over for humans, what if they simply filled in some gaps? Today, while technological advances have made certain tasks easier, many have also eliminated jobs once held by humans. For example, walk into any major chain store in Canada or the United States and you will see an ever-increasing number of "self-checkout" stations: machines that have taken over for human cashiers... until an unexpected item is in the bagging area (a "semi-automatic system" according to Licklider). Licklider goes a step further, claiming:

> ... it seems worthwhile to avoid argument with (other) enthusiasts for artificial intelligence by conceding dominance in the distant future of cerebration to machines alone... [5, p. 5]

However, Salter has asserted the artificiality of the "continually propagated tension between the technical and the human" [6, p. xiv]; Mirzadeh et al. argue that technology alone, specifically artificial intelligence (AI), will never usurp human cognition but can only regurgitate output based on its code [7]. In the spirit of Licklider's philosophy, technological advances have allowed the development of intercorporeal biofeedback, as discussed by Vidal [8].

1.1.2 A brief history of the North American circus

The first modern circus, defined by circus historian Huey as "a self-contained, fully choreographed live production presenting acrobatics, animal acts, spectacle productions and comic relief" [9, p. 1], was produced in England by Philip Astley in 1768, although this new category of show was not denominated a "circus" until 1782 [10]. Previously, audiences were entertained by horse riding shows, and Astley's circus did not deviate far; it simply added acrobatics and comic relief to the ring [9]. The first modern circus to hit North American soil debuted a decade later, on April 3, 1793 in Philadelphia [9]. 1825 saw the addition of the tent, which come to be known as the "big top" and would eventually become the symbol of

circus itself [9]. Top American circus moguls Barnum and Bailey combined their single-ring circuses in 1881 and completed their invention of the classic three-ring circus in 1882; they later incorporated with the Ringling Bros. to emerge as "The Greatest Show on Earth", a title their show maintains to this day [9], [11]. The mid-1970s saw the invention of the nouveau circus, a departure from the traditional three-ring circus that focused on artistic expression and strayed away from animals [9]. Cirque du Soleil emerged from this movement, returning to the heightened spectacle of the traditional North American circus through specialized stages complete with giant machinery and trapdoors [9]. As Huey puts it:

> If there is any one word that could justifiably subsume the memory of the imagined American circus experience — derived from the co-mingling of three-ringed classic circuses, one-ring community shows, theatrical productions and digital imagery in both animal-friendly and animal-less shows — that word would be HYBRID. All the old rules regarding the creation, production and exhibition of circus arts and talents have been cast aside and replaced with new formats that transgress outdated sacrosanct boundaries. And from that blending of the new and the old, the tried and untried, the popular and the passé, the traditional and nouveau, the North American circus industry has spread its influence throughout the entertainment industry to ensure that the circus will remain the unique ever-changing, never-changing entertainment choice of the masses. [9, p. 10]

Today, small contemporary circuses such as Circus Cirkör and Cirque Éloize coexist with these circus giants. Audiences can find a show to fit their desires: a spectacle-laden production filled with trick after trick designed to overwhelm and dazzle, or an artistry-focused show intended to leave the viewers deep in thought about what they just witnessed. Other performing arts and artists have also taken inspiration from the spectacle inherent to circus and have transposed it to other contexts. For example, pop star P!nk has become known for adding various aerial apparatuses to her musical performances [12]. At the same time, circus has continued to push boundaries and audience expectations with the addition of technology; Ringling Bros. and Barnum & Bailey shows have included human cannonballs, large rotating machinery, and even a robot dog named Bailey [13].

1.1.3 What about music technology?

Advances in technology have irrevocably changed the music industry. In 1895, the first patent was submitted for the Telharmonium, a monstrous 200 ton instrument following the slogan of the times — "electricity the liberator" — by using electricity to produce sound [14], [15]. While it did not last the test of time, the Telharmonium is considered the "first significant electronic musical instrument" [15] and was followed by the popularization of more recognizable instruments such as the player piano and the theremin [14].

Music technology is a flourishing field, but, as the only standard artistic technological field, it leaves much to be desired. Classic touchstones, when examined, are often revealed to be accidents, instead of intentional decisions. The invention and widespread distribution of the ten-inch, 78-rpm record, for example, is directly linked to the modern trend of the three-minute pop song [16]. Furthermore, these developments are often confined to sound. As Katz writes in his book, "Capturing Sound: How Technology has Changed Music":

> ... all phonograph effects are ultimately responses to differences between live and recorded music. Most broadly, live and recorded music differ in the ways in which they exist in space and time. When performed live, musical sound is fleeting, evanescent. Recordings, however, capture these fugitive sounds, tangibly preserving them on physical media, whether wax cylinders or plastic CDs or silicon computer chips. Once musical sound is reified — made into a thing — it becomes transportable, salable, collectable, and manipulable in ways that had never before been possible [16, p. 4].

This phenomenon has not been as cleverly transposed to other artistic fields. While video recordings of dance, theatre, and circus performances exist, they are often lacking, and can feel like an afterthought. Real time recordings of live events are often particularly problematic, as the videographer often seems to struggle between choosing a wide-angle or close-up shot; while the wide-angle can display the entire scene so as not to miss any key movements, a close-up shot can feature a facial expression or follow a trick that may otherwise be lost from far away. Moreover, it is rare to find a videographer familiar with capturing circus performances, let alone one who is already familiar with the exact show or acts, which results in awkward cuts to half-begun tricks, or limbs cropped out of the frame in favor of a performer's smile.

However, there is a small but notable number of musical performers out there who eschew recordings in favor of live performances, interactive electronic musician Laetitia Sonami among them [17]. In Sonami's own words,

> The idea of fixing sounds, and thinking of sounds repeating themselves outside of a context, is so much against what I like about sounds, that I'm having trouble thinking about recording—the idea of "objective" sounds adaptable to any situation or time [17, p. 233].

This mindset is especially interesting considering Sonami's use of technology within her work (see Section 2.4.1.2). Dobrian and Koppelman note that "computer interfaces can dissociate gesture from result to varying degrees by the way that software intermediates the relationship between gesture and resulting sound" [18, p. 278]. One would think that musicians using interactive technologies to create their works, such as Sonami, would view recordings as a natural extension to their creation, yet this is clearly not the case. Instead, Sonami has created a symbiotic relationship with her instruments, and relates to Katz's statement on the fleetingness of live musical performance. When asked if she would record for the sake of documentation, Sonami responded:

> ... if you can't come to the concert, well, you just can't hear it! For some reason, musicians got into this idea that everything you do has to be recorded. If you use a recording medium, fine. But if you're not, if you're doing performance, that is a very different situation [17, pp. 233–234].

Suffice it to say, even within the established field of music technology, there is no consensus on the benefits of various technological advancements, only that technology can provide interesting new venues for expression and experience.

As the modern circus has been established in North America for almost two and a half centuries, it would be prudent to follow music's example and add electricity into the mix beyond stage lighting and mechanical set pieces. From developing better methods for capturing and archiving performances to incorporating interactive elements within apparatuses and performance spaces in order to boost creativity and innovation within the circus world, the combination of technology and circus arts holds considerable potential.

1.2 Scope

Circus encompasses a wide range of disciplines, generally grouped into one of three categories: aerial, ground, and object manipulation. This thesis focuses on the ground discipline of inversions, more specifically handbalancing, also known as handstands, and even more specifically on traditional, two-handed, straight body handstands. To exemplify the potential of this domain, this thesis presents a context-dependent apparatus that is able to switch between pedagogical (practical) and performance (artistic) settings.

Chapter 2

Balance Training, Interactive Technologies, and Performing Arts

Because this thesis spans a multitude of domains, this chapter follows suit when presenting relevant background information and is split into two halves: Sections 2.1 and 2.2 focus on balance and methods for balance correction, while Sections 2.3 and 2.4 focus on existing interactive works meant for the stage. Section 2.5 coalesces these two parts by elucidating the close pedagogy-performance relationship within circus arts. While less technical, the first two sections cover necessary information regarding handbalancing technique and traditional balance training, before moving on to more standard engineering and HCI-related material. Existing circus resources and research can be found in Appendix C.

Section 2.1 provides a foundational overview of balance, both upright and inverted, including proper handstand technique. A more in-depth discussion of upper and lower body analogues and their connection to balance can be found in Appendix D. Subsequently, Section 2.2 presents traditional methods for balance correction, both upright and inverted, including haptic methods for upright balance training. No currently existing haptic methods for inverted balance training were found. A short primer on haptics can be found in Appendix E.

Because handbalancing and, more broadly, circus arts, are performing arts, Section 2.3 presents an overview of designing interactive devices meant for the stage. Subsequently, Section 2.4 presents a literature review of existing interactive technologies meant for the stage, including those within music tech, dance tech, and circus tech. Multimodal gloves, respon-

sive footwear, and interactive floors are given particular consideration, as the mat, gloves, and sleeves used in HAND and HAND⋆*CS* directly relate to these interactive technology subcategories. Finally, as previously mentioned, the close relationship between pedagogy and performance within circus arts is discussed in Section 2.5.

2.1 The science of balance

Balance requires body to surface contact; in the case of humans, it is usually in the form of feet to ground. Where the body touches the balancing surface, it pushes against the ground (due to the gravitational attractive force) and the ground pushes back with an equal and opposite force known as the ground reaction force (due to the electromagnetic repulsive force) [19].

It is worth noting that there are two categories of balance: static and dynamic. Static balance involves maintaining one's center of balance within a base of support with minimal movement, while dynamic balance requires one to maintain balance while either performing a task or while on an unstable surface [20]. While a classic handstand traditionally involves static balance, both classes of balance are included within the handbalancing discipline.

2.1.1 Perception of self and the environment

Proprioception is one's sensation of the body's position and its movement in space (contrasting with exteroception, which focuses on the sensation of external stimuli such as visual and audio input) [20]–[23]. It is influenced by the body's frame of reference, i.e., visual, audio, motor, and somatic inputs [23]. Postural control is the ability to maintain agency over one's position in space and is integral to balance [24]. As children, humans develop their proprioception primarily within the frame of reference of their feet on a stable surface and the ability to see everything around them; turning upside-down or closing the eyes interferes with this sense and, in turn, balance and stability [22], [25]. However, the sensorimotor system may be trained, resulting in improved proprioception within less frequently-experienced reference frames [26].

For example, Erismann and Kohler's famous "Innsbruck Goggle Experiments" concentrated on just that: altering one's frame of reference through the use of mirrored lenses that allow the wearer to see "with the back of your head" or "upside down" [27]. Their experiments displayed that the brain's plasticity and active correction allows for adaptation to a new frame

of reference after a sufficient period of adjustment [27]. As another example, Lackner and Dizio demonstrated that participants were able to adjust for their environment when asked to reach towards a target while standing on a rotating platform. When back on non-rotating ground, participants still reported feeling a force acting upon their arm, as if they still had to correct for rotation [28]. These experiments highlight the flexibility of one's awareness and relationship to space as well as the potential for technology to provide additional sensory information that can help to train or reorient a person.

2.1.2 Proper handstand technique

Learning the basics of handbalancing is a key skill in several movement-based disciplines, such as in gymnastics, martial arts, yoga, and circus arts [29]–[31]. While much of the current handstand research has been done using gymnast participants, findings may be transferable to handbalancing within other disciplines.

According to an instructional document on proper handstand technique published by Cirque du Soleil and National Circus School (*École national de cirque*), a basic handstand consists of:

> ... the weight on the palms of the hands, the fingers spread apart and bent, the index finger forward aligned with the arms, and the pelvis in a posterior tilt. The shoulders, torso and pelvis are aligned, and the head can be slightly raised. The body must be perfectly aligned, both front to back and side to side. The muscles are contracted, but breathing remains regular [32, p. 12].

See Table 2.1 for three common mistakes and their associated corrections and corrective exercises as published by Cirque du Soleil and National Circus School (*École national de cirque*). Notably, the third common mistake is instability, and its associated correction is balancing with the hands and not the lower body. While the entire body may influence balance, the onus of control should rest solely on the hands; the rest of the body should remain as straight and as tight as possible [33]. The center of balance should remain at the base of the fingers; too much weight at the tips of the fingers indicates "overbalancing" and too much weight at the heels of the hands indicates "underbalancing" [34]. With the weight centered at the base of the fingers, the handbalancer can then use the fingers for control. Hands should be rotated slightly outwards with the index fingers pointing forward so the elbows are less likely to bend [35]. See

Figure 2.1 for a visual representation of where the weight should be distributed on the hands during a handstand. Note that the ideal center of mass in a one-arm handstand differs from that of a two-arm handstand, and may change depending on different leg and non-supporting arm positions [36].

Considering that the normal range of wrist extension varies between 60 to 85 degrees of extension [37], many handbalancers prefer to balance upon handstand blocks, which allow for five more degrees of wrist extension to get to a square 90.

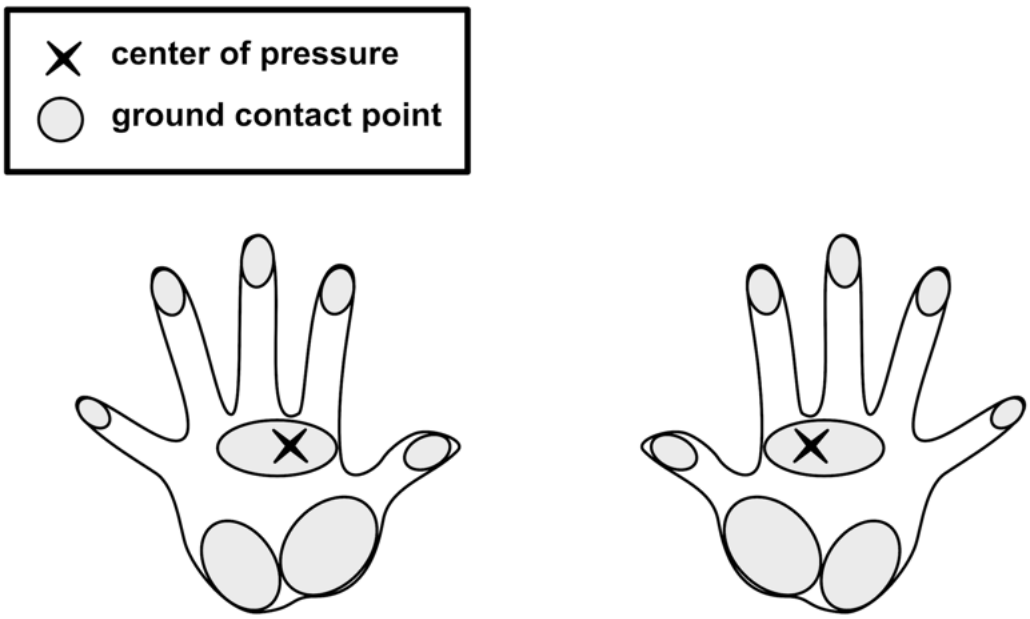

Figure 2.1: Ideal weight distribution and center of pressure on the hands during a straight body handstand. While actual contact points may vary according to personal preference, most handbalancers maintain contact to the ground with the fingertips and fleshiest parts of the palms [38]. Due to anatomy and finger positioning, the ideal center of pressure within each hand rests just below where the index and middle fingers meet [39].

Pietrobon recommends envisioning oneself as a flexible reed rather than a rigid oak [30]. At first glance, this metaphor appears to contradict the proper handstand form as stated; however, Pietrobon is viewing balance through a philosophical lens and not purely a kinesthetic one. It is still possible to use the metaphor of a supple reed while still controlling movement from the base of the structure, i.e., the hands. This metaphor becomes especially apt when comparing

balance on a tightwire to that on a slackline; one balances oneself atop a tightwire, while one balances a slackline underneath oneself, and so must allow for some flexibility in body posture. In the case of a handstand — where one's hands are affixed to the ground — one must allow the other terminus of the body to move as needed to maintain balance — or as Gatti puts it, the body becomes an inverted pendulum [33].

Table 2.1: Common handstand mistakes and their corrections. Table adapted from "Basic Techniques in Circus Arts — Handstand" [32].

Common Mistakes	Corrections and Corrective Exercises
The participant has trouble kicking up.	Wait to be in handstand before bringing the legs together. Position the shoulders over the hands while kicking up in order to subsequently unroll through the back.
The participant falls backwards.	Position the legs over the base of support and correctly align the entire body.
The participant is unstable.	Try to balance with the hands and not with the legs or hips.

2.1.3 Handbalancing, technique, health, and safety

Regular handbalancing training can have long-term beneficial health effects [40]. However, injury is a significant concern for circus artists [41]. It has been shown that asymmetry of an athlete's legs is correlated with a higher risk of injury [42] and it is easy to extrapolate that the same is most likely true for the upper body: asymmetry of a handbalancer's arms may indicate a higher risk of injury. Fortunately for handbalancers, balance training itself is helpful in injury reduction [43]. Not only is balance training a preventative measure, but it can help improve posture, bodily symmetry, and performance in athletes in general [44], [45]. More discussion on anatomy — including lower and upper body analogues and their relation to upright and inverted balance — can be found in Appendix D.

2.2 Traditional methods for correcting balance

Balance can be maintained by two distinct strategy categories: the center of pressure stabilization (COPS) strategy and the center of mass stabilization (COMS) strategy [46]. Humans standing on the ground typically employ COPS through the use of three postural control strategies depending on the magnitude of disturbance: the ankle strategy, the hip strategy, and the change-in-support strategy (stepping and grasping strategies) [19], [24]. The ankle strategy involves using the ankles and toes to maintain the center of pressure somewhere within the bounds of the feet while the center of mass remains stable and is used for small disturbances in balance. When the ankle strategy is not forceful enough, the hip strategy may be employed. The change-in-support strategy is usually reserved for large disturbances where the center of mass is shifted outside of the subject's base of support and may result in a step of the foot or a grasp of the hand. When in a handstand, the wrists and fingers replace the ankles and toes and the shoulders replace the hips, but COPS still applies. COMS becomes useful when balancing on unstable surfaces: in this strategy, the center of pressure becomes fixed and the center of mass must be adjusted to sustain balance.

2.2.1 Balance training

balance training (BT) tools focus on assessment, athletic performance, and rehabilitation of standing and walking [47]. Traditional balance training (BT) typically involves challenging the participant to correct and maintain balance when the equilibrium between the body's center of gravity and base of support is disturbed [48]. A task-oriented approach to balance rehabilitation involves having the patient intentionally perform tasks relevant to their daily life while developing strategies and techniques for maintaining balance within three postural categories: steady-state (static), reactive (dynamic), and anticipatory (also dynamic) [49]. It is worth noting that according to neurologist Janda, any new kinesthetic movement must pass through an active feedback phase where the subject fully concentrated on the movement while also receiving constant feedback [26]. In other words, any new exercise must be simplified and accompanied by continuous corrections and over time the corrections may become fewer and the exercise can become more complex as the subject gains familiarity with it.

Lately, several BT tools have been developed that incorporate haptic feedback (see Ap-

pendix E for a short primer on haptics). Lee et al. developed a balance assessment tool using virtual reality (VR) techniques paired with a "movable force platform to provide somatosensory input" [50]. Compared to established methods such as the Clinical Test of Sensory Integration and Balance (CTSIB) — which has significant faults due to outdated methods, including rudimentary visual inhibitors and subjective assessment scoring [51] — and the Sensory Organization Test (SOT) of the Smart Balance Master system — which is expensive, requires significant floor space, and is inflexible — Lee et al.'s tool is cheaper, less-space-intensive, and more immersive [50]. More recently, Anlauff et al. concluded that utilizing tactons on the bottom of the foot could be used for rehabilitation purposes [52]. Kingma et al. developed a "balance" belt with embedded vibrotactile actuators to help patients with bilateral vestibular deficits [53]. Spelmezan et al. incorporated "tactile motion instructions" when giving feedback to athletes [54]. Shumway-Cook et al. took a different approach from using vibrotactile haptics and instead used force-plate biofeedback to help patients with hemiparesis regain balance control while standing [49].

These current tools demonstrate some of the challenges of developing BT tools but also highlight the benefits and potential uses. However, these tools primarily focus on patients and test subjects in a standing or upright position. They have yet to explore other orientations of the body or different body parts that may be used for balance, such as the hands or forearms.

2.2.2 Standing and walking

When focusing on vertical standing posture, patients are often given verbal and physical cues, may use a mirror paired with a vertically-striped shirt, or use a wall for somatosensory input along the spine. To improve control over movement, a clinician may gently shift the patient's center of balance through nudges, or manually shifting the patient's leg while under different conditions and in different directions. Tools such as chairs, walls, or parallel bars may be used to assist a patient, while blinders, glasses covered in petroleum jelly, or unstable surfaces may be employed to increase the difficulty of a task [49]. Notably, the tools generally employed within traditional balance rehabilitation methods are frequently improvised from common objects and are not specially designed for balance rehabilitation tasks.

2.2.3 Handbalancing

Yeadon and Trewartha recorded a feedback time delay of 160 to 240 ms during an unperturbed classic handstand with straight body and legs together [55]. However, their participants were all "skilled male gymnasts" and so had already mastered this handstand shape. Many handbalancers will employ the use of a "spotter", an individual who carefully monitors the handbalancer and provides physical and verbal cues as needed [31]. Even light touch has been shown to improve handstand stability [56], though the locus of the touch has not been investigated. Perhaps this light touch aids in the reduction of feedback time delay, prompting the handbalancer to better recognize and correct imbalance [57].

2.3 Human-computer interaction on stage

Buxton — a pioneer of HCI — and Sniderman, stress that when designing for humans, it is vital to consider two viewpoints: that of the engineer building the device, and that of the layperson actually using it [58]. They make the case for iterative design for "real world" situations, as, "it is unlikely that the first implementation of any user interface is going to function as well as it could or should" [58]. Seminal usability researcher Nielsen also champions the iterative design cycle and stresses that each successive design should explicitly and intentionally address the problems noted when observing test users [59]. Furthermore, when HCI is combined with interaction design (IxD) through interactive technology it becomes important to design for intercorporeality, i.e., "enhancing how people teach and learn movement by designing and using biofeedback technologies," as discussed by Vidal [8].

With these considerations in mind, the idea of somaesthetics becomes relevant. Part philosophy, part interdisciplinary field, somaesthetics incorporates heightened somatosensory awareness into the design process [60]. Nowadays it is standard for even the most basic of smartwatches and fitness trackers to log statistics such as heart rate, step count, calories burned, and sleep [61]–[63]. With constant access to these measurements, it is no wonder that athletes use such devices as extensions of themselves in attempts to fully internalize workout progression [64].

2.3.1 Designing for interaction

According to Norman — an influential advocate for user-centered design — one key factor in designing for user interaction is visibility of information regarding how a system works and its status, and immediate feedback from any user interaction [65]. As he succinctly puts it, "Well-designed objects are easy to interpret and understand. They contain visible clues to their operation" [65, p. 5].

When designing for bidirectional informational flow, as shown in the local feedback loop in Figure 2.2, it is important to consider how negotiated interaction comes into play. Negotiated interaction allows the interaction designer to convey subtle changes in an interaction based on the feedback loop between participant and interactive device [66]. Sonic interaction design (SID) is a specialized subfield of interaction design (IxD) focusing on how sound can be used in interdisciplinary ways to communicate meaning, information, emotion, and other contextual information [66]. Turmo Vidal et al. introduced the concept of intercorporeal biofeedback, a technique that uses technology to augment movement learning and can be especially useful to help both the subject and instructor embody feedback [67]. Augmentations such as sensors, prostheses, and actuators can allow the human body to transcend its limitations [6].

2.3.1.1 The neglected senses: touch, smell, and taste

While most interaction modalities focus on our visual and aural senses, the field of haptics has shown the validity of using our sense of touch as well, as discussed in Section **??**. It is worth noting, however, that there is little exploration regarding our olfactory, gustatory, and even haptic senses with regards to artistic experience [68]. One major issue is the lack of sense-specific language; another is the lack of artists primarily working in these modalities [68]. Both of these concerns can be ameliorated by the formal creation of more interdisciplinary fields.

With the establishment of forums such as the Haptics Symposium in 1992 [69], the World Haptics Conference in 2005 [70], and the EuroHaptics Society in 2006 [71], the field of haptics research has significantly grown and the haptic experience design (HaXD) subfield has been established to help hapticians, participants, and potentially artists better discuss haptic experiences [72].

It has remained difficult for the haptics community to establish a standard for touch-based communication due to various factors including technological limitations, access to technology,

and lack of a singular standardized mapping between language and haptic tactons [73], [74]. However, Steinbach et al. stress that "haptic communications is not meant as a replacement of traditional audiovisual communications but rather as an additional dimension for telepresence that will allow us to advance in our quest for truly immersive communication" [75, p. 937]. With that in mind, perhaps a standardized mapping for communication disregarding context should not be the goal. Enriquez et al. demonstrated that users could remember arbitrary associations between haptic phonemes (the smallest haptic unit that can convey meaning) [76]. This finding encourages the design of interfaces that incorporate haptic communication as part of their use. An example of such an interface is discussed in Chapter 3.

2.4 Existing works within related performance disciplines

2.4.1 Music tech

When considering digital musical instruments (DMIs), it is important to note that there is a distinct separation between the input device — which is the modality through which the performer interacts with the instrument e.g., keys, strings, buttons, knobs, sliders — and the sound generator — which is what produces the actual music [77].

One major issue confronting electronic music performers is making sure the audience is aware of what the performer is actually doing on stage [78]. According to Buxton (also a noted music technologist), "A major problem of synthesizers to date, especially recently, is that they constrain the performer to expressing ideas through a limited set of gestures" [78, p. 49]. Kramer adds onto Buxton's idea, stating, "It would be very helpful if onlookers could connect our actions to the sounds produced. That is, after all, one of the elements that makes it worth their while to get out of their living rooms and into the concert space" [78, p. 49]. At the same time, because the performer's gestures are not purely aesthetic in nature and so must also provide input to the computer, there is a balance that must be struck between gestural information to the instrument and visual information to the audience. These concerns bring up the discussion surrounding the role of gesture within music, a topic that Cadoz has spent significant time defining and analyzing [79]–[81]. However, the audience may not be fully aware of which gestures are sound-producing and which are flourishes or neutral motions, such as brushing away dust. Depending on the magnitude of the gestures, it is possible the audience

may even miss some gestures altogether. For example, when discussing her interdisciplinary work *append* — a blend of music tech, contemporary circus, and improvisational performance — Rose has stated that the audience "thought choreography and sound were all fixed and missed the interaction and improvisatory [sic] elements" [82].

Since Buxton and Kramer's comments, trends in input devices for musical expression have forked into two main categories: instrument-like controllers and, for lack of a better term, "novel" controllers [83]. Instrument-like controllers, as the name suggests, attempt to emulate an existing acoustic instrument, while novel controllers may take inspiration from existing acoustic instruments, but ultimately significantly diverge in design [83]. One classic example of an instrument using a "novel" controller is Termen's theremin, an instrument that uses proximity and motion as the means of control [15]. A more recent example is Malloch's T-Stick, a family of musical instruments in the form of ABS plumbing pipe that use capacitive touch sensors, pressure sensors, an accelerometer, and a piezoelectric crystal to detect various inputs [84]. When working on whole body movement and or multi-person interactive instruments, a "novel" instrument is more appropriate as it affords a multimodal approach that can be tailored to a performer's specific needs. For example, the T-Stick's form readily lends itself to be scaled up and reinforced to become an interactive suspended pole, a dance pole attached only to the ceiling or to rigging that allows for significant movement by the apparatus while the performer is on it [85].

2.4.1.1 The T-Tree

The T-Tree is "a digital musical instrument (DMI), interactive music system (IMS), hub, and docking station that embeds several T-Sticks" [86]. The idea came about when considering the T-Stick's limitations, especially concerning the lack of visibility of system status — Don Norman's key usability heuristic, as discussed in Section 2.3.1. One of the main goals when designing the T-Tree was to increase recognizability of how to interact with the T-Stick, as well as create a plug-and-play interaction style [86]. The hope was that novice users would understand the visual tree metaphor and want to grasp the protruding sticks from the central structure, as one might do when encountering a living tree, thereby lowering the barrier of entry to a formerly unfamiliar apparatus [86]. By integrating Malloch's original T-Stick design into a structural hub, performances were able to transform from pure music to interactive

dance, thereby blurring the lines between audio and visual performance [87]. In the future, the boundaries could be pushed even further by improving the structural integrity and durability of the T-Stick to allow them to be thrown, spun, and passed, such as in a juggling performance. See Section 2.4.4 for a discussion on previous interdisciplinary juggling performance.

2.4.1.2 Multimodal gloves

One notable trend in gestural interfaces that begins to blur the line between pure musical performance and dance is the multimodal glove. One colloquially and commercially recognized example is that of Imogen Heap's MiMU gloves, which have been reported on by news organizations including the BBC, Wired, and CNN and have been used on stage by not only Heap herself, but pop star Ariana Grande [88]–[90]. Heap's "innovation and contribution to Music and Technology" have earned her an honorary Doctorate of Technology from the Berklee College of Music [91]. Composer and performer Pamela Z has also used gloves as sound modulators, such as in 2014's *BREATHING*, where she used a fingerless glove designed by Donald Swearingen to modulate her voice in real-time [92]. However, Heap and Z are far from the first music technologists to develop and perform with musical gloves.

In 1985, Waisvisz revolutionized the music tech world with The Hands [93], modestly captioned as "a set of remote MIDI-controllers" [94, p. 313]. The Hands are an example of a DMI with a novel controller: "two aluminum ergonomically shaped plates with sensors, potentiometers and switches strapped under the hands of the performer" [94, p. 313]. While The Hands captivated Waisvisz himself for 25 years, they also entranced the music tech world, including the community of The International Conference on New Interfaces for Musical Expression (NIME), which Waisvisz himself helped co-found [95].

Another pioneer to embark on a multimodal glove was Sonami, whose first iteration of the *lady's glove* was created in 1991 for the Ars Electronica Festival [96]. Originally "a pair of rubber kitchen gloves (the perfect housewife's tool) with five Hall effect transducers glued at the tip of the fingers and a magnet on the right hand", the glove has since lost one of the pair and, over 20 to 25 years, has metamorphosed and refined into a significantly more complex instrument [96], [97]. According to Sonami:

> The intention in building such a glove was to allow movement without spatial reference, and most importantly to allow for multiple, simultaneous controls. The

> sounds are now "embodied," the controls intuitive, and the performance fluid. It has become a fine instrument [96].

Beginning in 2012, Sonami began collaborating with Wekinator developer Fiebrink on *Spring Spyre*, which has now become her primary instrument [98], [99]. Where the lady's glove had developed organically, about the Spring Spyre, Sonami has said in a 2018 interview: "it's been four and a half, five years. It's only now that I realize that my imagination is starting to be shaped by the instrument" [97]. Sonami's process with the Spring Spyre was so impactful it spurred a publication on using machine learning (ML) in instrument creation [99]. When asked about the benefits of incorporating ML into instrument creation, Sonami stated that ML allows her to create mappings that afford an "exchange" between herself and the instrument: "Not just forcing my intentions onto it, but letting it inform the composition and performance... It is an open system which allows for continuous exploration in sound synthesis, expressivity and adaptability" [99, p. 239]. This collaboration expanded Fiebrink's views on ML's potential, adding: "I've learned to see ML less and less as something whose value for instrument building lies primarily in its ability to build accurate models from training examples... and more as a technique that is wonderful for supporting richer modes of interaction with computers during both performance and instrument building" [99, p. 240].

It is worth noting here that many multimodal gloves have also been created for non-artistic applications such as those created by CyberGlove Systems LLC [100] and HaptX [101]. These enhanced gloves can be used in applications ranging from gaming to rehabilitation to skill training [101], [102].

2.4.2 The broadening of technology-embedded performance art

Humans have been experimenting with technology in physical performance as far back as the turn of the 20th century, when Loïe Fuller revolutionized the dance world with new lighting techniques and her "Garment for Dancers" [103]. While Fuller and her contemporaries sought to transcend the corporeal form within performance, they did not fully explore the limits of the body as circus artists are wont to do.

In 1965, choreographer Merce Cunninhgam and composer John Cage produced *Variations V*, a collaboration that could be seen as one of the first instances of performers interacting in real-time with a sensor-embedded system [103]. Almost a decade later, Gordon Mumma

fit dancers with sensor-augmented belts that used the dancers' movements to influence his composition *Telepos I*, made for Cunningham's *TV Rerun* [103]. Marcel.lí Antúnez Roca's 1994 *Epizoo* used audience participation to control aspects of the performance and was possibly the first instance of the audience being allowed to control the artist's own body through a remote-controlled exoskeleton [103].

2.4.3 The creation of dance tech

Following Roca's *Epizoo*, the late 1990s saw the rise of a new genre of performance called "dance and technology", or "dance tech" [103]. In her 1996 work *Dance Space*, Flavia Sparacino was one of the first to incorporate computer vision as a way to create a direct relationship between a performer's movements and sound triggers within the performance space [103]. She continued her research on interactive spaces through the 1990s and 2000s [104]–[107].

Interdisciplinary artist, director and composer Klaus Obermaier has created what he calls "inter-media performances and artworks" for over thirty years [108]. In collaboration with Ars Electronica and as part of their "poetic systems story", Obermaier has produced works such as 2004's *Apparition* and 2006's *Le Sacre du Printemps* [109].

OpenEndedGroup is a collaboration between digital artists Marc Downie and Paul Kaiser, whose works "span a wide range of forms and disciplines, including dance, music, installation, film, and public art" and, most recently, 3D projection [110]. Works such as their 2005 *how long does the subject linger on the edge of the volume...* use motion capture in real-time to generate accompanying projections. For several of their works — such as the oft-reworked *Loops*, created in collaboration with Cunningham and originally commissioned in 2001 by the MIT Media Lab with another version for Ars Electronica — Downie and Kaiser employ their custom Field2 software, described, in their words, as "a live-coding environment for making digital art" [111].

Media performance group *kondition pluriel* is a collaboration between Montréal-based artists Marie-Claude Poulin and Martin Kusch [112]. Notable works include *schème* (2001), *the puppet(s)* (2005), and *[In code]* (2012).

In 2015, Hsu and Kemper published their findings on developing the Remote electroAcoustic Kinesthetic Sensing (RAKS) system, effectively combining dance tech and music tech [113]. The RAKS system was created specifically for belly dance, and uses a LilyPad Arduino [114] to

map dance moves to sonic output [113].

Artist and researcher Jessica Rajko explores the use of haptic feedback throughout her works, and states:

> Our sense of touch is what orients us to space, objects, and others. It is always actively seeking. It never stops. As such it is commonly the first sense to recede from our conscious attention. As a somatic practitioner, I recognize the value of developing a sophisticated practice of making touch conscious. This has deeply influenced my current work with haptic (touch-based) feedback [115].

Rajko exemplifies this philosophy through works such as *Vibrant Lives* and *Momento Mori*. Notably, these works eschew the traditional proscenium setting audiences are used to today in favour of placing the audience among the performers. In this way, along with using haptics to make touch conscious, Rajko fully immerses the audience within her works.

2.4.3.1 Responsive footwear

Paradiso also took an interest in dance tech in the 1990s; where Sparacino focused on software, Paradiso focused on hardware and, more specifically, responsive dance shoes [116]–[120].

Paradiso's work with responsive footwear is not alone. In 2014, designer Lesia Trubat created Electronic Traces (E-Traces): augmented ballet pointe shoes embedded with inertial measurement units (IMUs), pressure sensors, and accelerometers controlled by LilyPad Arduino wearable microcontrollers [114], [121]. E-Traces take the input from a dancer and transforms it into a graphic representation of the movements; Trubat's intention was to create a versatile tool that could be used in situations ranging "from self-learning or dance classes to the graphical representation of live performance" [121].

In a more specifically pedagogy-focused vein, Vyas focused her attention on the viability of using the feet as haptic receptors [122], [123] and created a pair of ERM-embedded sneakers with the aim of using them to guide novice dancers through beginner salsa steps [124]. Schulthess et al. created a similar device but for skiiers: an augmented ski boot that is able to monitor and give feedback to users when performing jumps [125].

Similar to footwear, some research has focused on augmented insoles, though most research appears to focus on measuring and performing gait analysis for injury prevention and rehabilitation [126]–[129].

2.4.3.2 Interactive floors

Other artists and researchers have focused on the environment instead of footwear in the form of interactive floors. As stated by Miranda and Wanderley, "Sensing surfaces are not difficult to build, but do-it-yourself devices may not always be reliable" [130]. However, even simple responsive floors such as the one built by Lima et al. can be used by dancers "control such parameters as volume, velocity, pan, program change, among others" [131, p. 1]. In 2016, Shibasaki et al. developed a tap dancing floor augmented with haptic microphones to convert the dancing on stage to haptic feedback on special chairs, floor mats, and handheld objects [132].

In a less artistic context, Visell et al. explored the use of floors as tools to "enhance or enable many computer-supported activities that involve movement on foot" through haptics [133, p. 148]. Building on that research, Law et al. presented a multimodal floor interface meant to mimic the experience of walking on natural terrain [134]. Using auditory, tactile and visual feedback, the user can experience walking on a frozen pond or through a snowy field.

2.4.4 Pioneering circus tech

In recent years, there has been a small but growing trend towards interdisciplinary circus research. As mentioned in Appendix Sections C.3 to C.6, a few institutions have begun laying the groundwork for circus tech, but there is still no recognized circus tech field or dedicated conferences. However, there have been a handful of publications that could be classified under the circus tech umbrella.

In 2001, Reynolds et al. developed a responsive environment for the acclaimed Flying Karamazov Brothers [135] using ultrasonic trackers, accelerometer-embedded gloves, and augmented juggling clubs [136].

In their paper, Reynolds et al. claim:

> The performance leaves a strong impression on the audience due to the surprising technology, a nicely integrated set, fancy costumes and, most importantly, the charisma and professionalism of the Karamazovs ... [136, p. 7]

However, the authors do not support this claim with any audience comments or surveys and even downplay the effect of the technology by emphasizing qualities of the performers them-

selves that make them captivating to watch. However, they make the compelling observation that their devised "stage instrument" requires practice to use, "much as they would practice with a traditional acoustical instrument" [136]. This observation offers significant fodder for future research within circus tech.

Around the same time, Willier and Marque developed a technique to allow jugglers gestural control over sound generation through electromyography (EMG) [137]. While their original publication did not include support for real-time sonic production through juggling, Willier and Marque were able to distinguish the significant muscles used during a classic three-ball cascade and provide a framework to convert this muscle data to music data. More recently, Leischner et al. approached the question of sonifying juggling from the opposite end and used juggling balls augmented with accelerometers, gyroscopes, and WiFi sensors to generate musical output [138].

Salter distinguishes performance from other forms of information-sharing through seven characteristics:

> (1) an interest in enaction or doing, (2) real-time, dynamic processes over static objects or representations, (3) engagement with the temporal moment of the present, (4) embodiment and materiality, (5) immanent experience, (6) the effect of both human and nonhuman presence, and (7) transmutation and reconstitution [6, p. xxiii].

By incorporating sensors into the performance space, and designing for interaction, as discussed in Section 2.3.1, the performers will be able to better embody these characteristics. Freeing the performance from strict cues allows the artist to eschew the mental overhead of focusing on strict timing and choreography and better engage with the performance as it currently is developing in the space.

According to Elblaus et al., in reference to their work on three proofs of concept for different modes of sonic interaction within circus arts, "In summary, the use of interactive sound in circus is an excellent way to add new channels of expressivity to the communication between performer and audience" [139, p. 1705].

In 2017, Rose presented the Sonic Aerialist eLecTrOacoustic system (SALTO), an interactive musical system developed for dance trapeze [140]. With SALTO, Rose embodied Elblaus

et al.'s quote, giving the dance trapeze artist control over musical expression through an armband containing eight EMG sensors, and a nine-axis IMU. By harnessing both biometric and spatial data, the composer and performer can work in harmony to "emphasize gestural movements, dynamic whole body inversions and rotations, or any combination of these types of movements" [140, p. 303]. A few years later, Rose presented *Hollow*, another interactive musical system as part of *Pressure Zones*, an "improvisational interdisciplinary performance" that "integrate the disciplines of electroacoustic composition, contemporary circus arts, and improvisation" [141], [142, p. ii]. With *Hollow*, Rose employed the use of a Microsoft Kinect RGB camera and depth sensor to capture movement data. By eschewing a wearable device, Rose was able to expand the range of input to include three apparatuses: a cloud swing, a wooden box, and the ground [142].

Circus tech need not be constrained to the artistic and performative, but can also be used to explore the pedagogical. Hummel et al. published their findings on using interactive sonification to self-modulate German wheel training at the 2010 Interactive Sonification conference [143]. Their findings indicated that adding real-time sonic feedback to training improved the performance of their participants when executing tricks on the German wheel [143].

In 2019, Vidal et al. created BalBoa, a handbalance training board that provides a real-time visualization of weight distribution on the left hand [144]. Though BalBoa was just a prototype, their preliminary trials with seven handbalancers (four advanced and three beginner) indicated promise [144]. Chapter 3 discusses a related project, HAND, which also builds upon the idea of handbalance pedagogy, but with the addition of haptic feedback for posture correction.

2.5 The pedagogy-performance relationship in circus arts

As shown in Figure 2.2, the pedagogy-performance relationship in circus technology is akin to the composition-performance relationship in music tech, as discussed in Section 2.4.1, and the pedagogy-performance relationship in dance tech, as discussed in Section 2.4.3. Unlike related movement disciplines such as yoga — which is traditionally used as a meditative or spiritual practice — or gymnastics — where the emphasis rests on pure skill augmentation — circus artists train with the explicit intent to perform. As such, the environment, including apparatus, must be considered both during training and performing circus as they are inextricable. For

this reason, HAND and HAND⋆*CS* were designed with such a relationship in mind.

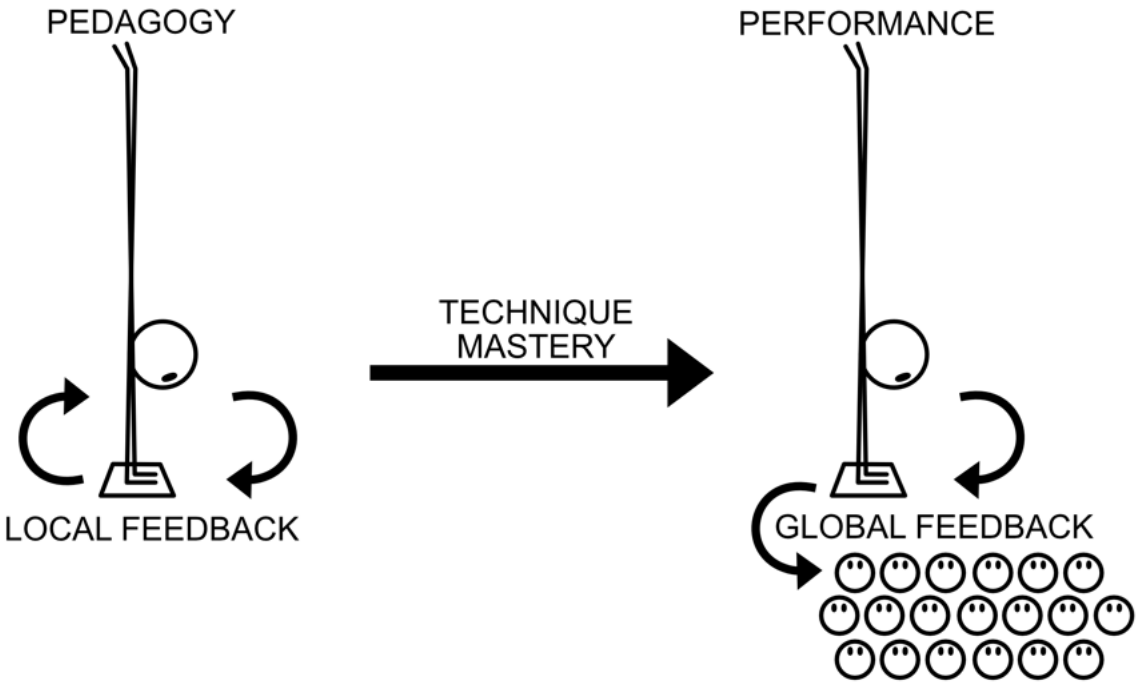

Figure 2.2: Pedagogy-performance relationship. Through local feedback, a performer can achieve mastery of a specific technique and can then purposefully employ the same types of inputs within a performance to produce global feedback for the audience through sound, lighting, or other cues.

Considering the example of music tech, specifically SID, we see that the field of circus technology has much to draw from. As Jordà et al. directly state, exploration of the connection between HCI and music tech "can lead to a fertile two-way cross-pollination that can equally benefit both fields" [77]. The same can now be said for HCI and circus technology. While Bischoff may have said, "to bring into play the full bandwidth of communication there seems to be no substitute, for mammals at least, than the playing of music live" [145, p. 28], it can be argued that circus arts (extending to dance) alter the form from aural to kinesthetic, thereby broadening the means of communication. For example, while Prokofiev's *Peter and the Wolf* differentiates character and demeanor through instrument choice and motif, Cirque

du Soleil's *Amaluna* differentiates the same properties through apparatus and choreography, while musical score takes a backseat.

The examples in Section 2.4.4 have focused on either the artistic or the pedagogical aspects of a discipline. While it would be feasible to bridge the gap between pedagogy and performance using any of the other systems, the authors of said systems focused on one or the other. In 2007 Boverman et al. bridged that gap and published their work *JUGGLING SOUNDS*, a sonification of club juggling patterns with the capabilities for exploration, moderation, and art [146]. This exploration between the boundaries of pedagogy and art exemplifies the lack of strict categories determining pedagogical tools and tools for artistic expression, another area with rich possibilities for circus tech. Following this idea, Chapter 4 augments HAND from a training device, as discussed in Chapter 3, into a performance apparatus.

Chapter 3

Haptics-Assisted iNversions Device (HAND) and Pedagogical Applications

3.1 The HAND System

Haptics-Assisted iNversions Device (HAND) consists of a pressure-sensitive mat and a pair of haptics-augmented, palmless, fingerless gloves. Since vision plays a significant role in balance [22], it is clear that an optimal handbalancing aid would eschew any direct visual feedback. Therefore, haptic feedback was selected as the primary source of feedback. While audio feedback might seem a natural substitute for visual feedback (and, in fact, has significantly better response time [147]), it is important to note that most circus artists train in warehouse-like gyms with little to no sound dampening, and so listening for audio cues could end as an exercise in frustration management. Noise-cancelling headphones could be effective in the use of audio feedback, but over-ear headphones can be bulky and obstruct arm positioning and in-ear headphones can be finicky fit-wise.

More specifically, vibrotactile feedback was selected, as it can provide simple skin surface stimulation to multiple areas of the body [147]. Humans are so perceptive to tactile stimulation, especially patterns, that we can distinguish successive pulses within as little as 5 ms [147].

Note that HAND is intended for intermediate and advanced handbalancers aiming to prolong their ability to maintain a handstand. After learning the basics of a handstand, "less skilled" and "more skilled" handbalancers are differentiated by how long they are able to hold

a basic straight body handstand [148]. The quest to achieve a prolonged handstand can be likened to the quest to run a marathon: the stamina and strength required to sustain a prolonged handstand and longer runs are both achieved through consistent training. During this stage of skill acquisition, it is not required, nor is it necessarily beneficial, to have a coach monitoring every practice session, as it is important for the student to internalize previous corrections given to them and learn how to correct mistakes on their own. Notably, there is currently no reliable method to receive real-time feedback during solo training; instead, handbalancers must rely on either active participation from a "spotter" (often another handbalancer) to help correct form in real-time, or amateur self-recording and analysis of the video playback while training alone.

By focusing on the hands and their relationship to the ground, the hope is that HAND will allow the handbalancer to feel secure in their perception of balance and be able to focus on concrete, physical feedback to prolong their ability to hold a straight body handstand. Furthermore, HAND may aid the handbalancer in strengthening the connection between their proprioception and neuromuscular coordination [149]. If successful, HAND will be able to replace the need for a spotter once a handbalancer is able to maintain a short prolonged handstand and no longer requires significant manual and verbal feedback.

3.2 Development of HAND's design

When designing HAND, it was important to consider both the engineering as well as the user constraints, as advised by Buxton and Sniderman [58]. Following Nielsen's iterative design cycle model, HAND's design was not finalized all at once, but was refined over time through participatory design after small trials with domain experts. The design process was previously discussed in Section 2.3.

However, a few design criteria remained consistent, namely safety, freedom of movement, simplicity of use, and cost. Handstands are a physical discipline involving significant use of the hands and requiring a training space without potential obstacles. Therefore, it was important to make sure HAND's design eschewed covering the palms and fingers, as well as avoiding wires as much as possible in order to eliminate tripping hazards. Furthermore, simplicity of use was a concern as when a performer is practising a skill, it is key to keep corrections simple; the

mental load of performing the skill occupies most of the performer's concentration, making it difficult to process nuanced feedback. Additionally, it would most likely be difficult to convince handbalancers to use a new, complex technology when low tech methods already exist. Finally, financial accessibility was also important, as most artists do not have the means to heavily invest in new technologies.

3.2.1 Interaction design

The motivation behind the mat and glove design was to create a fully wireless apparatus with as little disruption to the user as possible. Originally, a tactile pin array was considered as both input and output surface, but was quickly rejected due to durability concerns. Furthermore, though the glabrous surface of the hands (the palms and pads of the fingers) has more tactile acuity than that of the hairy surface (the back of the hands and fingers), performing a handstand on a reactive surface would interfere with the hand to surface contact needed for a proper handstand. Ultimately, a two-part system was chosen: a simple pressure-sensitive mat for its similarity to a typical surface a handbalancer might use, and a pair of vibrotactile-actuator-embedded gloves to provide posture correction feedback. It was decided that the gloves be wireless for safety reasons, which would allow for as much freedom of movement as possible and minimize interference. A Flask server was set up to communicate instructions to the gloves [150].

See Figure 3.1 for an architecture diagram of HAND.

3.2.2 Version 1.1 (V1.1) — Preliminary design

3.2.2.1 The mat

The mat used for all versions of HAND is the SensingTex pressure mat platform "Health Mat Dev Kit 1.9", which consists of a 48×48 array of 6 mm diameter sensors with a 10 mm sensor element resolution [151], [152]. The mat has a sensing area of 480 mm by 480 mm [152] and is made out of a slightly stretchy rubbery material. The software utilities provided with the mat use sensor coordinates in units of sensor count ranging from 0 to 47. See Figure 3.2 for a visual of the pressure mat platform.

The minimum and maximum pressure each sensor is capable of measuring are 20 and

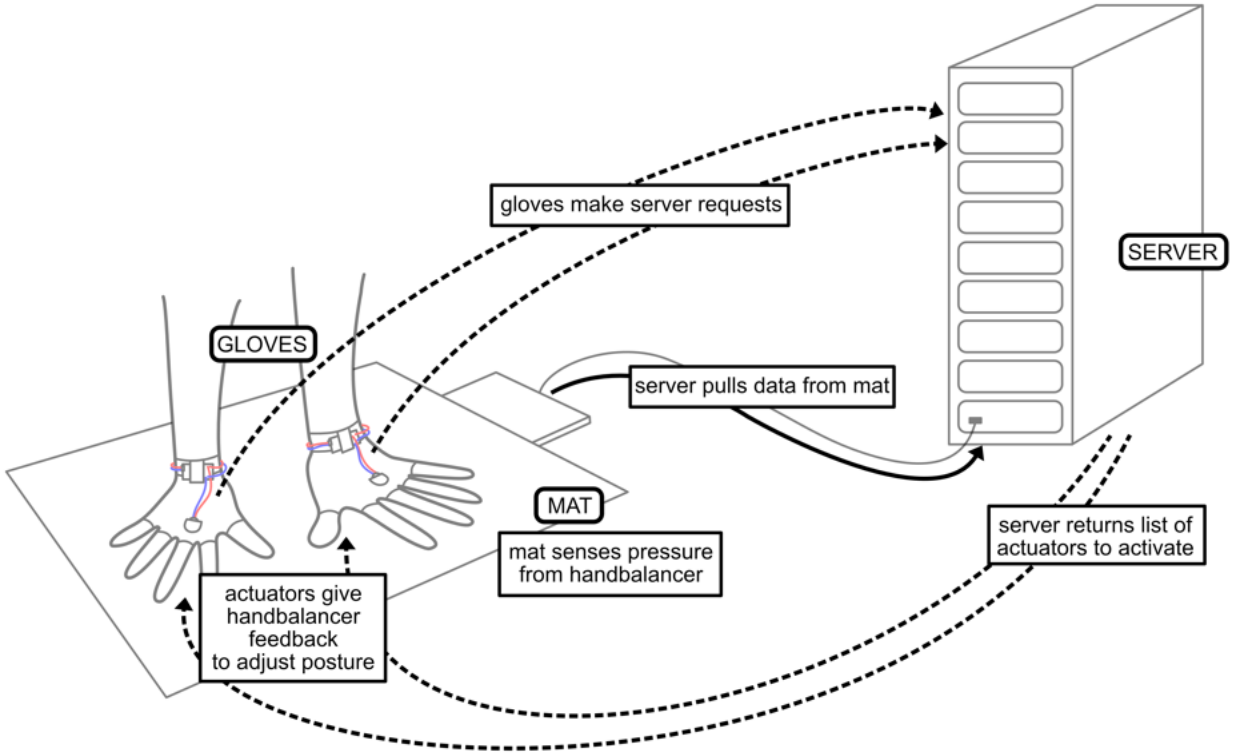

Figure 3.1: High level architecture diagram of HAND.

10 000 mmHg, respectively, with 10 mmHg resolution [152]. These parameters are equal to a minimum pressure per sensor of 0.0272 kgf/cm^2 (0.387 lb/in^2), a maximum pressure per sensor of 13.6 kgf/cm^2 (193 lb/in^2), and a pressure resolution of 0.0136 kgf/cm^2 (0.193 lb/in^2), which, for the 6 mm diameter sensors, is equal to about 48 gf (1.7 oz) resolution per sensor. Note that kgf and gf denote kilogram-force and gram-force, respectively, where 1 kgf is equal to 9.80665 N or 2.20462 lb.

Estimating that one hand approximates 10 by 20 cm in size, one hand would cover 200 sensors, and, assuming a uniform distribution across the handbalancer's two hands, the maximum force per hand would be 2720 kgf, or 5440 kgf for two hands. Imagining a typical person weighs 70 kgf (154 lb), this calculation translates to a multi-person two-handed handbalancing act with up to 76 people supported by a single base person; clearly the mat can support more

than enough weight.

Again for a 70 kgf person, the 48 gf per-sensor resolution is equivalent to a fractional resolution of 0.000 687 , or about $\frac{1}{15}$ of a percent, more than sufficient for measuring pressure variations within and between hands.

SensingTex provided demo software to view pressure distribution, as well as a simple Python [153] skeleton program for obtaining pressure data from the mat sensors. Software will be discussed further in Section 3.2.4.

Figure 3.2: The SensingTex pressure mat platform.

3.2.2.2 The gloves

The gloves were designed and built by the author. As mentioned in Section 3.2.1, wireless capability of the gloves was a priority for safety and freedom of movement. Each glove consists of a Wi-Fi-receiver-embedded Arduino board (a TTGO ESP8266) soldered to four 3 V DC vibration ERM motors and powered by a 3.7 V 100 mAh lithium-ion polymer battery. ERM motors were chosen over linear resonant actuators (LRAs) or piezoelectric actuators (piezos) for their availability, reliability, low price, and simplicity of use [147]. While LRAs allow for the freedom of separation between frequency and amplitude, and while piezos can duplicate the capabilities of both LRAs and the ERMs, this kind of control is not necessary when the aim is

to keep feedback as simple as possible. The original glove design used four ERM motors, with the goal of mapping each actuator to a basic directional correction. Actuator placement will be discussed in depth in Section 3.2.2.3.

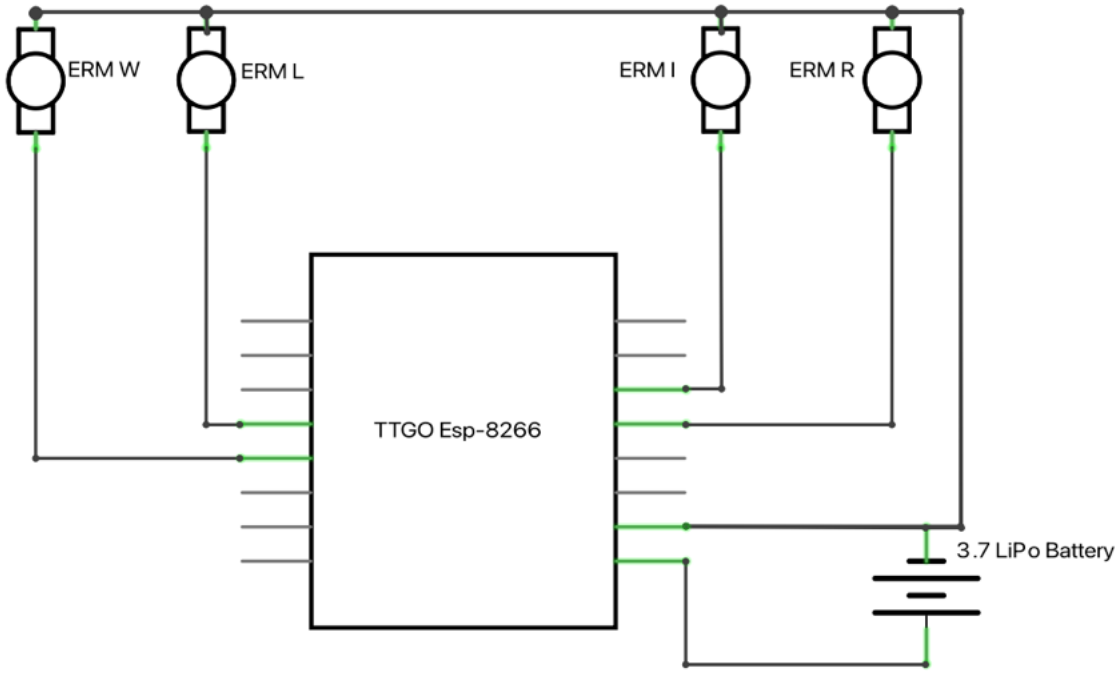

Figure 3.3: Schematic of the glove hardware. The design was kept simple for size considerations. The TTGO Esp-8266 was chosen for its Wi-Fi capabilities. A battery was used to allow wireless operation; a lithium-ion polymer (LiPo) battery was chosen because of its high specific energy and consequent light weight.

A schematic of the hardware is shown in Figure 3.3; this entire ensemble is attached to a customized pair of palmless, fingerless gloves to allow for ease of wear. The base glove design was modeled after sun protection gloves, such as those from SunSafe Australia [154], which provide protection to the backs of the hands without restricting dexterity or limiting touch. The gloves were originally cheap, stretchy, cotton gloves typically used in winter. The fingers were cut off and the palms cut out in order to allow the user the maximum amount of skin-to-surface contact. Because the original material of the gloves was so stretchy, the perimeter of the palm opening was reinforced with non-stretchy thread in order to prevent shape distortion.

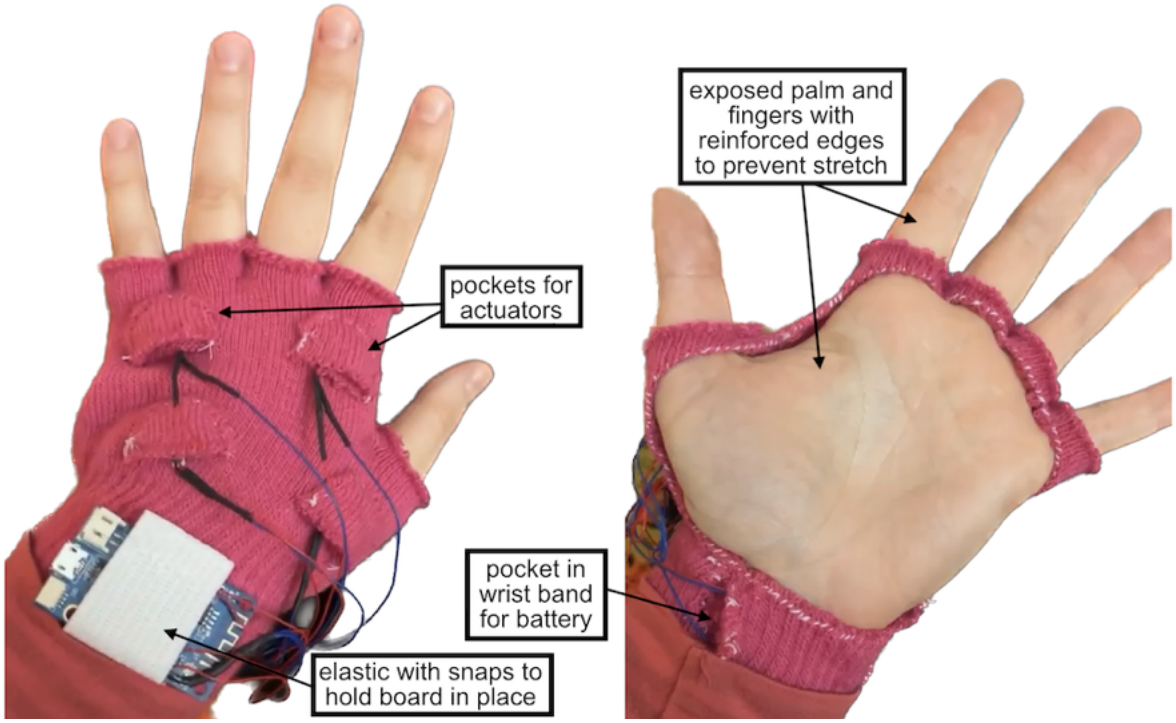

Figure 3.4: Design features of the gloves for HAND V1.1.

The glove fingertips were repurposed as actuator pockets and were sewn on the backs of the gloves to secure the actuators in place. A slit was cut in the cuff of the glove on the inside of the wrist to create a pocket for the battery. An elastic strap was secured to the cuff of the glove on the back of the wrist to secure the Arduino board in place.

See Figure 3.4 for a labeled visual of the gloves.

3.2.2.3 Actuator placement

Preliminary actuator placement was determined with the intention of maximizing safety and retaining freedom of movement while also remaining distant from other actuators. It was expected that placement could change based on feedback, once tested by a few competent handbalancers. The four ERM motors were initially placed in a cross formation, following the conceptualization of a coordinate plane: one by the index finger (labeled I), one by the wrist (labeled W), one as far right as possible between actuators I and W (labeled R), and one as far

left as possible between actuators I and W (labeled L).

As mentioned in Section 3.2.2.2, the intent was for each actuator to correlate with a primary directional change. When actuated, each actuator was intended to convey that the handbalancer should shift their weight toward the indicated direction, with the required magnitude of correction corresponding to the number of ERM pulses delivered to the actuator.

See Figure 3.5 for a visual of the original placement.

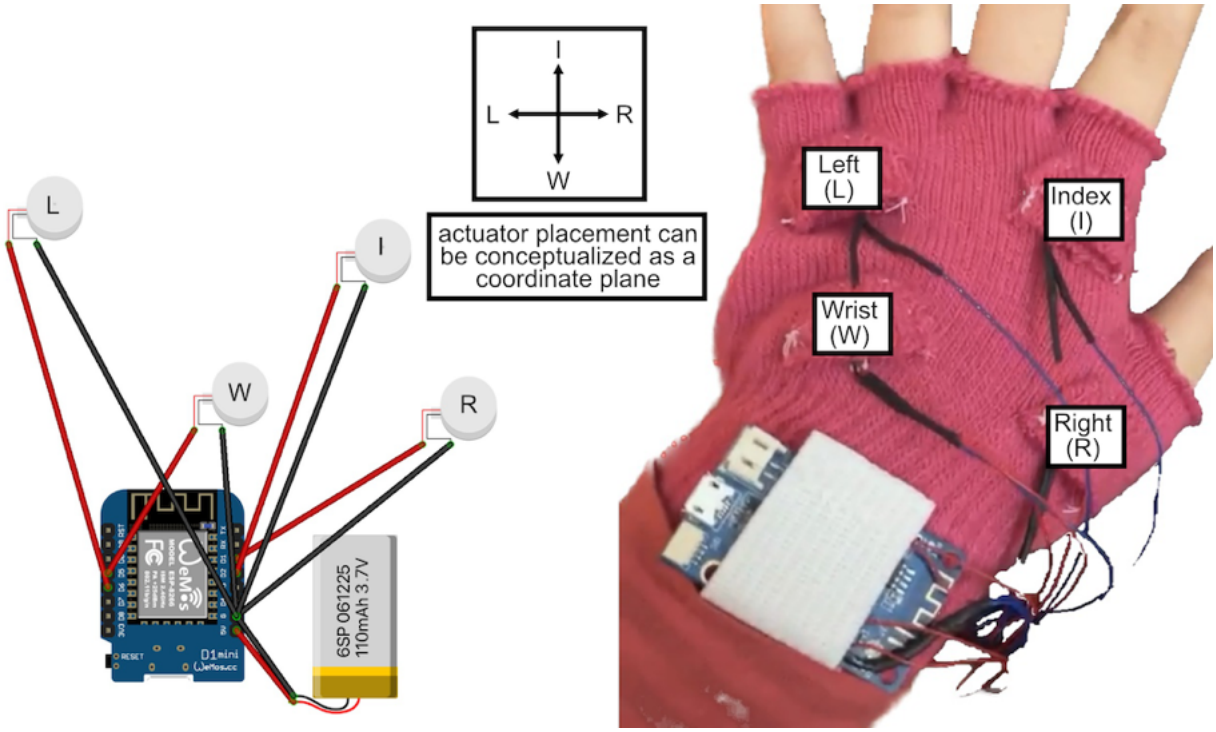

Figure 3.5: Actuator placement on the back of the hand for HAND V1.1.

3.2.3 Firmware

The TTGO boards are loaded with custom firmware written using the Arduino integrated development environment (IDE) [155]. The firmware can be found in the HAND GitHub repository (see Appendix A). The operating computer used is a 2021 14 in MacBook Pro with an Apple M1 Pro chip running MacOS 13.6.7. The operating computer sends Wi-Fi signals through a Flask server to the TTGO boards, which then send 3.3 V signals to activate the appropriate ERMs

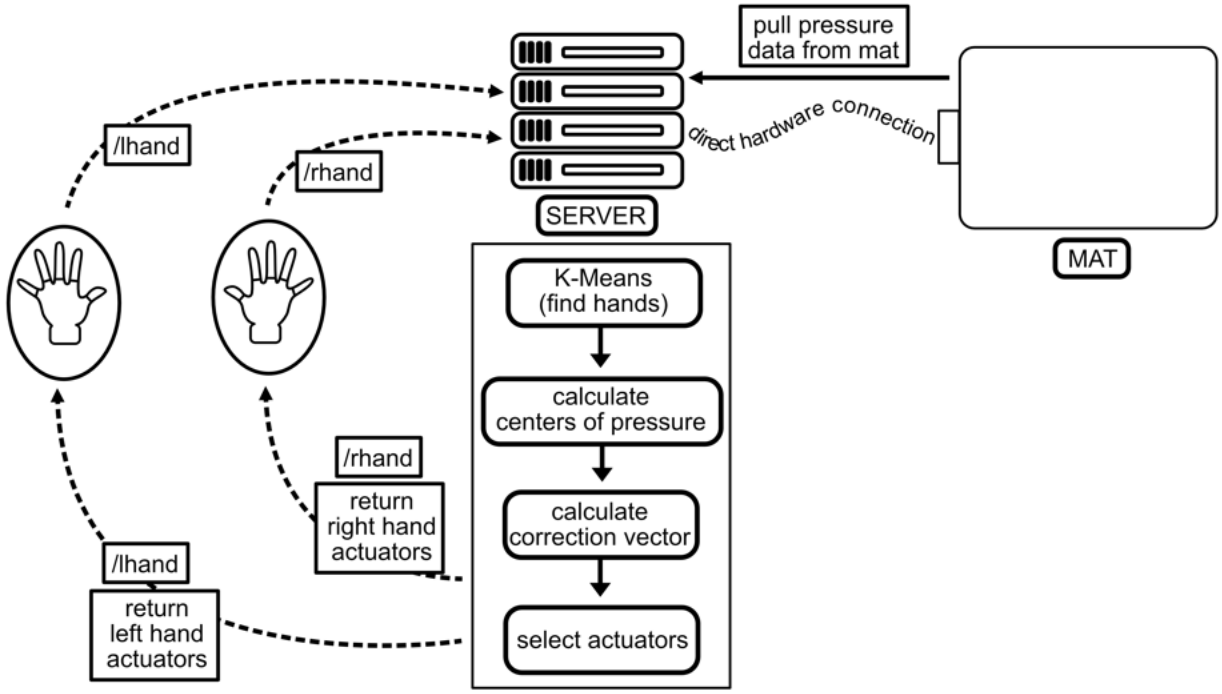

Figure 3.6: Software architecture diagram of HAND.

[150], [156]. The magnitude of correction needed is associated with an increasing number of ERM pulses; an example can be found in Figure 3.10. The actuators remain activated until the next loop. A preliminary loop delay of 1000 ms was added as a placeholder for later refinement based on participant recommendation. When activated, the actuators feel akin to a cell phone vibration notification.

3.2.4 Software

The SensingTex mat software is written in Python 3 [153] and can be found in the HAND GitHub repository (see Appendix B.2). SensingTex provided a skeleton code that acquired data from the mats and represented it as a matrix of pressure distribution. The current software takes this matrix and runs a k-means clustering algorithm to split the matrix into two sections to represent the hands. Generally, this algorithm is used to split N points into K clusters; cluster

J is determined by the function $J = \sum_{j=1}^{K} \sum_{N \epsilon S_j} |x_n - \mu_j|^2$, where x_n is a vector for point n, and μ_j is the geometric centroid of all the points currently in cluster S_j [157]. The algorithm reaches a natural stopping point once data points are no longer reassigned. On average, k-means runs with complexity $O(knT)$ where n is the number of points and T is the number of iterations [158]. The k-means algorithm is fast and already included in the scikit-learn Python library, and so was a natural choice for separating the two hands [158].

Once the hand clusters have been established, the center of pressure both within each hand and between the hands is determined. The center of pressure is calculated using the formula $x_{cm} = \frac{p_1 x_1 + p_2 x_2}{p_1 + p_2}$, where p_1 and p_2 represent the pressure at a particular coordinate, and x_1 and x_2 represent the coordinate value. This calculation must be done for both x and y. These values are then compared to the "expected" values, which represent an ideal pressure distribution while in a handstand.

This ideal pressure distribution follows Gendell [38] and Gatti [39], as previously discussed in Section 2.1.2 and visualized in Figure 2.1. These references indicate that the ideal center of pressure should rest just below the base of the index and middle fingers, which is approximately the middle of the hand. As shown in Appendix Figure D.1, the ideal pressure distribution for the feet when standing includes equal pressure across and within both feet, i.e., 25 % pressure across the front and back halves of each foot. Extrapolating to anatomical analogues while handbalancing would equate to 25 % pressure across the front and back halves of each hand and is simulated by assuming equal pressure across all points in the hand clusters. In the future, a more nuanced algorithm to determine ideal pressure distribution based off of recorded data from expert handbalancers would be beneficial, but is outside the scope of the current work.

A vector is then calculated to represent the direction and intensity of the correction that the handbalancer must make to achieve the ideal pressure distribution. The vector is compared to the coordinate plane defined by the ERM motors, and the motor within the quadrant that the vector indicates is activated. For a depiction of the coordinate plane, with the locations of the ERM motors and the quadrants that the motors define, see Figures 3.5 and 3.7 below.

The program then sends signals to the TTGO boards to activate the selected ERM motors. Originally, two corrections per loop were made: one associated with the magnitude of the correction vector along the x-axis and one associated with the magnitude of the correction vector along the y-axis. The importance of each correction was determined based on its mag-

nitude, which was normalized to a scale from 0 to 1, where 1 corresponded to the greatest of the two correction components. A high importance correction corresponded to any correction with a normalized value greater than 0.66, a low importance correction corresponded to any correction with a normalized value less than 0.33, and a medium importance correction corresponded to any magnitude between high and low. If selected, the motor was activated for three (high), two (medium), or one (low) pulse(s) at 100 ms duration for each pulse with a 200 ms delay between pulses. However, in the current system with two actuators per glove, only one correction per cycle is made, and is indicated with the high importance correction of three pulses. This process is then repeated each cycle until the handstand session is terminated.

For the preliminary design with four actuators per glove, both gloves receive the same actuator activation instructions and so using both is potentially superfluous. The gloves were originally designed with the intent of allowing for more nuanced feedback, including within-hands corrections where each glove could receive separate correction instructions. However, within-hands corrections were determined to be outside the scope of this work and were left for future development. Note that in the current system with two actuators per glove, each glove receives separate correction instructions and so both gloves must be used in order to receive all correction information.

See Section 3.2.2 for a discussion of the pressure specifications of the mat and example handbalancing pressures and forces, Figure 3.6 for a diagram of the firmware and software components, Figure 3.7 for a visualization of the data after each step of processing, and Figure 3.8 for a visual of the posture correction in action. Note that the corrections reflected in Figure 3.7 reflect HAND's V1.2 updated design, which is discussed in Section 3.3.3.

3.3 Preliminary evaluation of HAND

3.3.1 Expert participant trials for V1.1

A preliminary trial was run on HAND using two formally trained handbalancers (Participant 1 and Participant 2). Due to the specialized background requirements for eligible participants, as well as scheduling availability of potential participants and of the facilities needed for trials, two expert participants were deemed sufficient for an initial trial. To get a sense of their backgrounds and training preferences, both handbalancers were first asked to fill out the pre-

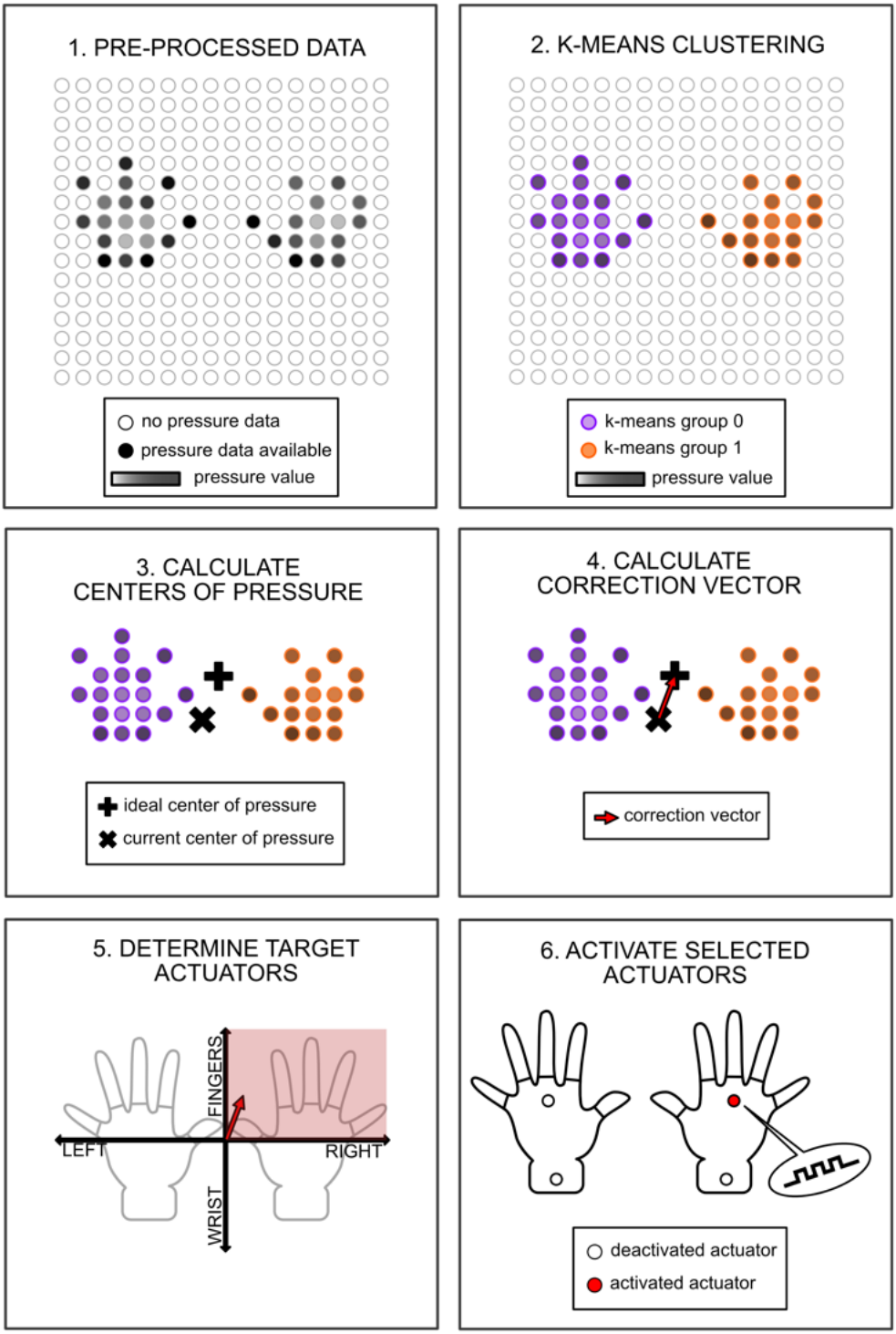

Figure 3.7: Visualization of HAND data after each step of processing. Note that this visualization uses a simplified 16 × 16 array of sensors and simulated data for clarity. Additionally, the gloves and corrections shown in box 6 reflect HAND's V1.2 updated design.

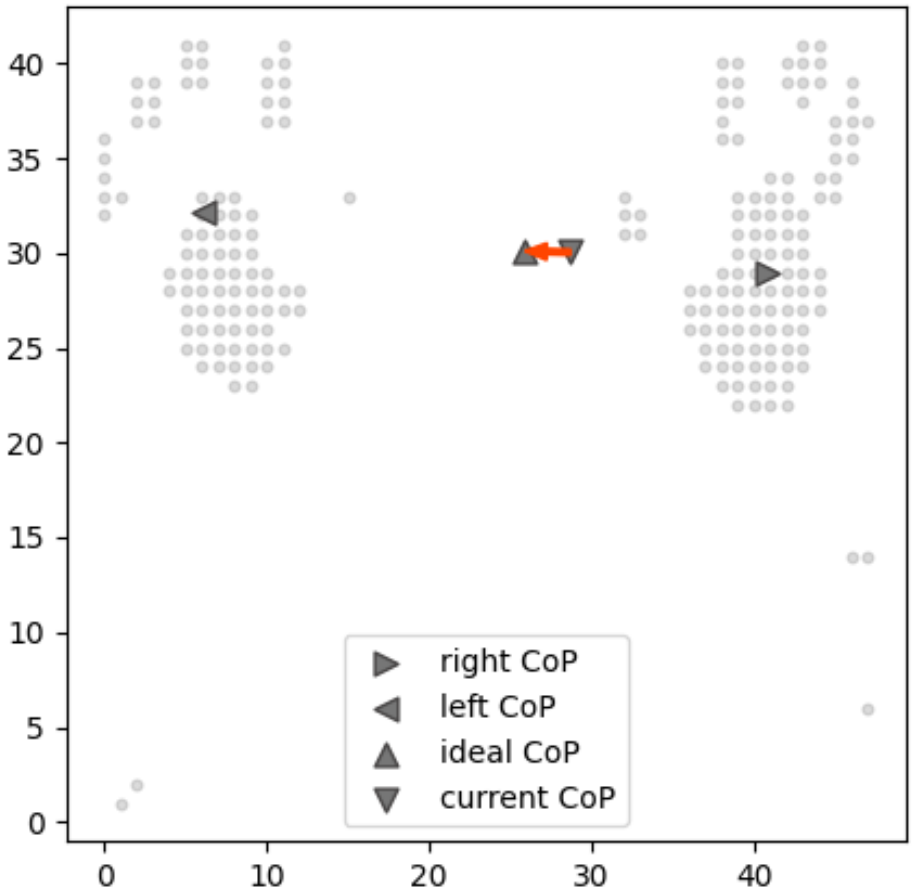

Figure 3.8: Posture correction of HAND in action. The center of pressure is calculated within each hand, as well as between the hands. The center of pressure between the hands is compared to the ideal center of pressure, and a correction vector is created and displayed. In this frame, the correction vector is pointed left, so the left hand actuators would be selected. The handbalancer would feel pulses on both actuators of their left hand, indicating more pressure is needed on the left hand as a whole. Note that the five points scattered below the two hands are mat artifacts with barely any registered pressure and so do not meaningfully affect any pressure correction calculations. These points are due in part to the mat being rolled up for storage. When unrolled for use, some of the curve is retained, causing a slight pressure on a few sensors.

test questionnaire found in Appendix A. Both participants identified as women and indicated they were between 25 and 34 years of age. Both considered themselves professional circus artists and had extensively trained for between one to three years with professional coaching to do handstands, but did not consider themselves professional handbalancers. Participant 2 indicated that habits formed during previous gymnastics training inhibited her ability to progress in handbalancing without extensive use of a spotter. Neither participant had used interactive technology while handbalancing, nor had experienced a wearable haptic device.

Due to a server issue where both gloves were attempting to access the same variable, participants were asked to choose a hand on which to receive haptic feedback. As previously mentioned in Section 3.2.4, since both gloves received the same actuation instructions, participants were able to use one glove without missing any feedback. Both participants chose their right (dominant) hand. Participants were then asked to explore handbalancing both with and without glove feedback. During both conditions, participants wore the gloves; the only difference was whether or not the gloves presented haptic feedback. Participants entered and exited handstands in their preferred manner (kicking up, straddling up, and split-press) as well as explored sustained static handbalancing on the mat.

3.3.2 Participant-recommended modifications for better feedback

3.3.2.1 Verbal feedback

Both participants requested less delay between correction cycles, so the delay was reduced from 1000 to 250 ms. This shortened delay is in accord with Yeadon and Trewartha's recorded feedback time delay of 160 to 240 ms during an unperturbed handstand [55]. They also indicated difficulties in distinguishing the signals, partially due to the form of the glove prototype, and partially due to the complexity and nuance of the feedback. In particular, Participant 1 mentioned having difficulty differentiating directionality of the corrections, and vocalized the desire for left and right corrections to be split between the left and right hands with actuators on each hand only indicating shifting weight towards or away from the fingers.

3.3.2.2 Written feedback

Participants were then asked to write down any thoughts they had about their experience with HAND, as well as note any recommendations for improvement. Both participants indicated a willingness to try haptic feedback in future training and both reiterated the use of a shorter feedback cycle period and more signal clarity. Participant 2 noted, "it was challenging with the slight time lag" and "having the signals split between two hands would help". The addition of a simple GUI with a cycle delay slider would allow handbalancers to fine tune the correction speed to their preference.

3.3.3 Version 1.2 (V1.2)

3.3.3.1 Notable modifications

Participant comments indicating the desire for instructions to be split between the hands in accordance with directionality and the difficulty in distinguishing the location of actuation motivated the decision to simplify the glove design to two actuators per glove: one placed near the fingers and one placed on the palm-side of the wrist. The server issue was fixed and feedback was successfully sent to both left and right gloves at the same time as needed. See Figure 3.9 for a visual comparison of the differences between V1.1 and V1.2.

In a future version, support for within-hand correction may be added, which would require the original four-actuator design — or perhaps with more than four actuators per hand — though more testing would need to be done to determine what level of granularity is most effective and worthwhile; see also the caption to Figure 3.10.

Feedback was also simplified to one correction per feedback loop. When selected, the target ERM motor is activated for three pulses at 100 ms each per pulse, with a 200 ms delay between pulses. See Figure 3.10 for a comparison between the original V1.1 feedback and the simplified V1.2 feedback. Simplified in this way, the feedback can be conceptualized more as a gentle nudge in the direction of correction rather than indicating directions paired with specific magnitudes. This type of correction is akin to the traditional methods of handbalancing correction discussed in Section 2.2.3.

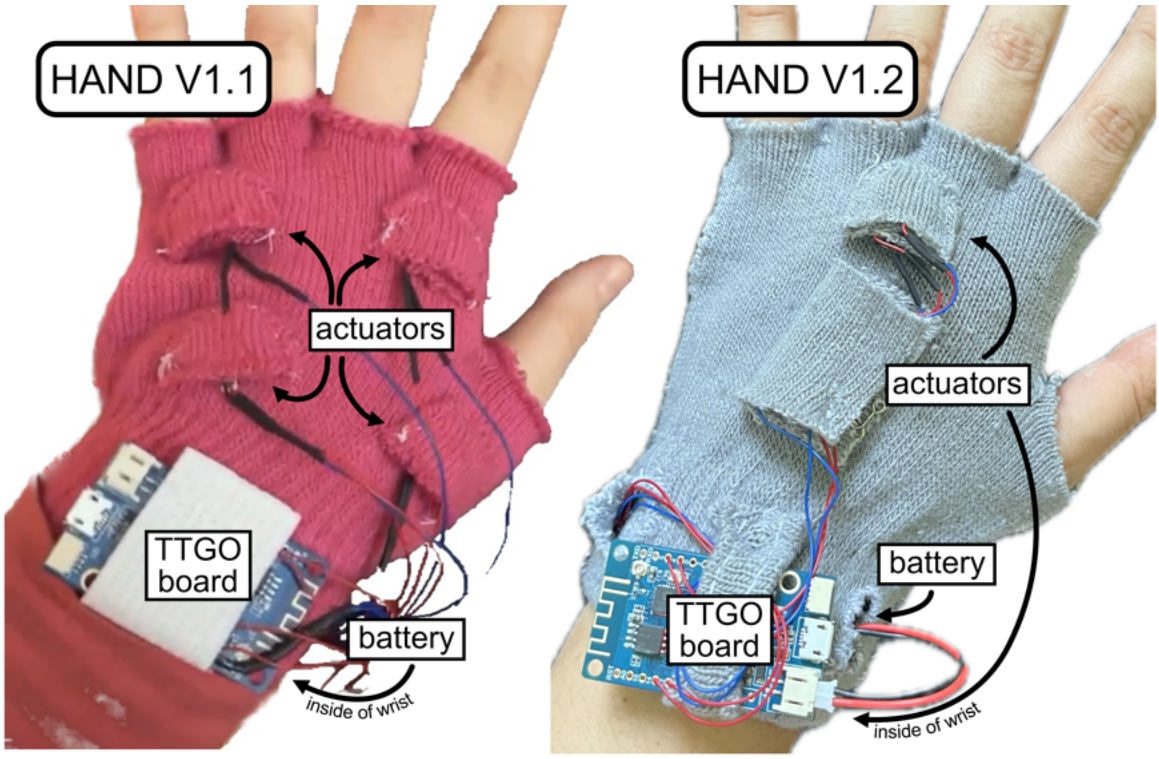

Figure 3.9: Comparison between HAND V1.1 and V1.2 gloves. The most notable difference is the reduction of actuators from four per glove to two per glove, making use of the innate left-right dichotomy between hands.

3.3.4 Expert participant trial for V1.2

A trial was run on HAND V1.2 with one expert participant (Participant 3) who identified as a woman in the age range between 25 and 34 years who had seriously trained handstands for four to six years but currently worked in a movement-based profession unrelated to circus arts as a physical therapist. She had been formally trained in handbalancing as well as in a handstand-adjacent discipline but did not consider herself a professional handbalancer. Contrary to the other expert participants, Participant 3 preferred training on the bare floor with the addition of a stability ball, ankle weights, and the wall. She also indicated frustration in handbalancing training related to day to day inconsistency and progressing her skills. Contrary to Participants 1 and 2, Participant 3 had previously used interactive technology while

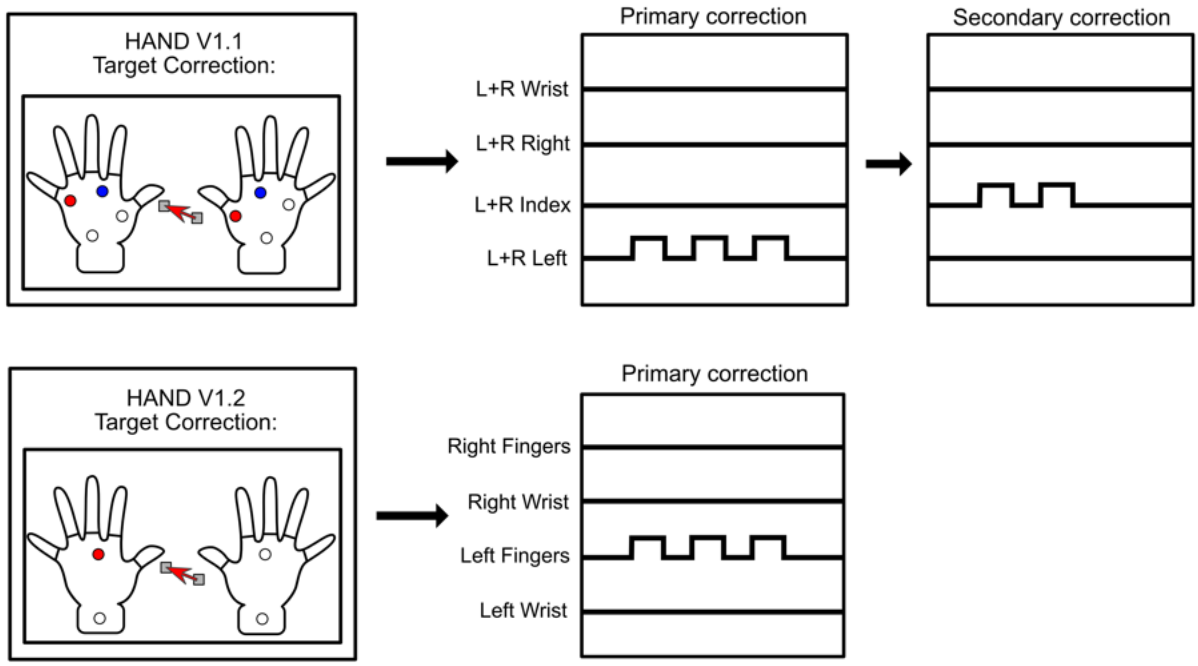

Figure 3.10: Comparison between HAND V1.1 and V1.2 corrections. The vector has a larger magnitude to the left (horizontally in the figure) and a smaller magnitude towards the fingers (vertically in the figure). In both the V1.1 (upper left) and the V1.2 (lower left) panels, the red dots indicate a correction needed in the corresponding directions, and, in the upper left panel, for V1.1, the blue dots indicate a smaller correction in their corresponding directions.

handbalancing:

> I used a musical instrument that was devised for a performance piece; a box with pressure sensors to manipulate sound output. It was a really neat experience to hear how my weight shifts and movements altered the sound; it made me realize that my body moved more than I thought it did while hand balancing.

With the server issue fixed, both gloves were able to give real-time feedback during the trial. As with the other two participants, this participant was directed to enter and exit handstands in her preferred manner and explore sustained static handbalancing on the mat.

3.3.5 Participant feedback and suggestions for future directions

Participant 3 noted that she had been told by multiple coaches that she consistently puts more weight on her right arm while handbalancing. She also had the opportunity to verify for herself by handbalancing on a force plate in a gait analysis lab. Additionally, Participant 3 mentioned that her current wrist and shoulder inflexibility may be interfering with her posture. With this background in mind, the HAND system began to gamify the correction for her:

> It was cool to feel using the haptic gloves that I needed to put more weight through my left arm. It became goal oriented for me to shift my weight enough to my left that I would stop receiving haptic signals or start receiving them in my right hand.

With regards to the correction cues, Participant 3 noted:

> I found it easier to control the weight shift left to right as compared to the weight shift forwards and backwards in response to the haptics. Through my handstand training I have become accustomed to maintaining balance and my hands automatically shift from heel to fingers to maintain my balance. I find that it is harder for me to manipulate the front/back shift in response to a cue or maintain the shift for the sensor to register the correction.

Ultimately, Participant 3 declared that she saw potential in HAND and its applications:

> I think it can be a really useful tool. I have had a right shoulder injury for several years now and I believe that may be related to consistently putting more weight through my right side. I think there is real potential here for limiting risk of injury. I think there is a lot to explore in terms of timing of the cues. I think it could have some great application on understanding errors when learning new skills, especially if it could give input quickly enough when learning new entrances or position changes.

Here, Participant 3 indicates interest in expanding HAND's pedagogical range to include the introduction of new skills and not just refinement of existing skills. In its current state, HAND is designed to improve posture when holding a straight handstand. When honing an existing

skill, constant feedback is not required and can in fact be distracting. Training a new skill requires different feedback from perfecting a skill; when learning a new skill, more feedback is required in shorter cycles. To train new skills, HAND would require new algorithms to be developed to guide the user into the desired position, which would include almost constant feedback.

Participant 3 had several suggestions for other future modifications, such as the addition of visual feedback on the hands on top of the existing haptic feedback:

> I think having the visuals of the pressure distribution on my hands would be super interesting and applicable to me.

This suggestion is interesting considering the justification for using haptic feedback in Section 3.1. It is worth noting here that this participant is not a contortion handbalancer, and so does not train handstand poses requiring extreme backbends resulting in the head looking at an opposing wall instead of at the hands. It would be interesting to gather opinions from a wider range of handbalancers in this regard.

Participant 3 also mentioned a few potential directions for expanding the range of the haptic feedback, including support for usage during warmup:

> It may be more versatile if the haptics indicate where your pressure is vs where it should be – for example, if I am working on a press handstand, or a negative press; I know that the weight needs to be more in my fingertips. As this is not a vertical, the current center of pressure map would not give me the right corrections, however it may help me understand why I fail if I feel the haptics where I am. Might be another direction to go in! I think it could also have really good applications during warm-up (for example on hands and knees) in terms of assessing range of motion and calibrating hand pressure and appropriate alignment.

Overall, the modifications made for V1.2 appear to have addressed the main issues brought up by Participants 1 and 2. Especially promising is the indication from Participant 3 that she was able to use HAND to correct known posture issues in real-time. More discussion and future directions are discussed in Chapter 5.

Chapter 4

Expanding to Artistic Applications with commensalisTECH symBIOsis (HAND⋆*CS*)

As discussed in Section 2.5, the relationship between pedagogy and performance has not been thoroughly explored. In order to demonstrate how such a relationship can be explored through an apparatus, and to embody the close pedagogy-performance relationship within circus presented in Figure 2.2, HAND was augmented into a performance apparatus, commensalisTECH symBIOsis (HAND⋆*CS*).

4.1 Licklider, Sonami, Fiebrink, and the philosophy of HAND⋆*CS*

In the tradition of Licklider's man-computer symbiosis, the name HAND⋆*CS* is based off of the concept of symbiosis where, in Licklider's words, two organisms become "heavily interdependent" and "constitute not only a viable but a productive and thriving partnership" [5, p. 4]. More specifically, HAND⋆*CS* takes inspiration from the commensalism form of symbiosis, where one organism benefits from a relationship and the other is unaffected [159].

Notably, Licklider defines two main goals of man-computer symbiosis:

> One of the main aims of man-computer symbiosis is to bring the computing machine effectively into the formulative parts of technical problems.
>
> The other main aim is closely related. It is to bring computing machines effectively

> into processes of thinking that must go on in "real time," time that moves too fast to permit using computers in conventional ways [5, p. 5].

When discussing his sculpting process, Michelangelo once said: "Every block of stone has a statue inside it and it is the task of the sculptor to discover it" [160]. This philosophy can be utilized in tandem with Licklider's man-computer symbiosis when examining how to achieve Licklider's symbiotic goals, especially when investigating artistic domains. While Licklider mainly focuses on applications with concrete solutions — such as military tactics and hypothesis testing — and fixates on human language communication between human and computer, more artistic applications and alternative modes of communication are left unexplored; however, Sonami and Fiebrink have done just that, as discussed in Section 2.4.1.2.

Through *Spring Spyre*, Sonami and Fiebrink created an instrument meant for symbiotic connectivity with its performer through the incorporation of machine learning (ML) [98], [99]. Notably, not only has Sonami stated that she actively collaborates with the instrument itself, but it took her over four years before feeling like she began to understand how to allow the instrument to inform her own creativity. This process is used as a model for HAND⋆*CS*.

4.2 Creating a responsive performance apparatus

Once a handbalancer has mastered control over their balance, it would be possible to use their weight distribution as input and transform HAND into a performance apparatus. By intentionally shifting weight, the performer could trigger different actions such as sound, visual, or light events. In this way, the performer would gain almost full creative control during an improvised piece, as HAND would allow for real-time expression. Ultimately, following the example of *Spring Spyre*, ML could be added to allow for further adaptability, complexity, collaboration, and nuance. However, a framework for such an apparatus would first need to be devised. For this proposed scenario, the haptic gloves would not be needed, as feedback would not be required unless desired by the performer. An example of a related work is Rose's explorations with circus arts and using movement data as input for accompanying interactive sound [142].

4.2.1 Reconceptualizing the handstand

The HAND software can provide a real-time visual representation of the pressure matrix (see Figure 4.1). However, a pressure-map visualization of a handstand is not particularly interesting on its own for performance, and in fact could be a hindrance. A significant consideration when using projections in performance is whether or not the projections may distract the audience from the performance itself [161]. Therefore, alternative modes of representation were explored.

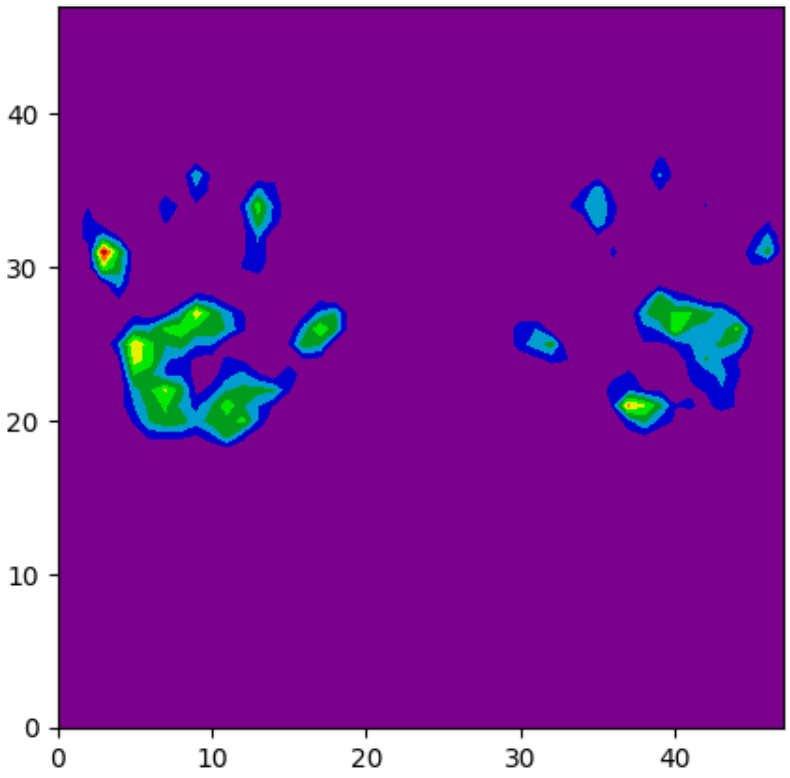

Figure 4.1: Visualizing the pressure matrix data. Purple indicates no pressure; red indicates highest pressure.

4.2.2 Adding additional biometric data

In order to augment the data gathered from the performer, and with the intent of enhancing audience understanding of the effort required to maintain even a "basic" handstand, MyoWare muscle sensors were added to collect muscle activation data [162]. The MyoWare sensors are surface electromyography (sEMG) sensors, which monitor changes in electrical activity of the muscle groups they are placed over [163]. Using a compression sleeve, conductive ribbon, snaps, and conductive thread, and referencing a tutorial from the MyoWare website,[1] a pair of reusable performance sleeves was built to each accommodate two MyoWare muscle sensors with LED shields — LED displays built specifically to snap onto the MyoWare sensors [164]. When activated, the target muscles trigger the LED shield to activate a number of LEDs corresponding to the intensity of the signal received (Figure 4.2).

Figure 4.2: Demonstration of the MyoWare muscle sensors with LED displays. At rest (left), not enough muscle activation is detected to light up any LEDs. When flexing the wrist (middle), all ten LEDs light up, indicating significant muscle activity. After the initial activation (right), the muscle signal is not as strong, so fewer LEDs are on.

[1] https://myoware.com/project/conductive-fabric-electrodes/

4.2.2.1 Placement of the MyoWare muscle sensors

To allow for some flexibility, four muscle groups were prepared as placement sites for the MyoWare muscle sensors: two on the upper arm, and two on the lower arm. More specifically, both the flexors and extensors of both the upper and lower arm were targeted, as they control the bending and straightening of the elbow and wrist joints [165].

See Figure 4.3 for a diagram of conductive ribbon and snap placement for each of the four targeted muscle groups.

4.2.2.2 Construction of the sleeves

The sleeves were constructed using commercial compression sleeves as the base. Each MyoWare sensor requires three electrodes in the form of snaps. In order to create reusable electrodes, three strips of conductive ribbon per muscle group were sewn onto the inside of the compression sleeves, using the placement determined in Section 4.2.2.1. To preserve elasticity, alternating cuts were made on the sides of the ribbon (see Figure 4.4 for a visual). Snaps were then sewn onto the other side of the sleeve using the same placement as the ribbon using conductive thread in order to maintain conductivity. Note that before using the sleeves, the conductive ribbon must be moistened to ensure conductance, similar to consumer electronics such as the Garmin HRM-Dual heart rate monitor [166].

Four pouches were created to hold the MyoWare muscle sensors with both the LED shield and cable shield attached. A rectangle cutout was created to maintain visibility of the LED displays and was reinforced with thread to ensure the sensors would not be able to slip out of the pouch through the display window. Snaps were sewn to the pouches on the top inside rim as closures and to the back as attachment points to the sleeves. Because both the lower and upper arm each have two muscle group options, two display sites were determined to ensure consistency.

Note that the sleeves are sided, as the muscle groups in the left and right arm are mirrored. See Figure 4.3 for a visual of the LED placement and Figure 4.4 for a detailed diagram of the sleeve construction.

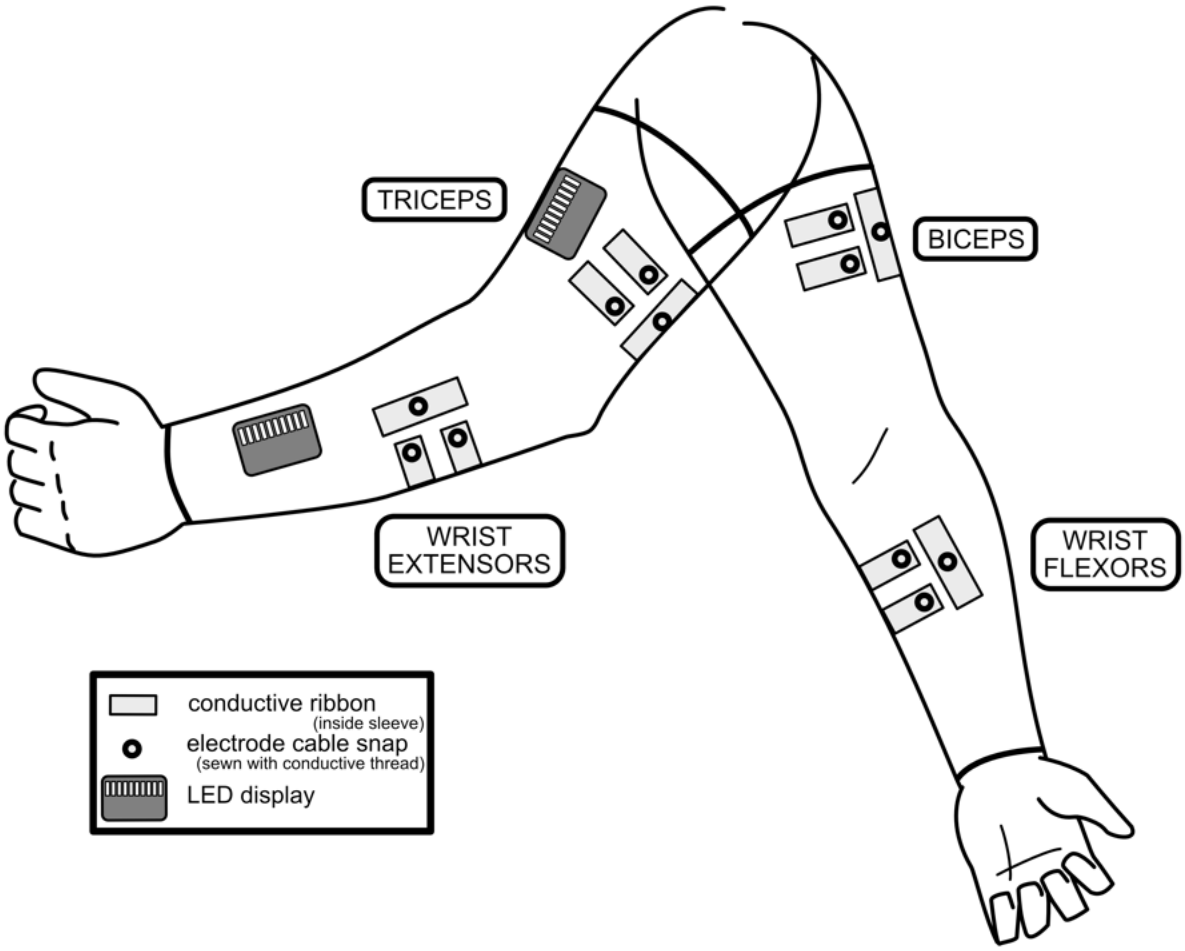

Figure 4.3: Placement of MyoWare muscle sensor electrodes and LED displays. Note that the conductive ribbon is sewn on the inside of the sleeves. The snaps are sewn on the outside using conductive thread to maintain conductance. The LED displays are mounted to the MyoWare muscle sensor, which are in turn mounted to a cable shield.

Figure 4.4: Overview of the MyoWare sleeves.

4.2.2.3 Sonifying the handstand

Drawing from examples from the music tech world (see Section 2.4.1), the SensingTex mat was reconceptualized as an input device for a "handbalancing instrument" where the performer can intentionally shift weight to trigger sound events. Music technologist and collaborator Christiana Rose was asked to create a sound patch to act as the equivalent of "keys" for the mat "keyboard".

The base software for HAND was repurposed to send data to Cycling '74's Max software [167]. While a free and open source tool such as Pure Data [168] would have been preferable for accessibility reasons, Max was chosen due to Rose's familiarity with the software. The correction vector used in HAND uses the same coordinates used by the mat software utilities (described in Section 3.2.2.1) and is used as a sound panning modulator, where the vector's

x coordinate (V_x) corresponds to panning right, and the y coordinate (V_y) corresponds to panning left. Each cycle, the four points containing the minimum and maximum x and y coordinate values for each hand are used as hand boundaries (x_{min}, x_{max}, y_{min}, and y_{max}, respectively). These points are then used as two primary sound modules: one module focuses on sonifying the data into discrete sound objects while the second module focuses on continuous manipulation of a sound object.

When the pressure at one of the four hand boundaries hits a pre-set threshold decided in advance by the performer, percussive sounds in the plink module and pre-determined time selections for each of the pre-composed sound files are triggered in the Max patch. The second module uses the hand boundaries to manipulate pitch and time stretch parameters of pre-composed sound files. The x_{min} and y_{max} values for each hand boundary map to pitch and playback speed (time stretch) and the y_{min} and x_{max} values map to sound file selection length (how much of the sound file is played) and playback controller state (play or pause).

Rose was asked to write a statement to elucidate her process for creating the sound patch and explain its various components:

> The challenge of sonifying the handstand is one that has captivated me for a long time. It was the initial spark that illuminated when I first pondered the idea of circus tech and experimenting with interactive musical interfaces. When Linnea approached me to sonify the handstand for HAND⋆*CS*, I was thrilled! Another opportunity to experiment and think through mapping, gesture and sound — a quest I feel I'll be pursuing for a lifetime. However, HAND and HAND⋆*CS* are unique in their pursuit to explore new territory that bridges the pedagogical and performance elements of an apparatus and interactive interface.
>
> At this early stage, the musical interface elements of HAND⋆*CS* draw inspiration from my previous creative endeavours and my journey as a keyboardist, composer and improviser, combined with the challenge of designing interfaces that convey both the broad strokes and subtle details inherent in circus arts. Additionally, the concepts of dynamic and static balance, ideas of effort, pressure and perception have fascinated me. I wanted to create a "springboard of creativity" (inspired from Anthony Braxton's idea of springboards of musical activity) or sonic palette that HAND⋆*CS* could start and jump off from.

The mapping structure aims to highlight several elements — that of the internal constant presence and energy in stasis, that of more dynamic movement, and creative dialogue between performer and apparatus. The mapping is described in simple detail within the Max patch as shown in Table 4.1. The sonic palette consists of both digitally generated and pre-composed and recorded sound files. The vectors calculated control stereo panning to communicate the experience of shifting balance. In the two sound generation and sound manipulation modules, for this first iteration the thresholds for triggering are arbitrary. This was intended to give a base and wide variety of possibilities. Similarly, the mapping range and scaling is also in the early stages with the same intention of creating a base range to allow for a wider set of sonic possibilities. This range was chosen after observing the sensor output from HAND with our performer for the demo, Molly Barger. With continued development the ranges will be fine tuned to achieve more precision over the generation triggers and manipulation ranges.

The plink module, inspired by the MyoWare sensors and pedagogical application of HAND, generates eight tones that are triggered when different thresholds are met within the eight boundary points. These tones are then sent through a preset delay and reverb, which could be sensor-controlled in future updates. They function as a constant reminder of the ever-present energy and rhythm of the hands, much like a metronome guiding a musician. This rhythmic quality was deliberately selected for the demonstration to accelerate the performer's learning process.

The pitch shift and time stretch module controls four pre-composed sound files, including percussive, melodic and harmonic layers made from metal, wooden, and electric organ. The idea behind merging these elements was to give performers a dynamic soundscape they could control with percussive and fluid changes. Although the interface only processes data from the SensingTex mat, it empowers the artist to use their whole body for expressive purposes. As the performer moves their legs, adjusting balance and pressure in the hands, the boundary data adapts accordingly. By leveraging parameters like stereo panning, time stretching, and pitch shifting, there's a dynamic link between the leg sweeps or the sharp bends and precise movements of knees and feet.

Table 4.1: Overview of sonic mapping for demo version of HAND⋆*CS*. The variable names correspond with variables used in HAND and are explained further in Section 4.2.2.3.

Variable	Effect
V_x	Pan right
V_y	Pan left
Left hand (L)	Percussive & organ sound
x_{maxL}	Playback controller
x_{minL}	Pitch
y_{maxL}	Time stretch
y_{minL}	Selection length
Right hand (R)	Organ sounds
x_{maxR}	Playback controller
x_{minR}	Pitch
y_{maxR}	Time stretch
y_{minR}	Selection length
Hand in trigger zone	Plink tones with reverb and delay

Though there is still much to calibrate and expand upon, this initial sonic springboard aims to set the stage for multiple types of interaction and interpretation from both performer(s) and audience. By embracing the concept of commensalism in symbiotic relationships, these sonic elements can be set in motion by the performer or autonomously continue without further intervention. This approach grants the performer flexibility and control — whether they're up in the air initiating sound or descending to transition seamlessly into a grounded move off the mat, the soundscape can persist or pause. This creates opportunities for extended durations of sound or silence, as well as moments of dynamic interaction.

4.3 Demonstrating HAND⋆*CS*

Performer Molly Barger, also a collaborator on this project, demonstrated handbalancing using HAND⋆*CS*, as shown in Figure 4.5. The demo video URL can be found in Appendix B.

Figure 4.5: Performer Molly Barger handbalancing with HAND⋆*CS*. Note that while the different leg positions provide visual interest, the ideal center of pressure between the hands remains the same, as evidenced by the consistency of the shoulder and torso position. The demo video URL can be found in Appendix B.

4.3.1 Some notes on posture

As Barger balances, the LED displays shift, demonstrating the effort required to maintain balance. The ever-changing display on Barger's right forearm (the left is obscured in the video) elucidates the constant adjustments Barger makes with her fingers. The stasis of the display on Barger's right bicep contrasts to the one flickering on her left bicep; to a trained eye this discrepancy indicates that her left arm is weaker and so must compensate with more adjustments. This conclusion is strengthened by the knowledge that Barger is right handed and by the raw pressure view at the end of the demo video — there is consistently more weight on the right hand than the left.

4.3.2 The performer's perspective

Barger was asked to write a statement on her experience trying out HAND⋆*CS*:

> I feel like it was pretty quick to get a gauge of the music side of things and I didn't quite have enough facility to play around with huge differences in weight shifts, but it was super satisfying to feel like the music automatically went with my movements and brought a different element, like a conversation almost. I had a lot of fun trying to figure out the responsiveness of the lights related to the MyoWare — I know part of that is related to my perspective and my area of expertise. I'm already super curious about what muscles are firing in a handstand and then to have a visual representation related to muscles on/off and speed and change of contraction was very neat to explore and definitely something I could feel myself leaning into more. It was nice to be able to "prove" the technology — testing out arm movements just standing and then comparing the lights in a handstand and I was excited to be surprised at which was the dominant muscle based on arm position.
>
> You know, I think I was maybe fully tuning the music out while I was doing it/it was not very loud if I recall correctly, but looking at the video it definitely feels like I had something to be in conversation with — which even if I don't understand it or feel like I can "control" it is a very fun thing to have as a performer. I feel like in my artistic experiences it is so rarely about control and more about interplay, play, and response. Authentic conversation whether with other artists, space, props, music is a really magical experience. You can definitely be in conversation with fixed music too, but even more enriching, engaging, and exciting when the music talks back to you.

It is validating that Barger felt inspired to experiment with the various components of HAND⋆*CS*. In particular, her perception that the music naturally accompanied her movements is encouraging. This sentiment directly relates to the inspiration behind HAND⋆*CS*, as discussed in Section 4.1. It could be speculated that more practice with the apparatus could result in greater comfort in exploring HAND⋆*CS*'s responsiveness, just as Sonami practices with *Spring Spyre*. Perhaps more familiarity with using this technology could mitigate the instinct that Barger mentioned to "tune out" the music. However, more experience with the connection between performer and device is needed before any conclusions can be drawn.

4.3.3 A tool for improvisational performance

While not a full performance, the demo video demonstrates HAND⋆*CS*'s potential and ease-of-use for a handbalancer. By creating music in real-time, the performer is able to fluidly improvise without fear of missing a musical cue or confusing an accompanyist. However, it is important to keep in mind that HAND⋆*CS* in its current state is a framework, not a final product. The addition of ML could help bolster performer creativity, as it does for Sonami in *Spring Spyre*, though significant time would be needed for an artist to become not only comfortable with HAND⋆*CS*, but to create a true symbiosis with it. Future directions will be discussed more in depth in Chapter 5.

Chapter 5

Implications, Reflections, and Future Directions

This chapter will evaluate HAND and HAND⋆*CS* through the use of introspective methods. While not as widespread as traditional qualitative methods of evaluation, introspective methods have been validated in various publications [169], [170], have been utilized by respected artist-researchers such as Sonami and Fiebrink [99], and are a legitimate evaluation technique. As such, some of this chapter will be written in first person to allow for this author's lived experiences to be taken into account.

5.1 Implications of HAND and HAND⋆*CS*

One of the most difficult corrections to make in handbalancing, once balancing upside-down has become ingrained within the proprioceptive system, is evenly distributing the body's weight between the two hands. HAND set out to mitigate this pernicious issue. As evidenced by the comments in Section 3.3.5 from Participant 3, HAND is successful in this pursuit. Furthermore, even after noting HAND's weaknesses typical of a prototype, all three participants indicated enthusiasm in the concept and interest in future engagement.

With the addition of HAND⋆*CS*, HAND was transformed from a purely pedagogical apparatus to a pedagogy-performance apparatus than can easily switch between modalities. This flexibility allows a performer to fluidly integrate their practice with HAND into a stage per-

formance without needing to become acquainted with a specialized apparatus. In particular, HAND⋆*CS* makes it possible for a performer to easily improvise on stage without fear of synchronizing with either pre-recorded music or an accompanyist. By creating responsive music in real-time, the performer may fluidly create a cohesive improvisational piece.

5.2 Why circus tech is important — some personal reflections

I am a trained circus artist who has delved into the world of engineering to create something that I wish had existed while I was at circus school. Handstands are an integral part of any circus artist's training, as many popular tricks and transitions are done while balancing on the hands. Just as students at music conservatories are taught skills such as sight singing and basic keyboard proficiency, students at circus trapeziums are taught skills such as handstands and basic juggling. As a contortion major with an analytical mind, I struggled to learn to hold a basic handstand through traditional training methods, which ultimately hindered my trick progression and performance repertoire. Many of the exercises I was instructed through during handstand training classes felt like rote movements to me; I was missing the connection to my proprioceptive sense. While spotting sessions were by far the most useful — Croix et al.'s [56] light touch to improve handstand posture in action! — they were few and far between, as the other students had their own schedules and goals to maintain. A tool like HAND would have helped me to systematically understand the primarily somatic handbalancing exercises while also allowing me to train more effectively alone.

I designed HAND with handbalancing in mind, emphasizing the need for safety, freedom of movement, simplicity of use, cost, and the ability to switch between pedagogical and performance modalities. Though these design considerations were already discussed in Section 3.2, I have a few, more personal, reflections.

Apparatuses built with circus performance in mind are important from a safety perspective, even if the apparatus is simply "the ground", as mentioned in Section 2.1.3. Rose has also discussed safety concerns when designing her circus apparatuses [140]. As an example: I recently observed a handbalancer and a juggler attempt an impromptu performance wearing a biomusic device on the forefinger [171], [172]. The device monitored electrodermal activity, respiration, and heart rate, which influenced the production of three intertwining streams of

music. While an optimal form-factor for its intended user — those with "profound and multiple learning disabilities" (PMLD) and "profound intellectual and multiple disabilities" (PIMD) — the device obviously and markedly impacted the abilities of both performers. The prominent placement impeded the juggler's ability to catch; the balls often glanced off of the device and fell to the floor before the he was able to compensate for the new, erratic movement factor. Similarly, the handbalancer was noticeably impacted by the new obstruction on her hand; though a master handbalancer and able to compensate for the new constraint, it was clear the bulk of the device was adding strain to her finger and impacting her ability to fluidly correct her posture. For these particular cases, simply moving the sensor to a different location would significantly mitigate the negative impacts to the performers' abilities.

Hsu and Kemper's RAKS [113] system, Trubat's E-Traces [121], and Leischner et al.'s augmented juggling balls [138] come to mind as examples of apparatuses with physical components built with a specific type of performance in mind, as discussed in Sections 2.4.3 and 2.4.4. These apparatuses were created for specific disciplines — belly dancing, ballet, and juggling, respectively — which is reflected in their design. The modalities of each discipline were harnessed and repurposed to generate digital output: hip, torso, and chest movements within belly dance for RAKS; footwork within ballet for E-Traces; and juggling patterns for Leischner et al.'s juggling balls. While E-Traces could conceivably be used during belly dance, or RAKS could be used during juggling, the mismatch between intended and practical use could have unintended effects on performance, as exemplified by my observation of circus artists using the biomusic device intended for PMLD and PIMD users.

Furthermore, as originally mentioned in Section 2.5, in circus there is a strong connection between pedagogy and performance that can be easily lost if not intentionally considered. Contrary to similar disciplines such as yoga, gymnastics, and rock climbing, circus training is done with the intention of performance in an artistic setting. While gymnastics does have a performance component (competitions), the critical difference is that each gymnastics event is performed in a strictly regulated setting with strictly regulated equipment, whereas circus venues can vary drastically depending on the stage, setting, apparatus, and costume. As such, it is crucial that circus artists are able to train on the apparatuses they will be performing on.

Every circus artist I know has a close, personal relationship with their own individual apparatus. Where every balance beam has standard dimensions and height [173], each trapeze

is customized to its performer. Even if two performers are using dance (single-point) trapezes, the ropes may be made of different materials, the bar may be of different lengths, and the padding where the ropes meet the bar may differ. Similarly, even if a handstand can be done on any mat, the relationship the circus artist will have with an "analog" mat will not be the same as with a "digital" one. However, with significant and focused practice, the relationship between a performer and a particular apparatus can become akin to a symbiotic one. Regarding handstands, I believe sustained practice with a technologically enhanced mat would allow a handbalancer to begin to feel as if they are conversing with the mat through their weight shifts and the mat's output, similar to Sonami's experiences with the *lady's glove* and *Spring Spyre* (see Section 2.4.1.2). By internalizing the feeling of weight shifting influencing feedback, the performer can modulate the experience to intentionally trigger events while on stage. Barger's initial explorations with HAND⋆*CS*, found in Section 4.3.2, indicate a promising beginning to this desired relationship.

5.2.1 Why not use the music tech or recent dance tech umbrella?

As discussed in Section 2.4.1.2, The Hands revolutionized the music tech world, propelling music tech into the academic sphere and culminating in the establishment of the International Conference on New Interfaces for Musical Expression (NIME). However, while music tech has been a pioneer in the realm of interdisciplinary art-tech fields, it cannot cover everything. Music is a primarily sonic discipline, and while many projects can squeeze under the music tech umbrella, it is important that there be enough room for non-aural innovation and exploration. On its own, HAND does not fit within the category of music tech, and is too interdisciplinary for purely traditional engineering.

Dance tech and its focus on responsive footwear creeps closer to circus tech, with stage performance and dynamic movement at the forefront of the discipline. However, dance tech lacks some of the key characteristics that make circus unique, for example, the use of external apparatuses and a focus on up-side-down and other non-right-side-up movement.

5.3 The future of HAND and HAND⋆*CS*

HAND and HAND⋆*CS* are works in progress and provide ample opportunity for future development and use.

5.3.1 An in-depth longitudinal study

To truly gauge HAND's efficacy at handstand pedagogy, a longitudinal study could be devised to monitor participant handbalancing progress over a number of weeks, comparing participants who regularly use HAND against those who do not.

5.3.2 Expanding HAND's pedagogical space

Provided that HAND is useful for improving basic handstand posture, the software could be expanded to include feedback for handstand variations, such as Mexican, contortion, and one-arm handstands [174]. While HAND would not give feedback on the position of the body itself, it would still be able to correct the user's balance with regards to an ideal pressure distribution and balance point.

As mentioned in Section 2.1.2, Gatti has already done an analysis on the ideal center of mass in a one-arm handstand, taking into account different leg and non-supporting arm positions [36]. To be most effective in training for one-armed handstands, HAND's V1.1 glove design would be a useful starting point, as both hands received all corrections. However, more research would need to be done to assess optimal positioning and potential addition of actuators. For example, it could be beneficial to assign one actuator per finger, as each finger gains significant control when switching from a two-handed handstand to a one-handed one. It might also be helpful to improve the spacial resolution of the pressure-sensing mat, to be able to more precisely measure and calculate the pressure distribution across a single hand. Otherwise, the calculation would remain similar to HAND's current implementation, though it would switch from a between-hands comparison to a within-hand comparison.

5.3.3 Collaborating with sports medicine practitioners

Circus is incredibly demanding on the body, yet circus performers are expected to perform multiple times a week, possibly even twice a day during a performance run. As such, injury prevention is a major concern. As mentioned by Participant 3, HAND was able to make corrections in line with rectifying a long-standing posture imbalance that had resulted in injury. Though spotters and coaches may provide adjustments in real-time, it is possible HAND may be able to detect asymmetries difficult to notice with the eye. Furthermore, as discussed in Sections 2.2.1 and 2.2.3, when learning new kinesthetic movements, artists must fully concentrate the movement while also receiving constant feedback, and light touch can help reduce feedback time delay of posture imbalances. These considerations lead to the conjecture that HAND could help handbalancers better internalize such corrections while training alone. Future studies of HAND could be done in collaboration with sports medicine practitioners to assess and monitor potential areas of risk and injury.

5.3.4 Porting HAND⋆*CS* to an open source language environment

As mentioned in Section 4.2.2.3, the current iteration of HAND⋆*CS* uses Cycling '74's Max, a proprietary and moderately expensive software system, costing $174 per year or $578 for a permanent license. Furthermore, users of proprietary software are held hostage to vendor upgrades, which are often mandatory, and often break existing codes written using previous versions of the software. A more attractive alternative, when available, is the use of open source software. For example, Pure Data [168] is free and open source, and would allow for easier collaboration with, and innovation from, other circus artists and musicians.

5.3.5 Augmenting HAND⋆*CS* for more expressive range and device collaboration

As a prototype, the preliminary design of HAND⋆*CS* was kept simple for feasibility of execution, but there is significant potential for improvement.

5.3.5.1 Visual interest

The current design provides limited visual interest in terms of responding to muscle activation, and could use a redesign with added intricacy, to provide more meaning to an audience.

5.3.5.2 Finer control and broader contexts

Expanding the algorithm sensitivity to use individual finger control, as discussed above in the context of individual finger feedback for training in one-arm handstands (see Section 5.3.2), could increase responsiveness and improve musical range. Furthermore, expanding the contextual range to include not only solo handbalancing, but groups of interchanging handbalancers and partner acrobatics acts would amplify HAND⋆*CS*'s adaptability. As weight limit is of no immediate concern (see Section 3.2.2.1), supporting a broader range of performance contexts would benefit HAND⋆*CS*'s performance potential and overall increase responsiveness, especially with further modulation complexity.

5.3.5.3 More complex modulation

It could also be beneficial to allow co-modulation of sound and light events through both muscle activation and pressure data. Additionally, as mentioned in Section 4.3.3, the addition of ML could elevate HAND⋆*CS* such that the apparatus could learn from the performer and vice versa, such as with Sonami and *Spring Spyre*. The sonic mapping choices and thresholds at this stage are still somewhat generic in order to demonstrate the proof of concept. For a performance or specific piece, next steps would involve a more precise calibration of the data range output for a specific performer or group of performers to an expressive output or outputs. Sonami and Fiebrink's approach with *Spring Spyre* and ML facilitates this kind of calibration in a more dynamic and organic way, which would be intriguing to explore in HAND⋆*CS*. The dynamic aspect of this method of calibration encourages an expressive dialogue between the performer, apparatus and creative output in real-time. It also allows the mapping paradigms to extend to more than one type of media, e.g., music, lighting, and graphics.

5.3.6 Performing with HAND⋆*CS*

To help in identifying which additions and enhancements to HAND⋆*CS* might resonate most strongly with audiences both within and without the circus community, a solo performance could be choreographed and performed, ideally in collaboration with a professional circus performer. Feedback could then be solicited from the performer and from a variety of viewers, for use in further development and adjustments aimed at improving the performance capabilities

of the HAND⋆*CS* system.

5.3.6.1 A proposed performance: *Stasis*

It would be intriguing to gauge audience engagement using a performance with minimal movement, in other words, a performance in static equilibrium or stasis, to see how much engagement HAND⋆*CS* alone can foster. Jensenius has explored this concept, though with upright performers, to research and develop micromovement-based performances [175]. In this related conceptualized performance, an expert handbalancer should be able to perform a straight body handstand with minimal movement, while still almost imperceptibly shifting their weight to trigger sound and light events. Through the weight shifting, the handbalancer would also be involuntarily firing various arm muscles, thereby triggering different visual events. By taking the handstand itself out of the equation, the audience would be left to engage with only the creations of HAND⋆*CS*.

Chapter 6

Conclusions

Circus tech is still in its infancy, but what has emerged so far has solidified its value as a field. Establishments such as CRITAC and the *Circus: Arts, Life and Science* journal demonstrate the small but growing desire for dedicated academic circus research. This thesis contributes to this new field by presenting a training and performance device for handbalancers, HAND and HAND⋆*CS*.

In developing HAND and HAND⋆*CS*, several prototypes were designed and engineered. These prototypes leveraged open source and existing technologies as well as participatory design and lived experiences to create a pedagogical tool and performance apparatus designed specifically with handbalancing in mind. Not only did these projects explore technological aspects, but they included significant consideration and development for implementation and usefulness in applied practice. A study was developed and conducted to evaluate the pedagogical side, a demo was created for the performance side, and both are promising topics of future studies that will extend beyond the scope of this thesis.

HAND has demonstrated that the addition of technology to handbalancing training can point out and correct between-hands pressure discrepancies which could, with future refinement, help correct posture when training in various handstand styles. In addition, HAND⋆*CS* has established a way of extending the HAND training apparatus into a performance apparatus, by taking the existing pedagogical methods of data collection and usage and transforming them into performative outputs. Collaboration with both a music technologist and a handbalancer indicated promising future explorations within the domain of music tech, especially

with regards to allowing for more creative freedom and impromptu improvisations on stage while maintaining sonic cohesion. In particular, following Sonami and Fiebrink's example with *Spring Spyre*, the addition of ML would further expand HAND⋆*CS*'s range and symbiotic potential with its performer. On stage, the demystification of handbalancing that HAND⋆*CS* attempts to provide may help audiences better connect to and appreciate performers on stage.

While there remains much to explore — as evidenced by the several proposed future directions in Section 5.3 — the explorations so far with HAND and HAND⋆*CS* have continued to legitimize circus tech as a valid specialization that can both synthesize research from, and provide new connections within, multiple existing fields, including but not limited to engineering, music technology, and performing arts.

Appendix A

HAND Documentation

A.1 GitHub repository

https://github.com/linneakirby/HAND

A.2 Pre-test questionnaire

What is your participant ID?

How old are you?

- ☐ Under 18
- ☐ 18-24
- ☐ 25-34
- ☐ 35-44
- ☐ 45-54+
- ☐ Prefer not to say

Which option best describes your gender?

- ☐ Woman
- ☐ Man
- ☐ Non-binary
- ☐ Prefer not to say

Which option best describes your occupation?

- ☐ Professional circus artist
- ☐ Something movement-based that is unrelated to circus arts (e.g. personal trainer, athlete, dancer, etc.)
- ☐ Other

How long have you been seriously training handstands?

- ☐ Less than 1 year
- ☐ 1-3 years
- ☐ 4-6 years
- ☐ Over 7 years

Which of the following best describes your handbalancing background?

- ☐ I am a handbalancing professional.
- ☐ I have been formally trained in handbalancing but I am not a handbalancing professional.
- ☐ I am currently being formally trained in handbalancing.
- ☐ I have been formally trained in a discipline adjacent to handbalancing (e.g. gymnastics, yoga)
- ☐ I have not been formally trained in handbalancing/I taught myself.
- ☐ Other (specify):

Which of the following tool(s) do you prefer/use for handbalancing?

- ☐ Blocks
- ☐ Canes
- ☐ Parallettes
- ☐ Wooden board/bench
- ☐ Yoga mat/thin mat
- ☐ Other (specify):

Which method(s) of feedback do you prefer/use for handbalancing?

- ☐ Instructor (Classroom Setting)
- ☐ Instructor (Personal)
- ☐ Instructor (Personal - Remote Setting)
- ☐ Friend/Spotter
- ☐ Videorecording yourself while training
- ☐ Other (specify):

What, if any, difficulties have you faced while training handbalancing?

Have you ever used any interactive technology while handbalancing? If so, how was the experience?

Have you previously used any wearable haptic devices?

- ☐ Yes
- ☐ No

A.3 Post-test questionnaire

Did wearing the haptic gloves assist you in your process of moderating the weight distribution between your hands? Why or why not?

Would you prefer to use haptic feedback to assist you in handbalancing in the future?

Do you have any other suggestions or comments?

Appendix B

HAND⋆*CS* Documentation

B.1 HAND⋆*CS* demo video

https://youtu.be/ePlOPTdzB7A

B.2 GitHub repository

https://github.com/linneakirby/HAND

The HAND⋆*CS* Python module and Max patch are located within the HAND repository.

Appendix C

Currently Available Circus Resources

Due to differences in interests among circus professionals, including desired skillset and technique [21], [176], [177], there is a lack of peer-reviewed research using circus artist participants. The closest comparison to be made is to gymnasts and dancers, but those fields still do not provide the full picture for circus arts [41].

C.1 Online circus dictionaries and encyclopedias

A few organizations have attempted to compile databases of circuses, circus history, and circus moves. *Circopedia* was founded in 2007 by *Big Apple Circus* with the goal of "us[ing] the Internet to help the public better understand and appreciate circus as a global artistic and cultural phenomenon, embracing both the populist nature of the circus and the democratic technology of a free-access web archive" [178]. *The Circus Dictionary* and *Acropedia* both compile entries of circus-related moves with visuals in order to document and standardize the names of circus-related moves [174], [179]. Both dictionaries, however, are far from being comprehensive resources. *The Circus Dictionary* significantly lacks information such as text descriptions; static images; alternate names; transitions into or out of moves; progressions; tips and tricks; safety warnings; and examples within performances. It is also limited in disciplines covered, lacking common apparatuses such as dance trapeze, cloud swing, tightwire, and trampoline. *Acropedia* concentrates solely on partner acrobatics, which has communities entirely separate from the circus world [180].

C.2 Circus libraries and library collections

A handful of libraries and library collections dedicated to circus arts and history exist, but their selections do not specifically focus on circus research. These notable collections such as the *Milner Library's Circus and Allied Arts Collection* at Illinois State University, *Circus World's Robert L. Parkinson Library and Research Center*, and the *National Circus School (École national de cirque) Library* broadly include any topic related to circus such as circus history, technique, and performance documentation [181]–[183].

C.3 Circus Research Network

The Circus Research Network is an email list-serve created in 2016 that "exists to promote and facilitate research relationships between circus practitioners and researchers" [184], in particular those in Britain and Ireland. In its current state it is as difficult to navigate and as inefficient to search through as an email archive.

C.4 Circus Arts Research Platform and associated journal

The Circus Arts Research Platform (CARP), founded in 2018, attempts "to compile an international, accessible bibliography of academic publications related to circus arts studies" [185], yet their thematic bibliographies lack a section for handbalancing, handstands, or inversions, and "circus medicine" is the closest thematically to any topic relating to circus and computers or engineering. Navigation to the "Journals" tab on the CARP website redirects the user to the homepage of *Circus: Arts, Life and Science*, a new journal that published its first issue in December 2022 [186].

C.5 Independent professional circus artists

Some professional circus artists interested in circus science and pedagogy conduct their own informal research and write articles on personal blogs. Prominent examples include Chris Gatti, Megan Gendell, Jen Crane (Cirque Physio), Fleur van Rens, and Catie Brier [187]–[191]. While

these blogs are undoubtedly invaluable to other circus artists, they are not peer reviewed and contain few or no sources.

C.6 The beginnings of scientific circus research

In 2011, the European Federation of Professional Circus Schools (FEDEC) found a lack of standardization within circus pedagogy, specifically with regards to instructor training [21]. As a consequence, the INTENTS project was launched in 2014 with the goal of creating some kind of standardization within circus pedagogy, and in 2017 they published a pedagogical guide titled "Support and Alignment: In Search of Balance" [192].

In 2013, the National Circus School (*École nationale de cirque*), located in Montréal, officially created the Center for Research, Innovation and Knowledge Transfer in Circus Arts (CRITAC) with the mission "to enhance human potential and performance through applied research and innovation in order to support the socio-economic development of Quebec" [193]. The CRITAC team has published various articles, reports, and chapters in venues ranging from internal reports to web magazines to scientific journals. A few years later, the Montreal Working Group on Circus Research was formed and soon became a research partnership between Concordia University and the National Circus School [194], [195].

Their goal is threefold: 1. preservation of circus knowledge and technique, 2. spreading circus-related research throughout academia and industry, and 3. advocating for multidisciplinary approaches to circus-related research.

Academic journals have slowly begun integrating circus research into their publications as well. Aside from the aforementioned Publications such as *w/k — Zwischen Wissenschaft & Kunst* [196] provide a platform for circus scientists to showcase their research.

Appendix D

Lower versus Upper Limb Structure, Function, and Stability

It is usually impractical to compare the functionality of the lower and upper limbs due to their functional and structural differences [197]. However, because the shoulder replaces the hip, the elbow replaces the knee, and the hand replaces the foot while handbalancing, it is critical to examine the function of the lower limbs and assess any adaptations that must be made by the upper limbs when superceding their functions.

D.1 Hip versus shoulder

Dynamic joint stability is the capacity for a joint to remain stable while withstanding significant fluctuating forces [24]. Lack of sufficient dynamic joint stability can lead to injury, especially when combined with poor postural control [198]. While both the hip and shoulder are ball and socket joints, the hip joint contains a cave-like socket for the femoral head called the acetabulum and a more significant joint capsule, resulting in increased stability compared to that of the shoulder [197]. Because the shoulder has the additional function of providing a wide range of motion for the hand and contains the body's most flexible joint — the glenohumeral joint — it relies significantly on dynamic stabilization through the surrounding muscles and ligaments [199].

D.2 Ankle versus wrist

The ankle and foot correspond structurally to the wrist and hand, but are constructed differently for functionality purposes [200]. The foot's purpose is to bear weight, provide stability, absorb shock, and withstand stresses on a wide range of surfaces [200]. Where the ankle consists of a single hinge joint with one primary degree of freedom, the wrist is considered to be the most complicated joint of the body [37], [200]. The radius and ulna in the arm add to the wrist's range of motion, whereas the tibia and fibula in the leg do not increase the ankle's range of motion; instead, their stability is integral to the ankle's normal range of motion [37], [200]. Finger range of motion and strength are contingent upon wrist position and vice versa [201].

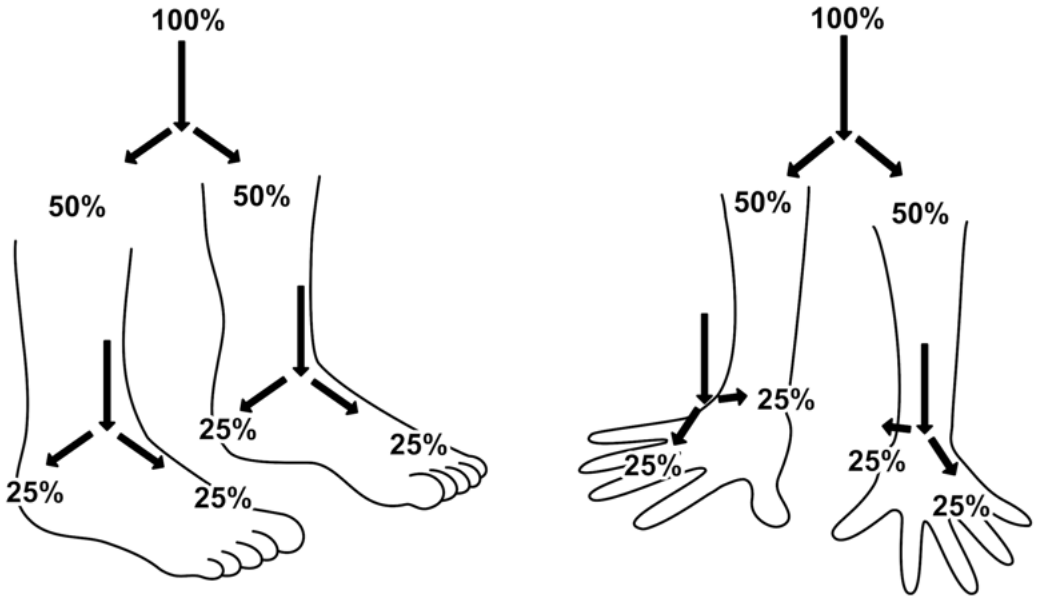

Figure D.1: Weight distribution comparison between feet and hands when balancing. Note that the 50% of the total weight is centered on each foot or hand while in a basic standing position. The foot distribution is referenced from Levangie and Norkin [19] and the the hand distribution is extrapolated from the lower limb anatomical analogues.

D.3 Foot versus hand

Within the palm of the hand exist the carpometacarpals — interconnected extensions of the fingers — and, correspondingly, within the ball of the foot exist the tarsometatarsals — interconnected extensions of the toes. The tarsometatarsals help the toes and ball of the foot hollow and flatten in order to adjust balance and positioning on a surface [200]. Correspondingly, the carpometacarpals do the same for the fingers and palm of the hand while in a handstand.

The foot develops its three permanent plantar arches through weight-bearing, i.e., while learning to stand and walk [200]. Should the center of pressure travel too close to the front of the foot, the toes activate to slow and then reverse this change in center of pressure [200]. It makes sense then, that classic handstand technique advises the fingers to actively press into the ground to prevent "overbalancing;" i.e., when the center of pressure travels too close to the tips of the fingers.

Not only do handstand blocks allow for a greater extension of the wrist (as mentioned in section 2.1.2), they also allow the hand to create more of a grip shape, which activates the palmar arch system and allows the palm and fingers to achieve maximal stability by maximizing surface contact [37]. Stability while standing is maintained in great part by the toes actively pressing against the ground [200] and so, analogously, the fingers must do the same while in a handstand position.

Appendix E

The benefits of haptics for balance and posture correction

E.1 What is haptics and why use it?

Haptic devices use the sense of touch to convey information. Haptic feedback has been shown to be viable during activities where audio and visual feedback may be hard to communicate in real time, difficult to hear or see, or even distracting [54]. Additionally, using either an audio or visual channel as feedback obstructs the sense for alternative use [53]. As usage of the hands is almost always under visual supervision [201], it would be a significant hindrance for any hand-specific task to require visual feedback in particular. While visual feedback could be placed on the hands, this method would only be viable for straight-body handstands where the optimal head position is at an angle conducive to looking at the hands. Any other position would require visual feedback in some other optimal location, e.g., in the case of a contortion handstand, the opposing wall. A viable alternative is the use of haptic feedback; i.e., feedback to one's sense of touch, especially considering response time to haptic feedback may be faster than responses to verbal feedback [54].

The human body has two main systems used to detect haptic feedback: tactile (cutaneous) and kinesthetic (proprioceptive) [147]. Cutaneous input is easily recognizable as haptic: pokes, prods, vibrations, tickles, and any other tactile sensation perceived by the skin. Proprioception has already been discussed in Section 2.1, but to reiterate: kinesthetic input is

movement and positioning of the body, its joints, and any forces upon them. Different types of haptic feedback are discussed more in depth in Section E.3.

E.2 Mechanoreceptors

Before comparing haptic tools, it is important to first understand how the body senses haptic feedback. Hands are surrounded by two categories of skin: glabrous (hairless) on the palms and hairy on the backs. Glabrous skin contains four types of low-threshold mechanoreceptors (LTMs), specialized nerve endings that detect cutaneous inputs [202]–[204]. Note that the hand also contains two types of high-threshold mechanoreceptors (HTMs) — used to detect pain — and four types of proprioceptive afferents, which share information processing regarding finger positioning and hand shape [203], [205]. All mechanoreceptors aid with stable and accurate grasping, but they also have specific functions and varying speeds of adaptation to input. Each mechanoreceptor has an afferent neuron which brings information to the central nervous system (CNS) (as opposed to efferent neurons, which transmit information from the CNS). Additionally, mechanoreceptors have different sizes of receptive fields — the surface area on the skin where the mechanoreceptor can detect input.

Meissner corpuscles are located in dermal ridges just under the epidermis — the topmost layer of the skin — and are the terminus of rapid-adapting (RA) afferents [203], [206]. They have a small receptive field (22 mm^2) and are quick to adapt to input [204]. While they are not able to detect stable deformations of the skin, Meissner corpuscles are excellent at recognizing dynamic changes, especially low-frequency vibrations in the 5 Hz to 40 Hz range [202], [206]. Additionally, Meissner corpuscles play an important part in grip, as their dynamic change detection aids in their ability to monitor the status of held objects, e.g., whether an object is slipping from the hand or if an outside force is acting upon a grasped object [204], [206].

Merkel cell complexes begin in the dermis — located beneath the epidermis — and their slow-adapting type 1 (SA1) afferents wind their way through the epidermis [206]. They have a small receptive field (9 mm^2) and adapt slowly to input [204]. SA1 afferents are only a fourth as sensitive to skin deformation as RA afferents [206]. They are related to finger precision; are best able to detect sustained, low-frequency vibrations in the <5 Hz range; and coarsely determine texture, especially in relation to points, edges, and curves [202], [204].

Ruffini endings are more ovular and are located in the dermis; they have a relatively large receptive field (60 mm^2) and are slow to adapt to input [204]. They are preceded by slow-adapting type 2 (SA2) afferents, which are five times the size of SA1 afferents, as well as only a sixth as sensitive to skin indentation; however, they are especially sensitive to skin stretch [206]. Because they are less sensitive to depression, SA2 afferents are able to send almost pure skin stretch perceptions to the CNS, which in turn converts the sensations into object directionality and force information as well as finger positioning [202], [206].

Pacinian corpuscles are the largest mechanorecepors and are located in the subcutis —— the deepest layer of the skin. Pacinian (PC) afferents are found throughout the hand at approximately 350 afferents per finger and 800 afferents per palm [206]. They have a large receptive field (entire fingers and hands) and are quick to adapt to input [204]; they are best at detecting high frequency vibrations in the 40 Hz to 400 Hz range and perceiving finely-grained textures [202]. PC afferents are twice as sensitive to skin deformation as RA afferents — they can detect a stimulation varying at 200 Hz within an area of $\leq$10 nm — and aid the corpuscles by significantly filtering the low-frequency input [206]. These receptors allow us to perceive texture at one end of a tool even when gripping the opposite end. For example, by grasping a stick at one end and dragging the other end across a picnic table, one can get a sense of the wood grain texture and the gaps between boards.

The cutaneous system sends sensations to the brain, which then attempts to interpret them; however, this system is by no means perfect. One key phenomenon in human touch perception is the two-point touch threshold, which is the smallest distance on some area of the body where two different stimuli can be reliably discriminated, e.g., 2 mm to 4 mm on the fingertip versus 20 mm to 40 mm on the top of the foot [202], [207]. Since the distribution of mechanoreceptors differs by body part, the two-point touch threshold will also differ accordingly.

E.3 Types of haptic feedback

There are two major categories of haptic feedback: vibrotactile and force-feedback. Section E.1 briefly described the tactile (cutaneous) and kinesthetic (proprioceptive) systems used to detect haptic inputs. As may be expected, vibrotactile and force-feedback correlate with these two systems.

Vibrotactile input uses vibrations in various amplitudes, frequencies, and durations to communicate information through actuators: small mechanisms that can turn on and off on command to provide discrete haptic sensations (vibrations, in the case of vibrotactile actuators). Vibrotactile "languages" made up of discrete, information-carrying "tactons" have been documented as early as 1957 [208]. Notably, it is not inherently necessary to increase the number of actuators in order to increase the number of tactons; adding a new parameter to each tacton may allow the use of one actuator while still encompassing a significant range of information delivery [209]. Tacton parameters may include amplitude, frequency, vibration pattern, and duration. With vibrotactile feedback, users can be alerted to events such as incoming text messages, enemy encounters in video games, or an alarm silently ringing.

Force-feedback uses pushing and pulling sensations to direct and react to a user. Using force-feedback, a museum-goer can "feel" a delicate artifact; a visually-impared user can haptically explore graph data; and medical students can prepare for surgeries through simulations that feel realistic [210], [211].

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