Foot-based Haptic Interfaces for Numeric Information Delivery and Dance Learning

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Abstract

Humans are skilled in sensing their surroundings via touch; they perceive variations in pressure, texture, and force through sensory receptors. Haptic interfaces leverage this ability and use the skin as a medium for communication. Among other body locations, the feet offer an unobtrusive site for communication through haptics. Owning to their richness of sensory receptors and role in locomotion, they can be used either as a location for displaying semantic information or conveying guidance cues relevant to any physical activity. Several foot-based haptic interfaces have been proposed for applications such as navigation, fitness-tracking, and dance learning. However, they are limited by the range of information they can communicate effectively. Most of these designs use multi-actuator placement on the plantar surface of the feet, which leads to the propagation of haptic stimuli, hence reduced recognition rate.

For effectively conveying a broad set of information with low cognitive load and a high recognition rate, there is a need to employ well-separated sites for actuator placement. The toes have similar anatomical and neurophysiological properties such as fingers, hence, they could serve as a favorable location. Hence, as the primary focus, this thesis explores the usability of toes as a ten-unit tactile display. Toes have not been explored earlier for haptic communication due to their reported susceptibility to erroneous perception. We hypothesize that this can be mitigated by careful design of the tactile encoding, increasing the perceptual accuracy of stimuli rendered on toes. To evaluate our approach, we first performed a perception study on the fingers and toes and later tested the encoding for conveying numbers. The results prove that the ten-unit tactile toe display is viable for conveying information.

Foot-based haptic interfaces can not only serve as a discreet information display but can also facilitate the process of learning any physical activity. Although several activities can benefit from haptic-assisted guidance, we focused on dance. Novice dancers often face difficulty in learning fundamental elements of dance movements, such as spatial footwork, rhythm, and weight transfer, which could be resolved by personalized guidance through foot-based haptic interfaces. Hence, as the secondary focus, this thesis presents a novel design of haptic-augmented shoes for dance learning and discusses the overall development of a foot-based haptic guidance system.

Résumé Scientifique

La capacité des humains à percevoir leur environnement par le toucher est exceptionnelle; ils perçoivent les variations de pression, de texture et de force grâce à une panoplie de récepteurs sensoriels. Les interfaces haptiques exploitent cette capacité et utilisent la peau comme canal de communication. Dans l'éventail d'emplacements possibles, les pieds offrent un site discret pour la communication par l'haptique. Grâce à la richesse de leurs récepteurs sensoriels et à leur rôle dans la locomotion, ils peuvent être utilisés comme lieu de présentation d'informations sémantiques, ou pour la transmission de signaux de guidage dans un contexte d'activité physique. Plusieurs interfaces haptiques basées sur les pieds ont été proposées pour des applications telles que la navigation, le suivi de la condition physique et l'apprentissage de la danse. Toutefois, elles sont limitées par la gamme d'informations qu'elles peuvent communiquer efficacement. La plupart de ces systèmes utilisent plusieurs actuateurs sur la surface plantaire des pieds, ce qui entraîne une propagation indésirable de stimuli haptiques, et donc un taux de reconnaissance réduit.

Pour transmettre efficacement un large éventail d'informations tout en minimisant la charge cognitive, il est nécessaire d'utiliser des sites de stimulation distincts où placer les actuateurs. Les orteils ont des propriétés anatomiques et neurophysiologiques similaires à celles des doigts. Conséquemment, ils pourraient constituer un site prometteur pour une interface de communication haptique. Pour cette raison, ce mémoire explore la possibilité d'utiliser les orteils dans une interface tactile de dix unités. Les orteils ont peu été étudiés dans un contexte d'interface haptique car il peut être difficile de reconnaître avec précision l'orteil qui est stimulé. Nous émettons l'hypothèse que ce problème peut être atténué par une conception minutieuse du codage tactile, augmentant la précision perceptive des stimuli présentés sur les orteils. Pour évaluer notre approche, nous avons d'abord effectué une étude comparative de la perception des doigts et des orteils, puis nous avons testé un nouvel encodage utilisé pour la communication de nombres. Les résultats démontrent que l'interface tactile à dix unités sur les orteils est viable pour transmettre des informations.

Les interfaces haptiques basées sur le pied peuvent non seulement servir d'affichage d'informations telles que des nombres, mais elles peuvent également faciliter le processus d'apprentissage d'activités physiques. Bien que plusieurs activités puissent bénéficier de l'assistance haptique, nous nous sommes concentrés sur la danse. Les danseurs novices éprou-

vent souvent des difficultés à apprendre les éléments fondamentaux des mouvements de danse, tels que le jeu de pieds, le rythme et les transferts de poids, qui pourraient être résolus par un guidage personnalisé grâce à des interfaces haptiques basées sur les pieds. C'est pourquoi, en tant que thème secondaire, ce mémoire présente une nouvelle conception de chaussures haptiques pour l'apprentissage de la danse et discute du développement global d'un système de guidage haptique basé sur le pied.

Acknowledgements

"No one can whistle a symphony. It takes a whole orchestra to play it."

— H.E. Luccock

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“If you don’t like how the things are, change it!”
– Jim Rohn

Chapter 1

Introduction

Humans are nearly dependent on visual or auditory channels for their interactions with technologies. Indeed the eyes and ears are often overburdened with information. Haptics—the interaction technology based on the sense of touch—can play a significant role in this situation. Several researchers have explored haptics for applications in communication, immersion, and guidance.

As the sensory receptors cover the human body from head to toe, one can explore various locations while designing haptic interfaces. However, the non-uniform distribution of these receptors across the body causes variability in the tactile perception. Owing to the high density of receptors, the hands can be a good site for haptic communication, but they are often occupied during day-to-day tasks. In this case, the feet, which consist of similar sensory receptors, can serve as an alternative for haptic rendering. The feet have better tactile sensitivity, when compared to the other locations explored in prior research, such as arms, legs, and back. Moreover, the interfaces designed for feet can be easily embedded in shoes or insoles, making the interaction unobtrusive and discreet.

The foot-based haptic interface has been explored as an input as well as an output device—the input signals are registered through several pre-defined gestures of the feet, for example, sliding the feet increases the volume in a music app; and the output signals are presented through haptic cues, either real-time to inform the user about their inputs or at defined intervals for conveying information relevant to specific applications, such as navigation, progress tracking, dance learning and gait training. In previously explored use cases, the information rendered by these haptic cues has been limited; for example, current foot-based navigation systems can only convey a set of directions but not distance to the location or time of arrival.

If we can expand the abilities of haptic foot-based interfaces to convey broad range of information such as numbers, we can add to their possible applications. This will benefit foot-based navigation systems, fitness tracking, hospital alarm systems, control room monitoring systems, and user-interface controllers. In order to realize this objective, we require haptic patterns that can represent such information. However, in this case, there is a trade-off between the size of the actuator array and complexity of rendering; for example, a four-actuator haptic display can easily convey directions as compared to a single actuator. Hence, conveying information with less cognitive load would require the use of multiple sites for haptic actuation on feet.

While considering different sites on the feet for information delivery tasks in which numerosity is the dominant concern, we assume that the toes can serve as a favourable choice. They are well separated and have similar neurophysiological properties as fingers. Moreover, we can use them as an ordered ten-unit haptic display and design either spatial or spatio-temporal rendering for conveying a broad set of information. Despite these advantages, researchers have dismissed the viability of toes as an alternative for haptic communication, given their low tactile discriminability. We expect that a deliberately designed haptic encoding can mitigate this issue. This motivates the primary research focus of this thesis wherein we explore the usability of toes as a possible rendering location on the feet and design haptic patterns suitable for conveying numeric information.

Apart from conveying information, foot-based haptic interfaces can also play a significant role in training lower-body motor skills. The feet are an essential part of the body responsible for locomotion. The sensory receptors on the sole gather information about the variations in force, texture, and patterns and inform the central nervous system, which in turn sends control signals to motor muscles and helps in maintaining balance and posture. While learning any motor activity, this connection between sensory and control units develops over time. If we need to build a guidance system for motor learning in physical activities, using the feet as a location for sensing motion and providing feedback would be very appropriate.

Although foot-based haptic guidance systems can facilitate several physical activities, this thesis focuses mainly on dance. As dance is a form of art involving complex movements, postures, and control strategies, a haptic-based guidance system can prove helpful in training novice dancers. Prior works have demonstrated dance guidance systems that considered the elements of direction or rhythm; however, they have not explored weight transfer training, which is essential to inform balance and posture. We consider these three elements of dance learning to design haptic-augmented shoes that can sense different parameters of movements and provide relevant guidance cues. This formulates the secondary research focus of this thesis, where we present a prototype of haptic shoes and discuss an overall design of the haptic-assisted guidance system for dance learning.

1.1 Thesis Overview

This thesis is organized in six chapters: this introduction, a review of prior literature, two previously published manuscripts, a chapter on a work-in-progress project and conclusion.

Chapter 2 provides a general discussion on haptic perception in the human body and a specific survey of prior perception studies on the feet. It reviews the research on haptic communication and presents several methods used by researchers to convey abstract and semantic information. Following the general discussion, it highlights the applications of haptic guidance system and semantic information delivery through feet. Lastly, it presents the earlier designs of foot-based haptic interfaces and discusses their limitations.

Chapter 3 explores the toes as a possible location for multi-actuator tactile rendering. It discusses their inferior performance, in terms of tactile perception, relative to the fingers and introduces a tactile toe encoding to reduce this difference. We evaluate the performance of this encoding against the default tactile rendering on the toes and the fingers. The results suggest that our encoding increases the perceptual accuracy of toes and makes it similar to that of fingers; this justifies the usability of tactile toe interfaces.

Chapter 4 discusses the application of the tactile toe display for conveying numeric information, as a continuation of the work discussed in Chapter 3. It introduces HapToes, a haptic numeric rendering technique for toes and compares its performance against ActiVibe, a previously presented method. Our method shows equivalent performance while rendering single values and establishes superiority when conveying three values.

Chapter 5 focuses on the high-level application of foot-based haptics in facilitating dance learning. It presents a new design of haptic-augmented shoes and an overview of the haptic-assisted guidance system for novice dancers.

Chapter 6 concludes this thesis with a comprehensive summary and discusses the directions for future research.

1.2 Summary of Contributions

As a primary contribution, this thesis demonstrates the usability of toes as an ordered ten-unit tactile display; this can significantly increase the extent of information communicated via the feet. As a secondary contribution, it presents a novel design of haptic-augmented shoes for facilitating dance learning; this adds to the research direction of haptic-assisted guidance and motor learning.

Chapter 2

Background

This chapter presents an overview of literature relevant to this thesis. First, it discusses the fundamentals of haptic perception in the human body, which inform the design of haptic interfaces and then it reports the prior work on haptic communication narrowed down to haptic guidance systems and semantic information rendering on feet. At the end of this chapter, prior designs of foot-based haptic interfaces are discussed. Further review of specific background is provided in Sections 3.1, 3.2, 4.1 and 4.2 of the following chapters.

2.1 Haptic Perception

The human body is covered with mechanoreceptors that sense changes in vibration, pressure, temperature and texture; and communicate them to the central nervous system (CNS) [5]. They are broadly of four types—Meissner's corpuscle, Merkel cell, Pacinian corpuscle, and Ruffini endings. Pacinian and Meissner's corpuscle rapidly adapt to the tactile stimuli and inform the CNS only when there is any change; they are called fast adapting (FA) receptors. Merkel cell and Ruffini endings continuously fire signals to the CNS and do not quickly adapt to the tactile stimuli; they are called slow adapting (SA) receptors. Each mechanoreceptor provides a particular set of tactile information to the CNS.

- **Meissner's corpuscle (FA I)** Light touch, grasp, vibrations between 40–60 Hz
- **Pacinian corpuscle (FA II)** Rapid vibrations between 200–300 Hz
- **Merkel cell (SA I)** Fine tactile details, form, texture, sustained pressure

- **Ruffini endings (SA II)** Skin stretch, tension, direction of motion, shape, position

The mechanoreceptors are distributed non-uniformly across the body. The fingers have a high density of receptors, hence, better two-point sensitivity [6]; this makes them a favourable candidate for haptic rendering. Although feet have comparatively less tactile sensitivity, researchers have explored them as an alternative when fingers cannot be used or availing of any other body location is obtrusive.

Kennedy *et al.* [7] examined the distribution of cutaneous mechanoreceptors on the feet. They reported the presence of large receptive fields on the plantar surface of the metatarsal region and wide distribution of the receptors across the feet without any specific concentration on the toes; this is unlike the hands, which have comparatively smaller receptive fields and accumulation of receptors on the fingers. These observations are natural because feet are generally involved in balance control and weight-bearing actions, where they do not require high tactile precision as hands.

Perry [8] reported the vibrotactile perception on four plantar locations—big toe, first metatarsal head, fifth metatarsal head, and heel. Researchers have considered these locations while designing haptic insoles and shoes [2, 9]. Although the plantar side has favourable tactile sensitivity, it allows for vibration propagation due to large receptive fields; this can be avoided by selecting well-separated locations in the plantar as well as the dorsal side of the feet. Hennig *et al.* [10] studied the sensitivity mapping of the human foot and performed an analysis at 30 plantar and dorsal locations. This work informed the actuator placement in our haptic-augmented shoes discussed in Chapter 5.

As the toes are well separated digits and have considerable sensitivity [10], they may seem a plausible candidate for tactile communication, but this is not the case. The perception studies performed by Cicmil *et al.* [11] and Manser *et al.* [12] reported their high mislocalization errors during tactile discrimination. Most of these errors were amongst the middle toes, and there was a directional bias associated with them; the second and third toes were biased towards the little toe, whereas the fourth one was biased towards the big toe. Cicmil *et al.* [11] concluded that this confusion might be because the body image incorrectly treats the toes as if they are of equal size. Resolving this confusion might facilitate the use of toes as a ten-unit tactile display for haptic communication; this motivates the design of tactile toe encoding presented in Chapters 3 and 4.

2.2 Haptic Communication

The community with vision and hearing impairment has been communicating through the sense of touch. In a method called *Tadoma* [13], they perceive speech by placing a hand on the face of the talker and monitoring facial actions associated with speech production. Using *Braille*, a tactile language, they read alpha-numeric characters through patterns of embossed dots. Hence, it is evident that the humans can be trained to perceive semantic information through touch.

Researchers have explored haptic communication at several levels—starting from a high-level rendering of a limited set of messages or cues [14, 15, 16], moving towards phoneme-based speech communication [17, 18, 19] and eventually a low-level rendering of alphanumeric characters [20, 21, 22]. In all these levels, they conveyed information through a differentiable, identifiable, and learnable set of tactile icons, often termed as *tactons*. To design these tactons, they employed single or multiple actuators at preferred locations and used variations in signal parameters such as amplitude, frequency, and duration. Brewster and Brown [23] discussed this design methodology, and provided an overview of parameters' range suitable for human perception.

Prior work provide evidence that these tactons can be easily learned and identified in real-world conditions. Hoggan and Brewster [24] explored crossmodal icons and discussed how users trained with audio modality could easily recognize tactile messages. Chan *et al.* [15] tested the learning and identification of tactons in workload conditions.

Most of the researchers used the upper body locations—hands [22], arms [17], and back [20]—to render tactile stimuli. Placing haptic actuators on the upper body may seem obtrusive or affect the natural work-flow. Hence, several researchers [2, 14] have explored feet as an alternative location, where these actuators can be discreetly embedded in footwear. As the feet play a significant role in locomotion, foot-based haptic communication has been used to facilitate guidance [25, 26] and learning [27, 28, 29]. The feet also have the potential for semantic information delivery, which has not been explored extensively before. The following subsections discuss these topics in detail.

2.2.1 Foot-based Haptic Guidance Systems

The feet are a natural location to deliver guidance cues for lower-body movements. Researchers have explored foot-based haptic guidance for navigation [16, 25], gym training [26], and snowboarding [29]. Velazquez *et al.* [16] reported that haptic patterns mapped to directional information is quickly learned and retained. Spelmezan *et al.* [29] concluded that tactile instructions achieved not only high recognition accuracy similar to that of audio instructions but also received quick responses. These works validate the efficacy of the haptic-based guidance system.

In dance training systems, researchers have either used full-body pose correction [30, 31, 32] or focused solely on direction of movement [33] and rhythm [28, 34, 35]. None of the previous work employed haptic cues for weight transfer training—a crucial aspect affecting body posture during dance. Minton [36] discussed that a correct posture facilitates poised body movements, and reduces compensatory movements and injuries. Prior research proves that recurrent feedback based on weight distribution over feet can improve posture [26, 37]. Hence, in our proposed foot-based haptic guidance system, we consider not only the aspects of direction and rhythm but also weight transfer.

We acknowledge that in dancing, full-body pose correction and training are very relevant and could benefit novice dancers. However, in our work discussed in Chapter 5, we are focused more on the training of fundamental foot-work, which guides the initial stages of dance learning.

2.2.2 Semantic Information Rendering on Feet

In the previous section, we discussed the applications of foot-based haptics in guidance systems. These applications use abstract tactile messages for conveying cues. Although researchers have explored the use of feet extensively for conveying these high-level messages, they have not yet used its full tactile capacity for rendering structured information such as alphanumeric characters or phonemes.

For communicating such a broad set of information, we can deploy an array of haptic actuators on the surface of the feet and design spatial and spatio-temporal tactile icons mapped to the alphanumeric characters or phonemes. However, as discussed in Section 2.1, the large receptive fields of sensory receptors on the feet, cause propagation of tactile stimuli and affect the performance of multi-actuator haptic rendering. The toes may overcome this limitation and serve as a plausible location for a ten-unit tactile display. In Chapter 3, we discuss the perception study performed on toes to assess if this can be viable. Progressing further in this direction, in Chapter 4, we discuss the research that explores numeric information delivery via the toes.

2.3 Foot-based Haptic Wearables

Researchers have proposed several designs for foot-based haptic interfaces. They commonly used pressure and motion sensors to gather information relevant to movement, and tactile actuators to provide feedback. These sensors and actuators are often embedded in shoes or insoles and controlled using micro-controllers. The actuator placement, hardware encasing, and overall footwear design are optimized based on the targeted application.

Lechal (`www.lechal.com`) designed a pair of insoles for navigation assistance; they consist of actuator pods that render vibrotactile patterns mapped to direction. Although they have well-designed tactons for conveying the cues, the hardware contains a single actuator and offers limited flexibility to haptic designers.

Elvitigala *et al.* [26] proposed design of shoes consisting of a pressure-sensitive insole and eight vibrotactile actuators embedded on the side walls. The haptic feedback informed the users about their posture based on the centre of pressure. Their study concluded that the feedback improved posture; however, participants perceived vibrations as obtrusive and alarming. This might be because this feedback was provided in all states via haptic actuators running at maximum amplitude, causing saturation of the mechanoreceptors on feet, hence overwhelming the participants. It was recommended that providing correctional feedback, exclusively using a single actuator would be helpful for this use case.

Anlauff *et al.* [2, 38] presented a design of open footwear with four actuators and sensors embedded on the sole. They rendered several tactile icons and assessed the recognition rate for standing as well as walking conditions. The performance of their test subjects was relatively lower in the latter case, which can be attributed to the dampening of vibration in the feet. The close placement of the actuators might have caused tactile confusion amongst the rendering locations.

Velazquez *et al.* [16] compared two insole designs—an array of 16 actuators vs. an array of four actuators on the plantar surface of feet, and stated that the latter design accounted for easier recognition of direction patterns. As the feet do not have a similar density of mechanoreceptors as fingers, there is a relatively higher two-point threshold; this makes it difficult to discriminate between stimuli generated by adjacent tactors of a sizable array. Although the stimuli rendered through the preferred insole had a high recognition rate (88%) when tested in immobile conditions, we assume performance will degrade during mobile conditions.

Although all these designs attempted to convey information using tactons, the information conveyed is limited due to signal propagation issues. This is because the prototypes mostly used the metatarsal arch and heel region for placing the actuators, which caused propagation of haptic stimuli. No design attempted to use the toes or any hybrid arrangement involving the dorsal and the plantar region. These placement strategies can provide well-separated regions for stimulation and hence less inter-location confusion arising due to tactile propagation. We used these placements in our designs for haptic rendering, as discussed in Chapters 3, 4 and 5.

Chapter 3

Can Toes Match Fingers for Haptic Discrimination?

Preeti Vyas, Feras Al Taha, Jeffrey R. Blum, Antoine Weill--Duflos, and Jeremy R. Cooperstock, "Ten Little Fingers, Ten Little Toes: Can Toes Match Fingers for Haptic Discrimination?." *IEEE Transactions on Haptics*, vol. 13, no. 1, pp. 130-136, Jan 2020

Preface

This chapter presents a manuscript published in a peer-reviewed journal. It incorporates minor changes based on the thesis examination; hence the version of manuscript presented here is slightly different from the one published in the journal. In this work, we explore the feasibility of toes as a location for haptic communication. We review prior perception studies performed on toes and fingers. They reported inferior performance of toes as compared to the fingers for tactile discrimination. To mitigate this shortcoming of toes, we design a tactile toe encoding. We perform a user study and compare the performance of encoded rendering on toes against the default rendering on fingers and toes. The results support our hypothesis that encoded rendering performs better than default rendering on toes and reaches a level similar to that of the default rendering on fingers. The findings justify the usability of toes as a tactile display, which we further test for numeric information delivery in Chapter 4.

Author's Contribution

This work is a result of collaboration. Preeti Vyas, Feras Al Taha, and Antoine Weill--Duflos designed the apparatus and implemented the hardware interface. All the authors contributed to the design of the user study. Preeti Vyas recruited the participants and conducted the experiments. She analyzed the experimental data and prepared the figures with help from Jeffrey Blum and Antoine Weill--Duflos. Preeti Vyas and Feras Al Taha wrote this manuscript. Prof. Cooperstock supervised the research and edited the manuscript.

Abstract In comparison with fingers, toes are relatively unexplored candidates for multi-site haptic rendering. This is likely due to their reported susceptibility to erroneous perception of haptic stimuli, owing to their anatomical structure. We hypothesize that this shortcoming can be mitigated by careful design of the tactile encoding to account for the idiosyncrasies of toe perception. Our efforts to design such an encoding achieved an improved perceptual accuracy of 18% for poking and 16% for vibrotactile stimuli. As we demonstrate, the resulting perceptual accuracy achieved by the proposed tactile encoding approaches that of the fingers, allowing for consideration of the toes as a practical location to render multi-site haptic stimuli.

3.1 Introduction

Haptics has been widely explored as an on-body communication modality. Prior work investigated single actuator haptic delivery to convey information using tactons created by varying parameters such as frequency, amplitude, waveform and duration [39], [40], [1]. However, the perceptual discriminability of these dimensions, within safe ranges, e.g., of amplitude, is limited. For this reason, exploiting spatial discrimination by a multi-actuator tactile information display represents a potentially superior approach. This has been explored at various parts of the body, including the back [41], waist [42], lower leg [43], and arm [44]. However, most of the skin, apart from fingertips, palm and sole, exhibit relatively low tactile resolution [45], which limits their effectiveness for multi-actuator tactile display. In contrast, the fingers not only exhibit high tactile resolution, but since there are ten of them, they provide physically independent loci for tactile information delivery [46, 22, 47, 48].

However, the fingers are typically occupied in day-to-day interactions with the everyday world, as we hold or manipulate objects, or perceive the environment through touch. In this respect, data gloves or similar actuated devices, used solely for the purpose of tactile information delivery, are generally undesirable [49], since they could interfere with the fingers' freedom of movement or reception of external sensory sensation.

One might expect that the toes would exhibit similar benefits, given that they are also separated into ten physically independent units. However, the ability to discriminate which toe received a particular stimulus is significantly inferior to that of the fingers, especially for the middle toes [11, 12]. If this limitation could be overcome, the use of toes for delivery of multi-point haptic information would present several compelling benefits: first, they are under-utilized and often idle for other purposes, especially while an individual is seated, and second, the mechanisms for delivery of haptic stimuli can be embedded in everyday footwear, thereby neither encumbering the user, nor being visible to third parties.

3.2 Background

Multi-actuator tactile rendering systems have been employed on different locations of the human body for a wide number of applications. Geldard [20] explored multi-site haptics with *Vibratese*, a tactile language consisting of alphanumeric symbols rendered at five locations, at three intensity and duration levels, for a total of $5 \times 3 \times 3 = 45$ combinations. Rendering of tactile icons, or *Tactons* [23], with multiple vibrotactile actuators, has been investigated by numerous researchers. Jones *et al.* [41] used a tactile vest consisting of a 4×4 array of actuators to convey navigation cues on a user's back. McDaniel *et al.* [42] designed a multi-actuator haptic belt to convey non-verbal communication cues to blind users during social interaction. Meier *et al.* [43] explored different multi-actuator setups such as sock bandages, wristband, insoles, and shoes for the purpose of pedestrian navigation. Cobus *et al.* [50] used multi-site tactile rendering to convey alarms from intensive care unit (ICU) on a vibrotactile wearable alarm system.

Hands and feet have ten physically isolated digits and thus can be used as a potential multi-site tactile rendering locations. Luzhnica *et al.* [51] and Nicolau *et al.* [22] designed systems to render alphanumeric information to the fingers. However, these are not suitable for applications where the hands are occupied, as they often interfere with manipulation and/or tactile perception of the environment. Wearables in the form factor of rings [52] avoid this problem, but can only convey a limited range of distinguishable patterns because of the constrained space available for housing actuators that are capable of rendering a wide range of effects. Newer actuators in development may offer greater flexibility to render multi-site haptics. Examples include *Tacttoo* [53], a thin, feel-through tattoo for on-skin tactile output, and *Springlets* [54], which offer expressive, non-vibrating, mechanotactile interfaces on the skin. However, we are unaware of any studies that have been conducted on the performance of these actuators for multi-site haptic rendering.

Researchers have explored perception of tactile stimuli on the toes, and compared this to fingers. Cicmil *et al.* [11] performed a study involving manual stimulation of the glabrous surfaces of fingers and toes. They found that recognition was robust when the big toe (99%) or little toe (94%) was stimulated, but individuals had difficulty discriminating between the middle toes, with perceptual accuracy of 57%, 60% and 79% for the second (immediately adjacent to the big toe), third, and fourth toes [11]. In contrast, all the fingers exhibited perceptual accuracy over 99%. Manser *et al.* [12] reported a similar trend in their follow-up study comparing tactile perception on both glabrous and hairy surface of fingers and toes.

The potential of a toe-based haptic information rendering system motivated us to examine whether a carefully designed encoding of the stimuli could allow subjects to better discriminate stimuli delivered to individual toes. We compared our proposed design to a simpler rendering of tactile stimuli [11, 12] to the fingers and toes in order to answer these research questions— Can such an encoding improve perceptual discriminability of the toes, and if so, can it be improved to approach the performance level of fingers?

In addition, we noted that delivery of vibrotactile stimulation in the closely spaced locations of toes risks propagation of the vibration to adjacent toes. This effect results in part from the large receptive fields of the Pacinian mechanoreceptors, located deep in the dermis layer. We speculated that the use of poking, instead, might allow for better localized stimuli since these are perceived by Merkel cells in the epidermis layer, which are sensitive to tissue movement at low frequencies, have relatively smaller receptive fields and well-defined borders [55], allowing for accurate perception [56].

Various studies related to tactile information rendering have explored the use of multiple actuators [41, 57, 58] and several papers have specifically investigated poking stimuli [57, 59, 60, 58]. In a recent study using a 3×3 multi-actuator tactile watch display, Shim *et al.* found that participants recognized poking more accurately than vibrotactile stimuli [61]. Motivated by this body of work, we wished to determine whether the perceptual discriminability of the toes benefits more from poking over that of vibrational stimuli.

3.3 Tactile Toe Rendering

Two tactile toe rendering methods were used in this paper—default and encoded, each using two stimuli—vibration and poking. Each toe was identified by a number from 1 through 5, starting with the big toe corresponding to number 1 and increasing laterally such that the little toe corresponded to number 5. We used a default rendering to replicate the individual toe simulation as performed by Cicmil *et al.* [11].

According to Cicmil *et al.*'s results, there was a directional bias in the perception of toes, significantly for the middle toes, causing misidentification. The second and third toes were biased towards the little toe, whereas the fourth one was biased towards the big toe. We therefore wanted to implement an easy-to-understand tactile rendering strategy to differentiate the toes, helping to decrease the effects of toe misidentification.

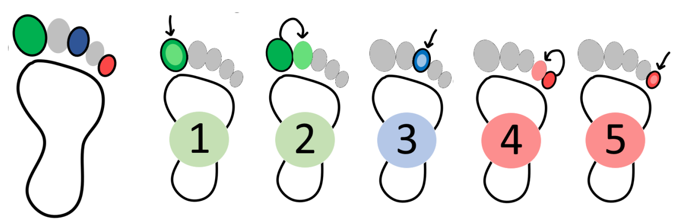

Fig. 3.1: Encoded tactile toe rendering for right foot: The first foot shows the directional toes (1, 3 and 5) highlighted in dark colors. For stimuli to be delivered to these toes, the target toe and directional toe are the same. For stimuli to toes 2 or 4, the corresponding directional toe is first stimulated, followed by the target toe.

We proposed an encoded rendering involving delivery of two consecutive stimuli, an initial stimulus to one of the directional toes (defined in Figure 3.1) followed by a stimulus to the targeted toe. For toes 1 and 2, the directional toe was 1; for toe 3, the directional toe was 3; and for toes 4 and 5, directional toe was 5. The initial stimulus to the directional toe was designed to serve as a cue for users, for which a short vibration or short poke seemed appropriate. The follow-up stimulus needed to be sufficiently different to emphasize that it identifies the targeted toe. As such, we chose to use a longer vibration or three small consecutive pokes, depending on the stimulus condition. Geldard [20] stated that for a range of 100 ms to 2000 ms, the skin can distinguish approximately 25 discrete, just-noticeable differences of stimulus duration, whereas durations below 100 ms are perceived as poke sensations on the skin. We thus kept the vibrational stimuli of our *Tactons* longer than 100 ms and the poking stimuli at 100 ms.

1. *Default Rendering:* a long vibration of 800 ms or a single poke of 100 ms on the targeted toe.

2. *Encoded Rendering:*

   - Vibration: a short stimulus of 400 ms on the directional toe, a pause of 500 ms and then a long stimulus of 800 ms on the targeted toe.
   - Poking: a single poke of 100 ms on the directional toe, a pause of 500 ms and then three pokes of 100 ms on the targeted toe, each separated by 100 ms pauses.

3.4 User Study

3.4.1 Apparatus

The prototype consists of ten ERM vibrotactile actuators (2 mm Mini Vibrating Disk Motor, RB-See-403, Seeed Studio) for rendering vibration stimuli, and ten small push-pull solenoids (Solenoid-5V, ROB-11015, SparkFun) for rendering poking stimuli. They were controlled by a microcontroller (Teensy 3.2) driving an H-bridge for the ERMs and driving a relay for the solenoids. The vibrotactile actuators were mounted on individual foam cutouts to localize the vibrations and avoid undesirable propagation. The push-pull solenoids were mounted on individual 3D printed encasings to allow an adequate clearance between the push-pin and the digit, such that a poking sensation is achievable. These foam pieces or 3D printed encasings were attached to the user's toes via velcro® straps to ensure proper placement in case participants accidentally moved their toes. Since participants had more control over the movement of their fingers during the experiment as compared to toes, velcro® straps were not used for these. The vibrotactile actuator provides an average acceleration of 0.8 g, where g is gravitational acceleration and the solenoid provides a minimum force of 0.78 N. The former was operated at 3.3 V, rotating at 10 000 RPM (167 Hz) whereas the latter was operated at 5 V. The experimental setup is shown in Figure 3.2.

Fig. 3.2: Hardware setup for rendering poking (top panel) and vibration stimuli (bottom panel).

3.4.2 Methodology

For the experiment, we followed a protocol similar to Cicmil *et al.* [11]. Each participant was tested individually in a laboratory setting, sitting comfortably on a chair with legs uncrossed, and their bare feet resting flat on elevated platform of 2 cm for vibration and 4 cm for the poking apparatus (Figure 3.2). For finger stimulation, the hand was positioned flat with the palm down on the padded surface of a table with the fingers comfortably spread. Participants were instructed to strap the actuators comfortably tight to the toes of their dominant foot and rest the fingers of their dominant hand such that each actuator was at the center of the distal tip of their digit. The experimenter then verified that all the actuators were in place and properly coupled. Each digit was identified by a number from 1 (thumb and big toe) through 5 (little finger and little toe). One digit was stimulated per trial. The participants were instructed to respond after each trial by verbally identifying quickly and accurately their first impression of the stimulated digit. They wore headphones playing pink noise to mask the sound of the actuators and were asked not to look at their fingers or their toes during the trials. Their individual response times were not recorded.

The experiment followed a repeated measures (within subject) design. We tested three conditions: default rendering on fingers (DF), default rendering on toes (DT) and encoded rendering on toes (ET), each for blocks of poking (P) and vibrotactile (V) stimuli. All possible orders of the three conditions (DF, DT, ET) were repeated twice and used across the participants. This order was the same for blocks of poking and vibration. The poking and vibrotactile blocks were counterbalanced across participants. We did not implement encoded rendering on the fingers since prior work reported perceptual accuracy as high as 99% for all the fingers [11].

After setup, consent form and pre-test questionnaire delivery, we ran a short exercise to familiarize the participants with the number identification of the digits: the experimenter pointed at one of the participant's fingers or toes and asked them to say the number with which it is associated. This was repeated for all the digits (maximum of two times per digit) to ensure that they understood the mapping. Before the trials for a particular condition started, the experimenter explained the rendering to the participants and gave them a demo trial, stimulating all the digits sequentially from 1 to 5. For each condition, 50 trials were rendered such that every digit, either toe or finger, was stimulated ten times in random order. The numbers were shuffled in blocks of ten (1 through 5, each appeared twice) using a Fisher-Yates [62] shuffle and five shuffled blocks were appended together. After each experimental block of poking or vibration, participants completed a post-test questionnaire.

3.4.3 Hypotheses

We expected that our tactile toe encoding would help participants to better differentiate toes, while avoiding confusion amongst the three middle toes. As per the conclusions of Cicmil *et al.* [11] and Manser *et al.* [12], we assumed fingers to have reasonably accurate perception. We expected that the perceptional discriminability of toes would be similar or better than that of fingers when an encoded rendering was used. Since poking is a localized stimulus, and does not propagate as much as vibration, we expected that poking stimuli might be better discriminated than vibration.

3.4.4 Participants

We recruited 16 participants from the McGill University community and compensated them CAD$10 for approximately an hour-long experiment. Data from the first two participants were not used as we made changes in the post-test questionnaire to solicit information regarding poking and vibration separately. For two other participants, hardware-related interruptions required us to cancel the experiment session. We analyzed data from the remaining 12 participants (7 male, 5 female; ages 18–33, median = 24.5).

3.4.5 Results

3.4.5.1 Pre-Questionnaire Results

All the participants reported their right hand and foot as dominant. Participants' foot widths measured at the toes were in the range of 8.9–11.4 cm (median = 10.0 cm) and shoe sizes were in the range of 23.8–27.6 cm (median = 27.0 cm).

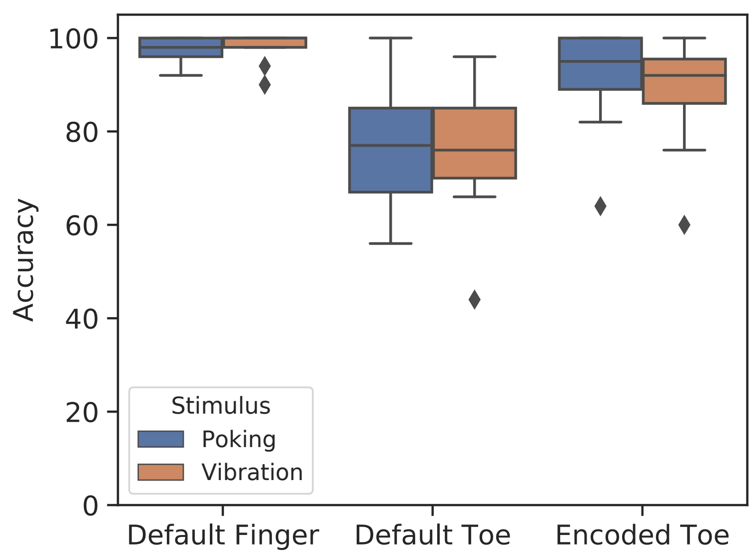

Fig. 3.3: Boxplot of accuracy under each condition

3.4.5.2 Accuracy and Confusion Matrix

Trials for which participants responded by verbally identifying the correct number against the stimulated digit were considered accurate. A lack of response to a trial was counted as an error. Across all participants, there were a total of four trials with a lack of response (1 in P-DT (toe 4), 2 in P-DF (finger 3), and 1 in V-DT (toe 4)).

We compared the accuracy of identification of perceived digits for all three conditions (DF, DT, ET) rendered with poking and vibration stimuli. As shown in Figure 3.3, the perceptual

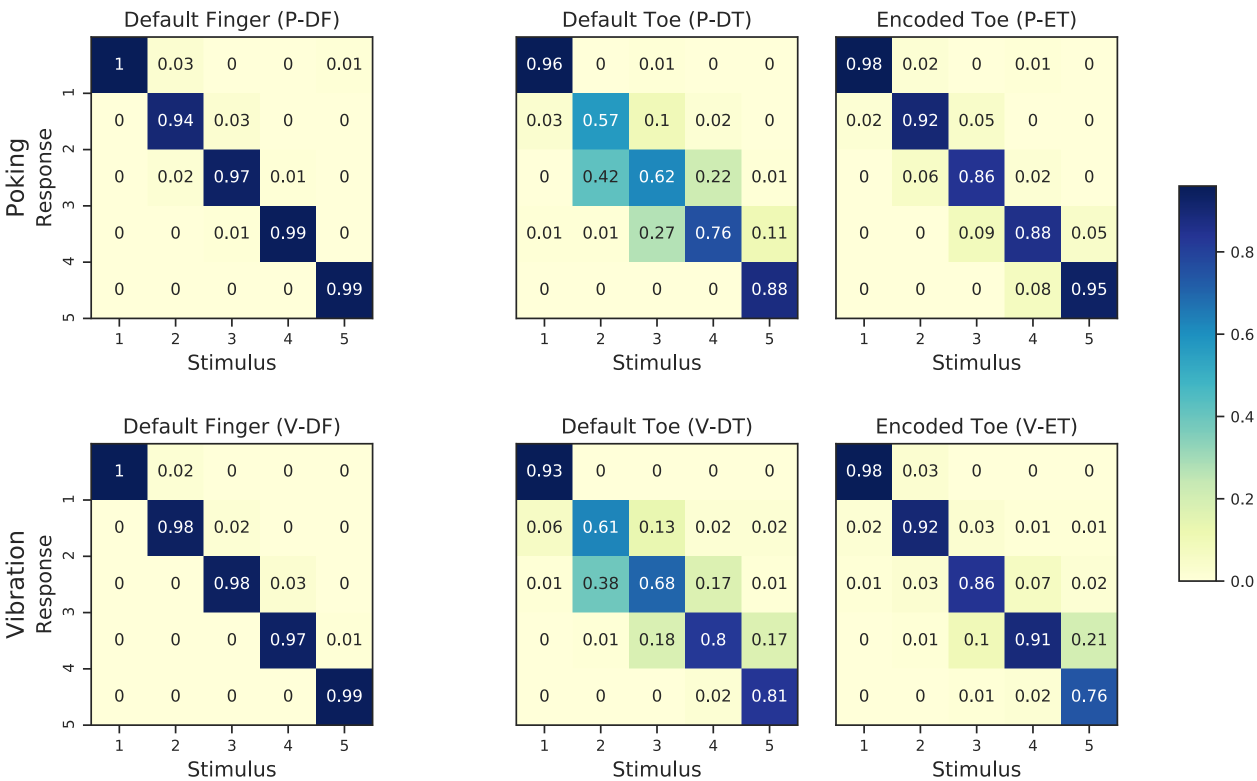

Fig. 3.4: Confusion matrices showing the proportion of stimuli responded as located on each of the five digits as a function of which digit was actually stimulated. Digits were identified by numbers 1 (thumb, big toe) through 5 (little finger, little toe). Data from the poking block are shown in the upper panel and those from the vibration block in the lower panel. The proportion of correct responses for each digit is shown along the diagonal from the top-left to the bottom-right. The values represented here only include the trials for which the participants responded.

accuracy for default rendering on fingers had a range of 94 % to 100 %, with medians of 98% for poking and 100% for vibration. As expected, these values decreased to medians of 77% for poking and 76% for vibration to the toes under default rendering. These results are consistent with those of previously published perception studies [11, 12].

As seen in the confusion matrices of Figure 3.4, only a few errors were observed for the fingers. In contrast, a fair number of errors were observed for the default rendering of poking and vibration stimuli on the toes. These aligned with the confusion matrix presented by Manser *et al.* [12] for their perception study. In Figure 3.4, the responses for toes 2, 3 and 4 were often confused with the adjacent middle toe(s), while toe 5 was sometimes confused with toe 4.

For our encoded toe rendering, we observed median accuracy of 95% for poking and 92% for vibration, with relatively fewer errors compared to the default toe rendering (Figure 3.4). This was accompanied by a reduction in the confusion between the middle toes, with the proportion of accurate responses increasing an average of 24% for toes 2, 3 and 4 in the poking condition and 20% in the vibration condition.

A Friedman's test [63] as implemented by Vallat [64] found a statistically significant difference when analyzing all renderings (DF, DT and ET) in poking block, $\chi^2(2) = 13.087$, $p<0.005$. A non-parametric pairwise t-test [64] with Holm-Bonferroni correction [65] was then performed, and found statistically significant differences for two comparisons—between P-DF and P-DT, $p < 0.01$, and between P-DT and P-ET, $p < 0.05$, with a large effect size. No significant difference was found between P-DF and P-ET (Table 3.1).

Table 3.1: Comparison between different renderings for poking corrected by Bonferroni-Holm. Uncorrected (p-unc) and corrected (p-corr) p-values are reported along with the CLES [3] and Hedges' g effect size [4]. Corrected p-values with statistical significance are highlighted.

Condition A	Condition B	p-unc	p-corr	CLES	hedges
P-DF	P-DT	0.0032	**0.0097**	0.910	-2.505
P-DF	P-ET	0.0673	0.0673	0.562	-0.831
P-DT	P-ET	0.0073	**0.0147**	0.812	1.250

A similar series of tests was performed for renderings in the vibration block as well. The Friedman's test found a statistically significant difference when analyzing all renderings (DF, DT and ET), $\chi^2(2) = 16.979$, $p < 0.001$. The non-parametric pairwise t-test found statistically significant differences for all the three comparisons with a large effect size (Table 3.2).

We also wanted to analyze how the different renderings performed under blocks of poking and vibration. Hence, we performed Wilcoxon tests [64] for the three blocks, DF; DT; and ET to compare if there is any difference in perceptual accuracy based on the used stimuli. The results of these three tests are available in Table 3.3. We failed to reject the null hypothesis and could not find any statistically significant difference between poking and vibration for each comparison.

Table 3.2: Comparison between different renderings for vibration corrected by Bonferroni-Holm. Uncorrected (p-unc) and corrected (p-corr) p-values are reported along with the CLES [3] and Hedges' g effect size [4]. Corrected p-values with statistical significance are highlighted.

Condition A	Condition B	p-unc	p-corr	CLES	hedges
V-DF	V-DT	0.0025	**0.0074**	0.958	-2.392
V-DF	V-ET	0.0206	**0.0206**	0.715	-1.277
V-DT	V-ET	0.0053	**0.0105**	0.722	0.886

Table 3.3: Comparison between poking and vibration stimuli for different renderings. Uncorrected p-values (p-unc) are reported along with the CLES [3] and Hedges' g effect size [4].

Condition A	Condition B	p-unc	CLES	hedges
P-DF	V-DF	0.51	0.507	0.280
P-DT	V-DT	1.00	0.507	0.045
P-ET	V-ET	0.44	0.549	-0.289

3.4.5.3 Post-Questionnaire Results

In the subjective questionnaire, eight out of twelve participants reported encoded rendering to be better than default for distinguishing the toes. Three participants (P4, P9, P12) stated that they had difficulty recognizing the middle toes under the default encoding. P9 mentioned, "...for toes [toe] default, it is quite hard to distinguish 2,3,4 but toes [toe] encoded solve this problem by grouping". However, three participants (P7, P10, P11) preferred the default over the encoded rendering in terms of effort. P10 wrote "...encoded method [has] cognitive load, default [method is] easy to guess...".

P11 mentioned, "I was not properly able to recognize the difference between 2,3,4 [in encoded rendering]". We found out that their individual performance indicated a much higher proportion of errors (36% for poking, 34% for vibration block) relative to the median (5% for poking, 8% for vibration block) for the encoded rendering. It is possible that they were unable to understand the encoding properly.

Two participants compared default finger and encoded toes, and they had diverging opinions. P5 wrote "perception was better in the encoded method than default method but was still lesser than that for fingers" where as P9 mentioned "by grouping toes, [the encoded rendering] is even better than fingers"

There was also disagreement with regards to the preference between vibration or poking stimuli, e.g., "the poking was more concentrated and helped identify the stimuli; the vibrations were diffused and could not clearly identify" (P2), "for toes poke was better as [it is] well separated" (P4), "[vibration] is more hazier than pokes" (P7), whereas others (P5, P11) expressed the opposite.

Commenting further on the differences between poking and vibration, P1 mentioned that "on toes, poking was better but on fingers, vibrations was better". This might be explained by the fact that fingers are well separated, and there is thus less propagation of vibration as compared to toes.

3.5 Discussion

The results of our study follow the same trend as previously published work by Cicmil et al. [11] and Manser et al. [12]. While both fingers and toes offer ten sites for tactile rendering, a default haptic rendering strategy on the fingers achieves higher perceptual accuracy with very few errors. In contrast, the default rendering on toes exhibited many errors due to the confusion between the middle toes. With this in mind, our proposed method helps tackle the difficulties in discrimination of haptic stimuli to the toes, apparent from a simple rendering approach. These problems, clearly in evidence in the confusion matrices, were addressed by the addition of our novel tactile cues. Toe discrimination using the resulting encoded rendering demonstrated significant improvement, both for vibration and poking stimuli.

Since toes have lower spatial separation than fingers, they are more prone to erroneous perception of tactile stimuli. To compensate for this limitation, we designed our encoded rendering to provide an initial cue to the "directional toes". This affords the participant an initial localization to a subset of the toes, followed by delivery of the final cue to the targeted toe. Although, performance of the encoded rendering on toes did not surpass that of the default rendering on fingers in terms of perceptual accuracy, it did nevertheless achieve a level that was close. This suggests that toes can be used as a viable tactile display in the many situations for which the fingers are inappropriate. Further studies may prove the effectiveness of our proposed rendering for conveying semantic information on toes. As the perceptual discrimination performance we have achieved for the toes remains imperfect, further improvements in pattern design may be considered, varying amplitude, frequency and time duration in an attempt to increase the perceptual accuracy. The designed encoding schemes can be compared based upon their accuracy as well as information transmission rates.

Two commonly used tactile renderings, poking and vibration, were employed for our study, but we failed to find a statistically significant difference in performance between them. Although such differences are likely to be more pronounced in the case of a single site multi-actuator tactile display, as shown by Shim et al. [61], we suspect that whatever the advantages of poking stimuli are, these are eclipsed by the ambiguity in tactile perception among the middle toes.

In the absence of further data to indicate a clear winner, we opt to employ vibration because of the more compact actuators that can be fitted comfortably in a wearable device for practical use. Alternatives of compact actuators to deliver poking stimuli are being developed, but are not yet commercially available. Future work may also explore other haptic stimuli such as squeezing or lifting of the toes, as well as consider stimulation of the non-glabrous surfaces of the toes.

A particular benefit of our encoded toe rendering is its simplicity. Participants in the study received minimal training to learn how to interpret the rendering. Only a scripted description of the rendering and a few demonstrative trials were presented to participants to prepare them for the experiment. The remainder of the learning occurred throughout the trials. Nevertheless, participants were still able to perform quite well in identifying the stimulated toes.

3.6 Conclusion

We proposed an encoded tactile toe rendering method to help distinguish stimuli applied to individual toes. The results from our study indicated that our proposed rendering outperforms a simpler default rendering, conveyed by either poking and vibration stimuli. Moreover, the perceptual accuracy attained for our encoded toe rendering approached the discrimination performance achieved at the fingers. This provides strong encouragement for consideration of the toes as a suitable location for multi-site tactile toe display.

Although we obtained fairly good results for our proposed rendering on toes, one drawback of haptic interfaces located on the feet is the haptic noise and tactile gating created while standing or walking. We expect that the performance of any haptic foot system will degrade while the user is standing, walking, or running. While the performance of this rendering with a user in motion has yet to be assessed, there are many scenarios where a foot-based interface is viable. Seated musicians, office workers or plant operators, for example, are typically in situations where the feet are unused and largely undisturbed. Thus, even if we cannot claim that the toe-based system described in this work is usable for all situations, there is considerable utility even in an apparatus that is limited to seated use. In addition, future work that improves foot-based haptic interfaces may result in the rendering techniques described in this work becoming viable for a broader range of user activities in the future. Furthermore, this style of encoded rendering can be adapted for other multi-site haptic applications to distinguish perception from different sites while minimizing confusion between adjacent locations.

Acknowledgment

We thank members of the Shared Reality Lab for their suggestions and help in the development of the prototype. We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC), RGPIN-2017-05013, and the MITACS Globalink Graduate Fellowship Award. McGill REB #83-0814.

Chapter 4

HapToes: Vibrotactile Numeric Information Delivery via Tactile Toe Display

Preeti Vyas, Feras Al Taha, Jeffrey R. Blum, and Jeremy R. Cooperstock, "HapToes: Vibrotactile Numeric Information Delivery via Tactile Toe Display." *IEEE Haptics Symposium (HAPTICS)*, 2020

Preface

This chapter presents a manuscript accepted at a peer-reviewed conference. It incorporates minor changes based on the thesis examination; hence the version of manuscript presented here is slightly different from the one accepted at the conference. The work discussed here is a continuation of our study on haptic communication through toes. In Chapter 3, we demonstrated that with our encoding, it is possible to improve the haptic discriminability of toes and achieve results similar to that of fingers. As we have ten toes, the natural progression of this work is evaluating if we can assign a numerical value to each toe and convey such information effectively via haptic stimuli. Several applications, such as a foot-based navigation system and progress-tracking shoes, can benefit from this functionality. We improve our encoding to make it more efficient and present HapToes—a haptic numeric rendering technique for toes. We perform a user study and compare our method with ActiVibe, a previously presented haptic numeric rendering. The results suggest that our method performs similar to ActiVibe for rendering a single value and superior while rendering three values.

Author's Contribution

This work is a result of collaboration. Preeti Vyas designed the apparatus and the haptic rendering. She recruited the participants, conducted the experiments, refactored the code for data analysis, analyzed the experimental data, and prepared the figures. All the authors contributed to the design of the user study. Jeffrey Blum wrote the code for data analysis. He developed the mobile and smartwatch applications used in the user study. These applications were later refactored by Feras Al Taha. Preeti Vyas and Feras Al Taha wrote this manuscript. Prof. Cooperstock supervised the research and edited the manuscript.

Abstract Tactile rendering of numeric information via a single actuator has been considered for such purposes as fitness progress tracking. However, multi-actuator designs, leveraging spatial mapping, may offer superior performance. Motivated to explore this approach without requiring hardware on the fingers or wrist, we designed HapToes, a novel ten-digit spatial mapping of numeric information to the toes, which overcomes inter-toe discrimination ambiguity. Compared to ActiVibe, a single-actuator wrist-based numeric rendering technique, under similar distraction conditions, HapToes demonstrates equivalent performance for single-value identification, and improved accuracy, response time, and cognitive load when conveying three values sequentially in a single message.

4.1 Introduction

Wearable devices often use haptic actuators to convey information in the form of tactons [23]. Applications such as navigation (`http://lechal.com`) [25], may benefit from the ability to convey numeric information such as distance and time. For fitness and health monitoring systems, it is helpful to display numeric information such as progress rate [1], or physiological parameters [66]. In systems employed in control room environments [67], it may prove valuable to convey monitoring parameters mapped to numeric information. Certain applications can also benefit from haptic number rendering to provide feedback on user input [68].

A single actuator can be a convenient and efficient mechanism for rendering numeric information haptically as demonstrated by Cauchard *et al.* in their ActiVibe study [1]. However, single-actuator based renderings can be restrictive due to actuator constraints and to a limited number of distinguishable patterns that can be achieved when varying parameters of frequency, amplitude and duration [69]. Multi-actuator systems add a spatial aspect to the haptic rendering, allowing for more distinguishable patterns, and ultimately providing a larger design space for hapticians [69]. These systems benefit from having rendering locations with better two-point discrimination.

Researchers have used multi-actuators displays in wearables to design spatio-temporal haptic patterns [70, 21] demonstrating promising results. However, these tactons have been used almost exclusively for categorical or abstract representations. The semantic associations of such abstract patterns to concrete numerical information might not be obvious. Indeed, abstract representations for ordinal information would seem likely to impose an additional layer of cognitive load.

Since there is evidence for a spatially defined mental “number line” [71], it is natural to consider the fingers as a particularly effective locus for spatial tactile display to represent values of 1–10. However, rendering haptic patterns on fingers may interfere with day-to-day interactions with the world, as we hold or manipulate objects, or perceive the environment through touch. As such, toes may serve as a more practical ten-unit tactile display alternative. They may equally facilitate location-based semantic associations [72] since, as fingers they are physically separated from each other.

Unfortunately, the differentiability of haptic stimuli applied to individual toes, especially for the middle toes, is worse than that of fingers [11, 12]. This limitation prompted our investigation of an improved tactile toe encoding method [73], for which we achieved perceptual accuracy approaching that of the fingers. As a result, we find that the toes are a viable location for delivery of tactile numeric information.

In practice, foot-based haptic displays suffer from imperfect coupling of actuators and dampening of vibration in mobile conditions such as during walking and running activity [2]. Demonstrating the ecological validity of such a rendering requires the development of compact hardware for shoes as well as field testing. As such, the results presented here can be seen as an initial exploration of the possibilities of tactile communication through the toes, which can be used for seated applications such as rendering alert messages in control room environments [67] or conveying information to users in smart wheelchairs. However, significant further work is required before the solution can be considered for mobile real-world deployment.

Our contributions include (1) the design of *HapToes*, a novel haptic numeric rendering on toes based on our fundamental toe perception study [73], and (2) the findings of a laboratory user study comparing our method with the existing ActiVibe haptic numeric rendering proposed by Cauchard *et al.* [1], but under distraction conditions, and for rendering both single and three values. We will use the term *values* throughout to refer to the discrete information presented to users in our study, which are the numerals 1–9, and 10.

4.2 Background

Researchers have explored numerosity, the ability to count sequential tactile, visual or audible pulses, in terms of how it is represented in the human brain [71] and compared numerosity discrimination across these modalities [74]. Most haptic numeric rendering applications, including progress tracking [1], reporting time [75], and feedback for menu selection [68] used single-actuator temporal patterns rendered on the wrist using a smartwatch, or to the hand via a smartphone. Other works have used multi-actuator rendering on locations such as the back [66], arm [67], or fingers [22] to convey alpha-numeric characters using spatio-temporal renderings.

Cauchard *et al.* [1] created ActiVibe, a temporal vibrotactile rendering on a commercial smartwatch, to convey numbers from 1 through 10. ActiVibe achieved a recognition rate of up to 96 % in a laboratory study and 88.7 % when used in the wild for conveying single values. The authors suggested that incorporating a pre-signal vibration before the actual haptic pattern may prove useful to cue users about incoming vibrations. Blum *et al.* [76] performed a follow up study using ActiVibe with such a pre-signal vibration, and compared it against other duration-based methods under distraction conditions for rendering single and three values. The results suggested that ActiVibe maintains a performance advantage in terms of accuracy and subjective preference against other methods for rendering single values but not for three values. Participants not only demonstrated decreased performance with ActiVibe when multiple values were rendered at a time, but also in conjunction with the added load of the distractor task. This raises questions about the robustness of ActiVibe's rendering strategy for real life scenarios. We hypothesized that as an alternative, a spatial, multi-point approach may prove effective for number rendering since it may reduce the complexity and rendering duration of vibro-tactile patterns.

We note that ActiVibe is a strictly temporal, rather than spatio-temporal, haptic numeric rendering technique. Nevertheless, given the dearth of alternatives, and in particular, the lack of multi-actuator systems that have been evaluated for numeric information delivery, we chose this technique as a benchmark against which to evaluate the performance of our method. We are interested in this comparison because prior research suggests that the mental "number line" is not only intimately related to space, but also to time [71].

Prior research has explored haptic rendering on the feet for use cases where the visual and audio channels are overloaded [25], and when the hands are occupied with other tasks [26]. A haptic rendering on the feet offers advantages of being discreet, and its hardware assembly can be embedded in footwear.

This approach has been explored for conveying information in various applications including navigation (`http://lechal.com`) [25], physical training [26], and dance training [27]. In all these applications, a small set of semantic messages, such as directions, are conveyed by vibrotactile signals at different locations beneath the feet. However, to the best of our knowledge, the rendering of broader sets of more complex information has yet to be explored for feet. This may require either designing a complex spatio-temporal rendering or increasing the number of spatial rendering locations.

Haptic rendering on the toes has been explored in prior work. Panarese *et al.* [77] reported that humans can incorporate spatial force feedback to the toes into their sensorimotor loop during robotic teleoperation tasks. Iijima *et al.* [78] used toes as a location for creating the sensation of a haptic illusion on the sole. Cicmil *et al.* [11] performed a study comparing perception of toes and fingers, finding high error rates for the trials on the middle toes, with confusion between adjacent toes. Manser *et al.* [12] reported a similar trend from their follow-up study, which compared glabrous and hairy surfaces. A large number of errors involved a specific directional bias. Counting from the little toe as first, the second and third toes were biased toward the little toe, and the fourth toe was biased toward the big toe. In our initial study [73], we designed a haptic rendering strategy that accounted for this directional bias and successfully mitigated the specific confusion around the middle toes, improving the recognition of stimulus on toes by 17%. However, there was still a possibility of further improvements, with approximately 88 % of the errors due to misidentification of the toe directly adjacent to the targeted toe. This motivated the work described in the following sections, intended specifically to reduce confusion between adjacent toes.

4.3 Haptic Number Rendering

In this section, we discuss the ActiVibe Final rendering (AVF) described by Cauchard *et al.* [1] and HapToes (TOE), our proposed method of haptic numeric rendering on toes.

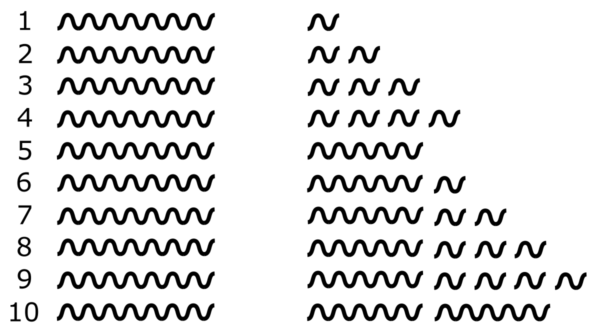

Fig. 4.1: AVF rendering based on Cauchard *et al.*'s study [1]

4.3.1 ActiVibe

ActiVibe is a temporal haptic number rendering in which each number from 1 through 10 is represented by one or more short (150 ms) or long (600 ms) vibrations, separated by pauses, rendered on the wrist by a single vibrotactile actuator, as illustrated in Figure 4.1. A pre-signal vibration of 750 ms followed by a pause of 1200 ms is used as a cue before rendering the actual values. To represent three consecutive values (AVF3), the pre-signal vibration was rendered only once at the beginning of the sequence, followed by the three values, rendered sequentially and each separated by a pause (800 ms). The total duration of vibration and pauses varies with the values being rendered: for single-value renderings, this was in the range of 2050 ms to 3900 ms, while for three-value renderings it was 3950 ms to 9500 ms.

Due to a coding implementation error on the smartwatch when replicating the rendering, there was an additional 200 ms inter-value pause after each 5 or 10 value in the AVF3 condition (e.g., the AVF3 value sequence 1-5-3 would have a normal 800 ms pause between the values 1-5, but a 1000 ms pause between the values 5-3). This extra 200 ms pause was also added to the end of each presentation of AVF or AVF3 encoded values that ended in a 5 or 10, such that the gap between presentations is extended by 200 ms. We believe these discrepancies are immaterial, and if the extra 200 ms gap between values has any effect at all, it is likely to make it easier to distinguish which vibration pulses are associated with each value. This will give AVF3 a slight advantage, albeit with extended total rendering time in these cases.

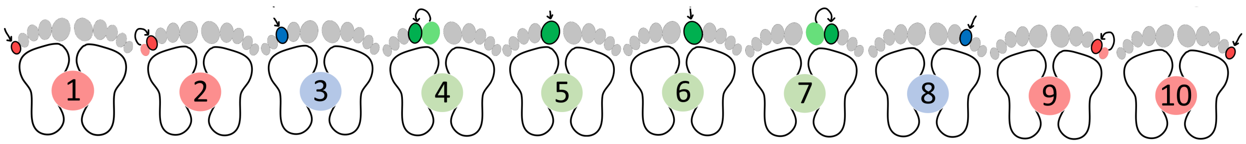

Fig. 4.2: Final design of HapToes for both feet. For numbers 1, 3, 5, 6, 8 and 10, a long vibration of 1200 ms is rendered on the targeted toe (darker color). For the remaining numbers 2, 4, 7 and 9, a short vibration of 400 ms is rendered on the closest edge toe, followed by a longer vibration of 800 ms on the targeted toes (darker color).

4.3.2 HapToes

HapToes is a haptic numeric rendering based on our fundamental perception study [73], designed to map values from 1 to 10 to the toes across both feet—proceeding from left to right, the leftmost toe of the left foot represents 1, and the rightmost toe of the right foot represents 10. This spatial association is reminiscent of a keyboard number layout with the toes as keys, and the zero replaced by ten. Unlike our basic design [73], with all the actuators placed below the toes, here, we alternate the placement of actuators directly below (for toes 1, 3, 5, 6, 8, 10) and directly above the toe, at the nail, to better differentiate adjacent toes.

As shown in Figure 4.2, for toes corresponding to values 1, 3, 5, 6, 8 and 10, termed as directional toes, a continuous long vibration of 1200 ms is rendered; for toes 2, 4, 7 and 9, a short vibration of 400 ms on the directional toe is immediately followed by a long vibration of 800 ms on the targeted toe. For example, to render 7, a short vibration was rendered on the big toe of the right foot followed immediately by a longer vibration on the second toe of the right foot. We posit that this difference between a continuous long vibration on one toe vs. two vibrations over separate toes provides a further distinction between adjacent toes, facilitating discrimination.

4.4 User Study

A user study was conducted to investigate the research questions and to assess the performance of the proposed rendering.

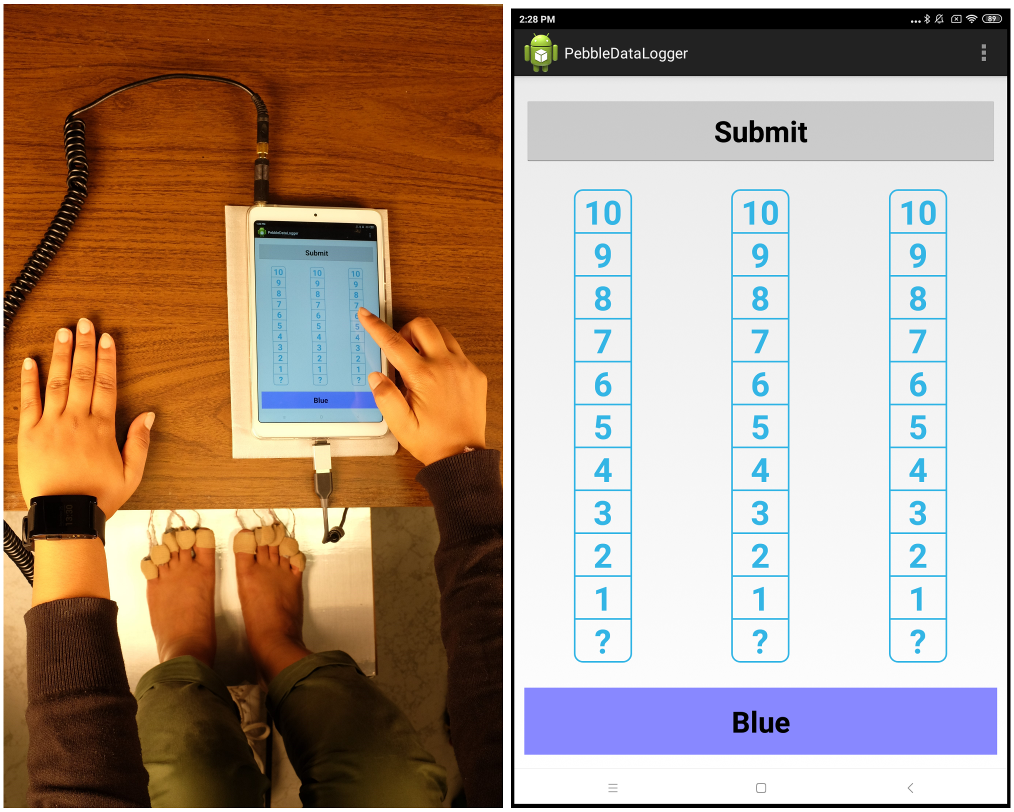

Fig. 4.3: Experiment setup and tablet UI for entering responses. In the experiment, the feet are obscured by the table, included here for illustration purposes.

4.4.1 Haptic Number Communication Task

Participants were seated at a table with a smartwatch strapped comfortably tight to their non-dominant wrist and the toe rendering device strapped to their toes. They used a tablet interface to enter their responses to the values they perceived. Participants were instructed not to look at their toes during the experiment. They wore headphones playing pink noise to mask the audible vibration from the rendering devices. In each trial, participants received either a single value or three values, rendered by vibration, for which they were asked to make a best-guess interpretation to submit using the tablet. The UI of the tablet, shown in Figure 4.3, consisted of one or three columns for entry of a single value or three values respectively. Columns contained numbers from one to ten as well as a question mark “?” (selected by default) for participants to use when they were completely uncertain of the rendered value. The responses in the UI could be modified until the participant pressed the “Submit” button to finalize their entry. Trials continued automatically upon submission of an answer or after eight seconds with no answer. The UI columns disappeared when the “Submit” button was pressed and reappeared at the end of the next trial’s rendering, immediately after the vibrations stopped.

4.4.2 Simultaneous Distractor Task

Participants performed an audio task [76, 15] in parallel with the numeric perception task to simulate a real-world distracted use of the rendering device. Throughout the experiment round, they wore headphones through which they heard color names being read along with the pink noise. The Android text-to-speech engine was used to generate the audio. Participants were instructed that their primary task was to report the color blue, every time it was spoken, using the “Blue” button in the UI. The color blue was spoken four times out of 20 in a randomized list along with 16 other color names, one color per second, after which the list was re-randomized. Thus, four blue stimuli occurred every 20 seconds, or 20% of the time.

4.4.3 Apparatus

The tactile toe display consisted of ten vibrotactile actuators encased in a rubber piece and attached to the participant’s toes with adhesive medical tape (AUPCON Self Adherent Bandage). ERM actuators (2 mm Mini Vibrating Disk Motor, RB-See-403, Seeed Studio) were used to deliver the vibrations, driven by a microcontroller (Teensy 3.2), which was serially connected to an Android tablet (RedMI 4) sending commands driving the trials. For AVF rendering, a smartwatch (Pebble model 301) was used. Participants reported their answers on a UI displayed on the tablet.

4.4.4 Methodology

The experiment used a within-subjects design to compare the performance of HapToes (TOE) against ActiVibe (AVF). We recruited 25 participants (11 male, 13 female, 1 gender-neutral, ages 18-31, median = 24) from the McGill University community and compensated them CAD$10 for their participation, which lasted approximately one hour. None of these participants took part in our previous study [73]. Data from one participant (P2) was excluded from the analysis for non-compliance with the instructions.

After participants signed the consent form and completed a pre-test questionnaire, the experimenter explained the Blue audio task and the simultaneous task of identifying numbers rendered by vibrations on the toes or wrist. The tablet was kept on the table, which obscured the participants' feet. The experiment was divided into training and testing phases. The following training was given to the participants:

1. *UI Training:* Participants briefly practiced using the tablet UI, responding to the Blue audio task while entering numerical values on the tablet based on the number of fingers held up by the experimenter near the tablet screen.

2. *TOE/AVF Familiarization:* Participants received a scripted verbal description of the rendering supported by visual aids. Following this, they were exposed to the values from one to ten in the form of vibrations. The value was displayed graphically on the smartwatch or the tablet during the rendering. Participants were asked to pay attention to the rendering.

3. *TOE/AVF Training:* Twenty randomized single-value trials were presented to simulate the real experiment round. Participants were asked to report the perceived value via the tablet UI while also responding to the Blue audio task in parallel. After they submitted their responses, the correct values were displayed on the tablet.

4. *TOE3/AVF3 Familiarization:* The same process as TOE/AVF Familiarization was run for ten randomized three-value trials.

Following training, we carried out separate testing rounds for single-value rendering and three-value rendering, lasting approximately 30 minutes in total. In each round, two sets of trials were run for each of TOE and AVF conditions, presented in reverse counterbalance order (ABBA or BAAB) across participants. The single-value rendering round (AVF, TOE) was followed by the three-value rendering round (AVF3, TOE3). For single-value rendering, within each set, the numbers were shuffled in blocks of ten using Fisher-Yates shuffle and two shuffled blocks were appended together, resulting in 20 trials per set. For three-value rendering, within each set, ten trials were presented, with each possible value included once in each of the three positions in random order. Although offered, none of the participants took a break between the rounds. Participants then completed a post-test questionnaire and were compensated for their time.

4.4.5 Measures

We measured missed rate (MR), error rate (ER), absolute Difference between Input and Answered value (DIA), response time (RT), render+response time (RRT) and performance on the distractor task. MR is the percentage of missed trials, i.e., trials where the participant either failed to enter a response within eight seconds or entered "?". ER is the sum of MR and the percentage of trials for which the submitted value differs from the correct rendered value. The DIA is the absolute difference between the rendered and perceived values, which measures the magnitude of the error. Missed values are assigned a DIA of 10. MR, ER and DIA are recorded per value for both single-value and three-value rendering.

Response time (RT) is defined as the time from the end of the haptic rendering to the user's submission of their perceived response. This represents the time required to interpret the rendering as one or more numerical values. The render+response time (RRT) is defined as the time from the start of the haptic rendering to the participant's submission of a response, equivalent to the rendering time plus the response time (RT). This metric is relevant to practical systems since it considers the overall time to convey numeric values to a user, including the time to communicate and interpret. Performance on the distractor task is the mean percentage of acknowledged blue stimuli. Tapping the "Blue" button within 3.5 s of a blue stimulus onset was considered acknowledged, and otherwise missed. We then analyzed the percentage of blue stimuli whose onset occurred during the one second before through one second after the vibrations in each trial. This provides a measure of cognitive effort required for the perception and interpretation of the haptically rendered values.

4.4.6 Hypotheses

We expected participants to exhibit more errors in the temporal rendering (AVF) condition than in the spatio-temporal rendering condition (TOE). The former requires participants to remember a sequence count, whereas the latter requires only memory of the stimulated site. We also anticipated that the spatial association of numbers [71] will help the participants to remember single and three values in their memory after it is rendered. Hence, we hypothesized that our spatio-temporal tactile rendering method (TOE) will perform better than single-site temporal rendering (AVF) method delivered on the wrist, both in terms of accuracy (ER, MR and DIA) and response time (RRT and RT). For both conditions, we expected accuracy to drop, and time response and DIA to rise in the three-value trials as opposed to the single-value trials. Participants' performance in the distractor task was also expected to be superior with TOE than AVF for both single and three-value trials.

4.5 Results

We selected non-parametric statistical tests since the experimental data did not follow a normal distribution. The experiment used a repeated measures design for comparing two conditions, hence, we used the McNemar Test for nominal data and the Wilcoxon signed-rank test for interval data. We implemented these tests via Pingouin 0.2.8 package [64] in Python. The effect size (r) reported is the RBC- rank-biserial correlation.

4.5.1 Pre-Questionnaire Results

Twenty participants reported their right hand and foot as dominant, two left hand and foot, one left hand and right foot, and one right and left foot. No participant reported reduced tactile sensation in their hands, arms, feet or toes. Five participants had already experienced vibration from a smartwatch prior to the experiment. Participants' foot width measured at the toes were in the range of 8.5 cm to 10.5 cm (median = 9.5 cm) and shoe sizes were in the range of 22.8 cm to 28.3 cm (median = 26.0 cm).

4.5.2 Missed Rate (MR)

As shown in Table 4.1, for single-value trials, mean MR for both TOE and AVF was 0.1%. Participants were able to recognize the correct value for almost all the trials. For three-value trials, MR increased for both the conditions, as expected (Figure 4.4). As per Wilcoxon signed-rank test results, we did not find a statistically significant difference in MR between AVF3 and TOE3 ($p > 0.05$).

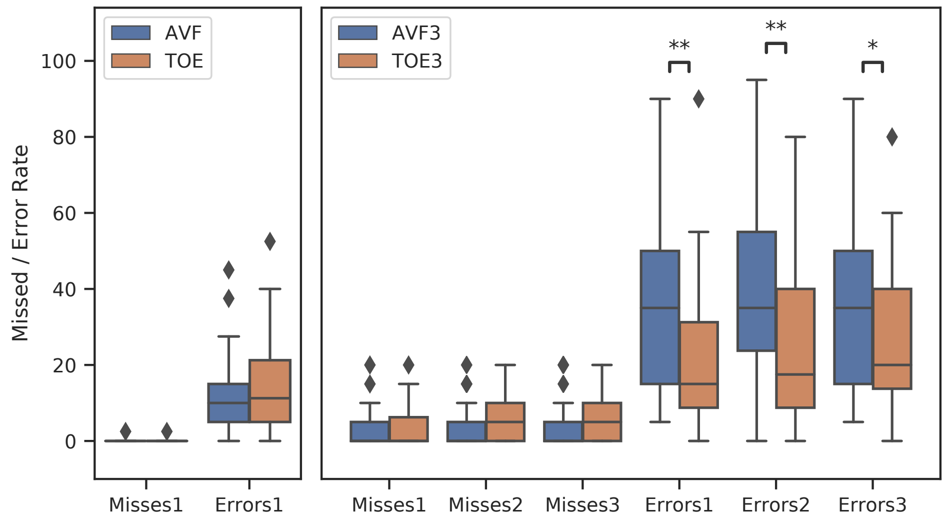

Fig. 4.4: Boxplot of missed rate and error rate for each condition. Error rate is inclusive of missed rate. Lines in the box centers represent medians.

Table 4.1: Mean missed rate and error rate (%) across all conditions

Condition	Missed Rate (%)			Error Rate (%)		
	Val 1	**Val 2**	**Val 3**	**Val 1**	**Val 2**	**Val 3**
AVF	0.1			11.9		
TOE	0.1			14.9		
AVF3	3.3	3.8	4.0	35.8	40.4	38.5
TOE3	4.2	5.2	5.2	21.7	25.6	26.2

4.5.3 Error Rate (ER)

As also shown in Table 4.1, for single-value trials, mean ER for TOE was 3% higher than AVF. However, we failed to find any statistically significant difference between these conditions as per a Wilcoxon signed-rank test ($p > 0.05$). For three-value trials, ER increased for both the conditions (Figure 4.4). Table 4.2 provides the results of a Wilcoxon signed-rank test, which indicated a statistically significant difference between AVF3 and TOE3.

Table 4.2: Wilcoxon signed-rank test for ER in three-value trials

AVF3 vs TOE3	W-val	z-val	p-val	r-val
Val 1	39.5	-2.59	<0.005	0.68
Val 2	48.5	-2.66	<0.005	0.68
Val 3	54	-2.08	<0.025	0.57

4.5.4 Difference between Input and Answered value (DIA)

For both single-value and three-value answered trials, DIA for AVF was mostly concentrated in the range of one to five but for TOE, the maximum proportion of DIA was between one and two (Figure 4.5). A Wilcoxon signed-rank test indicated a statistically significant difference between conditions as shown in Table 4.3.

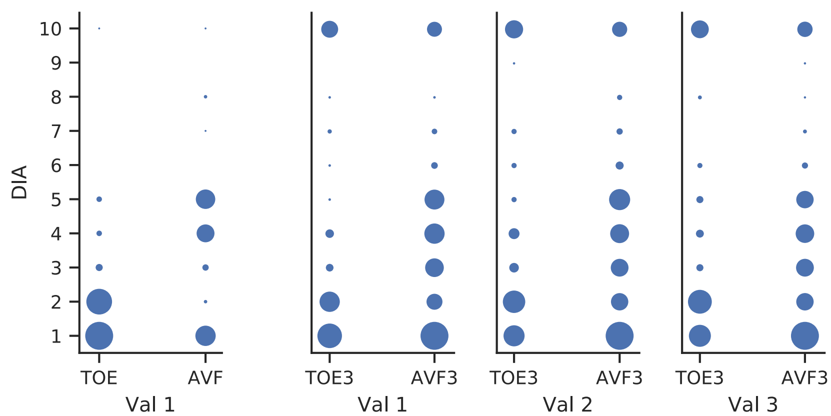

Fig. 4.5: Distribution of trials in which DIA>0, with misses assigned DIA=10. Dot sizes are proportional to the percentage of trials at each DIA level.

Table 4.3: Wilcoxon signed-rank test values for DIA

Condition	Values	W-val	z-val	p-val	r-val
AVF vs TOE	Val 1	10557	-1.83	<0.05	0.16
AVF3 vs TOE3	Val 1	7617.5	-4.53	<0.001	0.36
AVF3 vs TOE3	Val 2	10615.5	-3.59	<0.001	0.28
AVF3 vs TOE3	Val 3	10275	-3.07	<0.005	0.25

4.5.5 Response Time and Render+Response Time

As seen in Figure 4.6, the median value of render+response time (RRT) was higher for AVF than TOE for both single-value and three-value trials. Since the response time (RT) alone is fairly similar between TOE and AVF, these differences in RRT are predominantly due to the higher rendering time of AVF as compared to TOE. The median response time, i.e., time to interpret the value once it has been rendered, was higher for AVF than TOE both for single- and three-value trials. However, the effect size is insignificant for providing meaningful insight in practical applications.

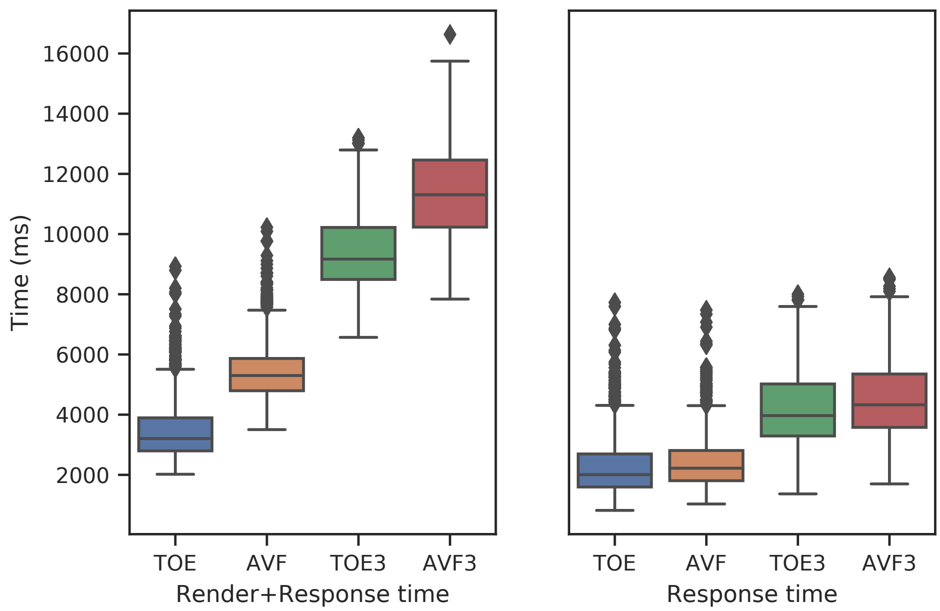

Fig. 4.6: Box plots of render+response times (RRT) and response times (RT). Lines in the box centers represent medians.

4.5.6 Distractor Task Performance

For single-value trials, the mean percentage of acknowledged blue stimuli was 67 % for AVF and 69.5 % for TOE. For three-value trials, this was 43 % for AVF and 52 % for TOE. This difference in performance was significant only for three-value trials as determined by a Wilcoxon signed-rank test ($W = 56$, $z = -2.43$, $p < 0.01$, $r = 0.63$). As we hypothesized, this indicates that

AVF requires more cognitive effort than TOE for three-number rendering.

4.5.7 Post-test Questionnaire Results

In the post-test questionnaire, we asked participants to select between AVF and TOE for their overall preference, accuracy and effort required. Since these data were nominal, we used the McNemar test to calculate statistical parameters. Out of 24 participants, 15 selected TOE over AVF in terms of overall preference (no significant difference), 19 participants selected TOE over AVF in terms of accuracy ($\chi^2 = 7$, $p < 0.01$), and 19 participants reported AVF to require more effort than TOE ($\chi^2 = 7$, $p < 0.01$). These subjective responses are consistent with our aforementioned objective measurements obtained during the study.

4.6 Discussion

Our proposed method, HapToes (TOE), performed on par with ActiVibe (AVF) for single-value rendering and exhibited a lower error rate than AVF for three-value rendering. This could be attributed to the spatial association of numbers in cognition, for example using a mental "number line". Although haptic signals can leverage duration to represent numbers, it has been reported that temporal tasks are easily disrupted by secondary tasks [71].

Another significant advantage of TOE/TOE3 over AVF/AVF3 is its smaller average DIA. Although TOE often exhibits DIAs of one, i.e., the perceived value is one unit off the rendered value, AVF suffers from DIAs in the range of one to five. By the nature of the AVF rendering, if a user confuses the long vibration representing five with a pre-signal vibration, and thus ignores it, or confuses the long vibration with a short one, this can result in a DIA of five or four, respectively. DIAs of two and three may also result from counting the short vibrations incorrectly.

Following termination of the haptic rendering, the time required for participants to interpret the rendered values differs by a negligible amount of 200 ms on average, with TOE obtaining faster responses than AVF. Additionally, the reduced rendering time of TOE results in a shorter overall time required to convey a value and have it interpreted, i.e., time from the start of the haptic rendering to the participant's confirmation on the tablet of the perceived value. This is, naturally, desirable for improved efficiency of information communication.

Furthermore, the results related to distractor task performance suggest that TOE rendering imposes lower cognitive demands than AVF. Indeed, the spatial mapping in TOE does not require the same sustained concentration effort to keep track of a series of vibrations, as does AVF. As one participant described, they “associated vibration to toes quite early so there was a visualisation component”. Once one identifies which toes were targeted and in what order, this information can be retained in short-term memory while attending to another (distractor) task. As soon as the distractor task is no longer occupying attention, the memorized toe sequence can then be interpreted as the intented values. In contrast, this strategy does not apply with a temporal mapping, requiring counting, as does AVF.

We note that the comparison of TOE to AVF is not intended to demonstrate a general superiority of one method over another. These are inherently very different techniques, with the former requiring instrumentation over multiple toes, and employing spatio-temporal tactons, while the latter uses a single consumer device worn on the wrist, and renders temporal tactons. These two options are therefore suited for different scenarios, one in which simplicity of hardware is preferable, and the other for which accurate delivery of multiple numeric values is required, or where the wrist is otherwise unavailable as a locus for information delivery.

Although, the performance of TOE is favorable when used for seated applications, its suitability to tasks involving a user in motion remains to be investigated. The current hardware only serves as a proof of concept prototype for the encoded rendering. An improved design would be required to ascertain its use as a wearable, and overcome challenges of inconsistent haptic coupling and interference from motion, which create haptic noise. While we expect that accuracy would decrease when the user is standing, it would be important to characterize the performance drop while walking or running, compared to the effects on wrist-based rendering. Moreover, improvements in foot-based haptic interfaces could help enhance the performance, leading to a more acceptable and practical device suitable for everyday use.

4.7 Conclusion

We presented HapToes, a novel numeric haptic rendering method for toes. HapToes outperformed ActiVibe, a previously reported method for communicating numeric values, establishing its possibility of serving as a ten-unit tactile display. Although it might not be possible to convey phone numbers haptically to distracted users using this method, the results of our study suggest that reasonably accurate identification of large numbers under modest cognitive load is feasible. Increased accuracy could be achieved with further improvements to the rendering device. For example, more capable vibrotactile actuators such as voice-coil actuators would enable delivery of a different frequency of vibration to each toe, to enhance the discriminability of adjacent toes, which remained the source of most erroneous trials. It would also be interesting to investigate how the rendering would perform using an entirely different haptic stimulus such as electrotactile actuation.

Acknowledgment

We thank members of the Shared Reality Lab for their suggestions and help in the development of the prototype. We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC), RGPIN-2017-05013, and the MITACS Globalink Graduate Fellowship Award. McGill REB #83-0814.

Chapter 5

Haptic Assisted Guidance for Novice Dancers

In the previous chapters, we discussed how we could enhance the capabilities of foot-based wearables to convey a broad set of information such as numbers. In addition to information delivery, owing to their role in locomotion and balance control, the feet could also serve as an apt location for sensing movement-related parameters and rendering guidance cues. Hence, in this work, we expand the scope of foot-based interfaces and propose their application in training physical activities such as dance. We discuss the problems faced by novice dancers during training and suggest solutions that can be implemented through haptic-augmented smart shoes.

For dance learning application, the shoes should not only convey guidance cues relevant to the movements but also sense the dancer's motion profile for analysis and feedback. Although several foot-based interfaces have been presented before, a group of these designs focused solely on conveying vibrotactile information [2, 16, 79], whereas another focused exclusively on sensing motion profile [9, 28, 80, 81]. The designs in the former group often suffer from the propagation of tactile stimuli between locations in mobile conditions as they used the plantar side of the feet for placing the actuators. In that respect, we propose a new placement of actuators considering both the dorsal and the plantar side of the feet and present a design of haptic-augmented shoes having motion sensing as well as haptic actuation capabilities. Several other groups [26, 82] have recently developed similar hardware, but since these are only research prototypes, not widely available, we decided to develop our own version to study haptic-assisted dance learning. The design of our shoes is presented in this chapter along with a proposed haptic-assisted guidance system.

Author's Contribution

Preeti Vyas proposed the research direction, initiated the collaboration with a dance instructor, supervised the design of the shoes, and wrote this chapter. She is currently leading the project. Antoine Weill--Duflos supervised the hardware design. Jennie Chen designed the PCB and assembled the hardware for the shoes along with Bruce Bu. Prof. Cooperstock edited this chapter; he is currently supervising this project.

5.1 Design Rationale

In a classroom setting, dance instructors train dozens of students in a session; hence, they are unable to provide frequent individual feedback. Indeed, the students often go through several practice sessions before recognizing their mistakes. If they are not corrected for their mistakes in the early stages, the prolonged repetition of incorrect movements can cause injuries. Hence, there is a need for a personalized system for dance training that provides frequent feedback to novice dancers in the initial stages of learning.

Any particular dance style is developed over a set of core movements, often referred to as the basic steps. Mastering these steps requires three fundamental elements: following the direction of movement, adapting to the rhythm, and learning the weight transfer technique. Novice dancers often struggle to grasp these concepts in a classroom setting. We assume that instrumented footwear can assist them in this process as it can serve not only as a medium for conveying instructions but also provide frequent feedback based on their motion.

The footwear has to deliver two things: first provide instructions during the training process, which maps to the directions, rhythm, and weight profile; then sense the motion profile so that we can convey necessary feedback. For the former, we have to formulate and present accurate representations of the information using a suitable modality; for the latter, we need to gather motion and pressure profile of the novice and the expert dancer and compare them to devise feedback strategies.

The instructions can be provided through visual, audio, or haptic cues. We focus on the haptic modality as the others may not be suitable for real-time guidance in dance learning applications. Audio cues would distract the user and affect their focus on music; similarly, visual cues would divert attention from their own body. As haptic cues are felt through the skin, we hypothesize that with practice, learners could adapt and perceive these cues with less cognitive load.

5.2 Architecture

As discussed in Chapter 2, the haptic perception capabilities of the feet and the prior work on foot-based interfaces informed the design of our prototype. The proposed solution requires motion and pressure sensors to learn about the dancer's movement and haptic actuators to convey the guiding cues or feedback. We embedded these sensors and actuators in the shoes for durability, convenience, and better coupling with actuators as compared to that of open footwear.

Fig. 5.1: Haptic shoes

5.2.1 Hardware

Each shoe consists of four ERM actuators (2 mm Mini Vibrating Disk Motor, RB-See-403, Seeed Studio) for rendering vibrotactile stimuli. They are placed in the shoes using resin support. The vibrotactile actuators have a rated voltage as 3 V and rated speed as 10 000 RPM (167 Hz); they provide an average acceleration of 0.8 g, where g is gravitational acceleration. The motor drivers (DRV8835 Dual Motor Driver Carrier) drive these actuators. We preferred the ERM over voice coil actuators because of their compact size and ease of operation.

Force-sensing resistors (Interlink Electronics 0.5″ Circular FSR) are incorporated in the sole to measure loading at critical points; prior work [2] informs their placement. These units are serially connected to 8.2 kΩ resistors. An inertial measurement unit (Adafruit BNO055 Absolute Orientation Sensor) is used for sensing the motion profile.

A microcontroller (Espressif Systems ESP32) powered by a rechargeable lithium-polymer battery (3.7 V, 1200 mA h) is used to drive the sensors and the actuators on each shoe. The battery is connected with a charger (5 V/1 A) to allow for easy charging. A custom PCB encases all the microelectronic breakout boards. The whole assembly is attached to the arch of the shoes (Figure 5.1). In the future, we plan to make this assembly compact and enclose it in a 3D printed encasing.

5.2.2 Actuator Placement

We discussed in Section 2.3 that previous foot-based haptic interfaces used plantar region of the feet to place the actuators [2, 16, 79]. Anlauff *et al.* [2] used a similar placement and reported that the tactile recognition rate decreases when their prototype is tested for walking conditions. As discussed in Section 2.1, this is because the mechanoreceptors in the feet have a sizeable receptive field and lower two-point threshold; it is possible that vibrations from the actuators placed near to each other could propagate.

We assume that selecting far spread locations for actuator placement would improve the recognition rate. Hence, we selected the locations considering both the dorsal and the plantar side of the feet [10]. Based on the design reported by Anlauff *et al.* [2], we placed two actuators below the ball and the heel of the foot but moved the other two from the metatarsal arch to the dorsal side (Figure 5.2). The actuators placed on the dorsal side are well coupled with the feet because of the closed shoe design and are not affected by the dampening that occurs in the mobile phase.

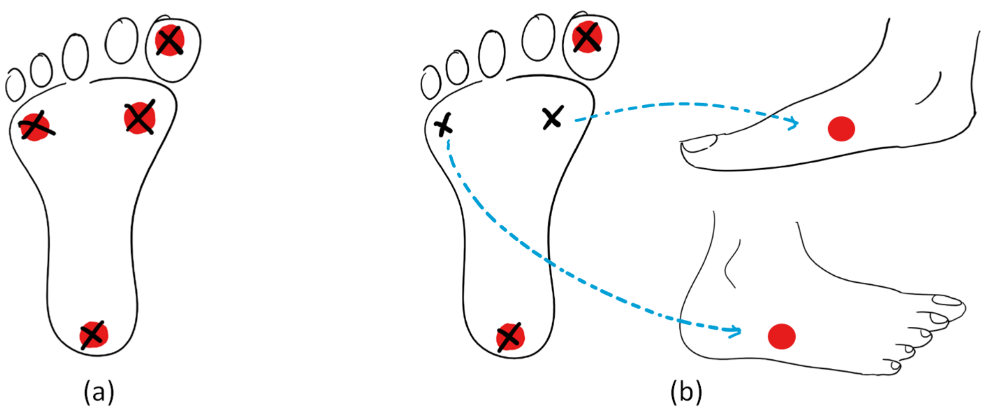

Fig. 5.2: Placement of actuators and force sensors. The actuators are marked by red dots and the force sensors are marked by crosses (X). Sub-figure (a) shows the placement used by Anlauff *et al.* [2] whereas (b) shows our proposed placement incorporating the dorsal side.

We conducted a pilot study on three participants and compared these placement strategies. The vibrotactile actuators were attached to the participant's dominant foot using medical tape. Based on the placement location, they were named as *front*, *back*, *left*, and *right*. During the study, we asked the participants to walk in a room and respond verbally when they perceive vibration. As an example, if they feel vibration on the actuator placed under heel, they will say *back*. We rendered 96 trials for each type of placement; a trial involved stimulating one of the locations with a 500 ms long vibration; subsequent trials were separated by 2 s gap. According to the results, our hybrid arrangement had a 17% increase in the average recognition rate of stimuli when compared with the plantar placement reported by Anlauff *et al.* [2]. Hence, we used the hybrid arrangement for placing the actuators on the shoes.

5.2.3 Communication

Wireless communication is preferred for this application. The microcontroller on each shoe serves as a client and communicates information over WiFi. A Python server running on the desktop connects to these microcontrollers and acts as a controlling unit. The communication is established using a ZMQ socket-based architecture (`https://github.com/vladglv/MAHFP`).

5.2.4 Software

In the current stage, off the shelf Python and Arduino scripts are used for interfacing and testing the prototype. The next step is developing a data processing pipeline and designing tactile cues for instructions and feedback. We also plan to build an interactive GUI for displaying visualization of motion profile and performance parameters. Figure 5.3 shows the proposed architecture of a haptic guidance system incorporating the shoes. It is discussed in detail in the following section.

5.3 Haptic Guidance System

In the previous section, we presented the design of haptic-augmented shoes. We can use this prototype to test different paradigms while developing a guidance system for dance learners. As discussed in Section 5.1, we are focused on three elements of dance—direction of movement, rhythm, and weight transfer. Developing a guidance system that incorporates these elements is a multi-step process and involves several design and research questions. In this section, we will be outlining these questions and presenting a proposed direction of work.

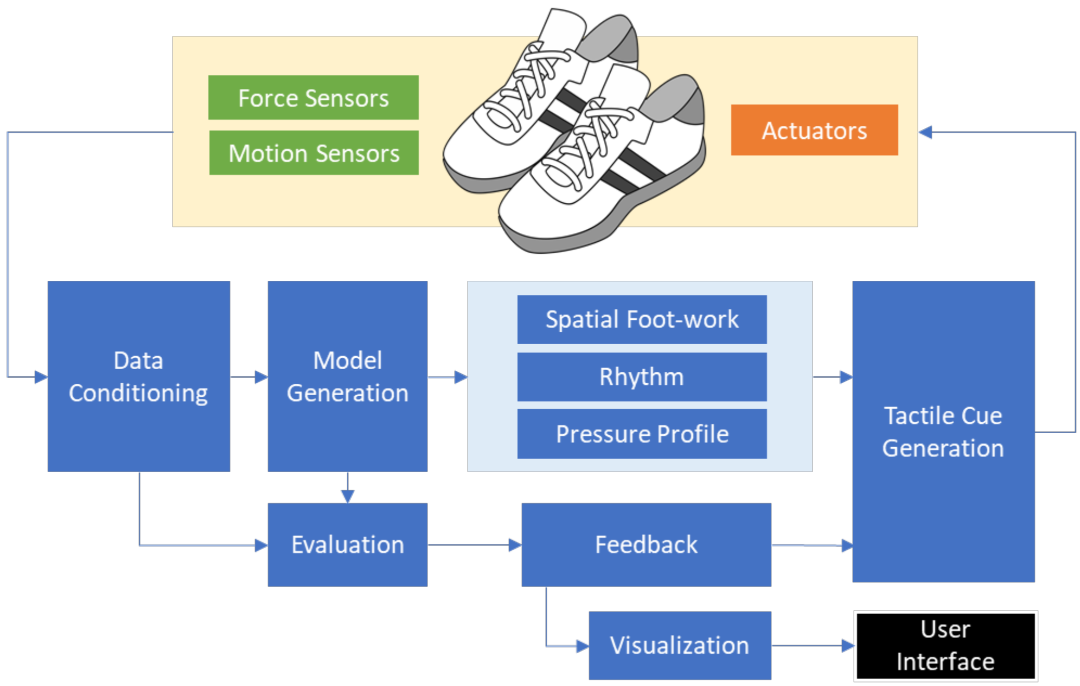

Fig. 5.3: Software architecture

5.3.1 Characterizing Dance Steps

To develop the guidance system, we first have to characterize expert dancers' movements and create a model that informs how they move in space, what their rhythm is, and how they distribute their weight on the feet while performing transitions. There can be two ways to derive this: we can either survey several expert dancers to create a fixed model or record their movements using the shoes and learn a model from the pressure and motion-sensor data. The latter method seems more plausible as it might capture the intricacies of movements that would not be noticed otherwise. Prior works have used the shoe-mounted accelerometer to detect the rhythm [35, 28, 34] and provide position and orientation estimation [83, 84, 85]. We assume that once we gather sensor data, we can incorporate these techniques to develop our model.

5.3.2 Conveying Instructions

After deriving the model, the next part of the process is conveying this information to the users through the haptic cues. In this part, we have to define the granularity of the instructions—whether the users need recurrent guidance or specific cues during the transitions. This decision will inform the design of haptic patterns. Figure 5.4 shows example haptic patterns designed to render the directional movement for the basic steps of Salsa. Using inspiration from prior research, different set of tactons [23] can be used to convey aspects of direction, rhythm and weight transfer. A thorough design and contextual user testing will inform their usability.

5.3.3 Evaluating Progress and Providing Feedback

While following the instructions to perform dance movements, the learners require a system in place to assess their performance and provide them with feedback. Hence, we need to explore methods for evaluation and feedback.

One method for evaluation can be recording user's motion data through the shoes and comparing it to that of an expert dancer. We can compare the average accelerometer and force sensor data by calculating the root mean square error. However, this method will require complex calibration, as the individual sensor data may vary based on the style of movements, weight profile, or movement latency. Calculating the cross-covariance can give a better insight into temporal as well as spatial relationships between the movements of novice and expert dancer [86].

The feedback can be given simultaneously during the movement, i.e., concurrent feedback, or at the end of a defined set of movements, i.e., terminal feedback. Researchers have debated the effectiveness of concurrent vs. terminal feedback [87] for motor learning. For our application focused on early-stage dance learning, a combination of concurrent and terminal feedback would be beneficial. However, when the dancer acquires specific fundamental skills, they would profit more from the terminal feedback. For delivering the concurrent feedback, we need to design a unique set of tactons, different from the ones used for guidance. Terminal feedback can be presented by visual or audio messages through the user interface [88].

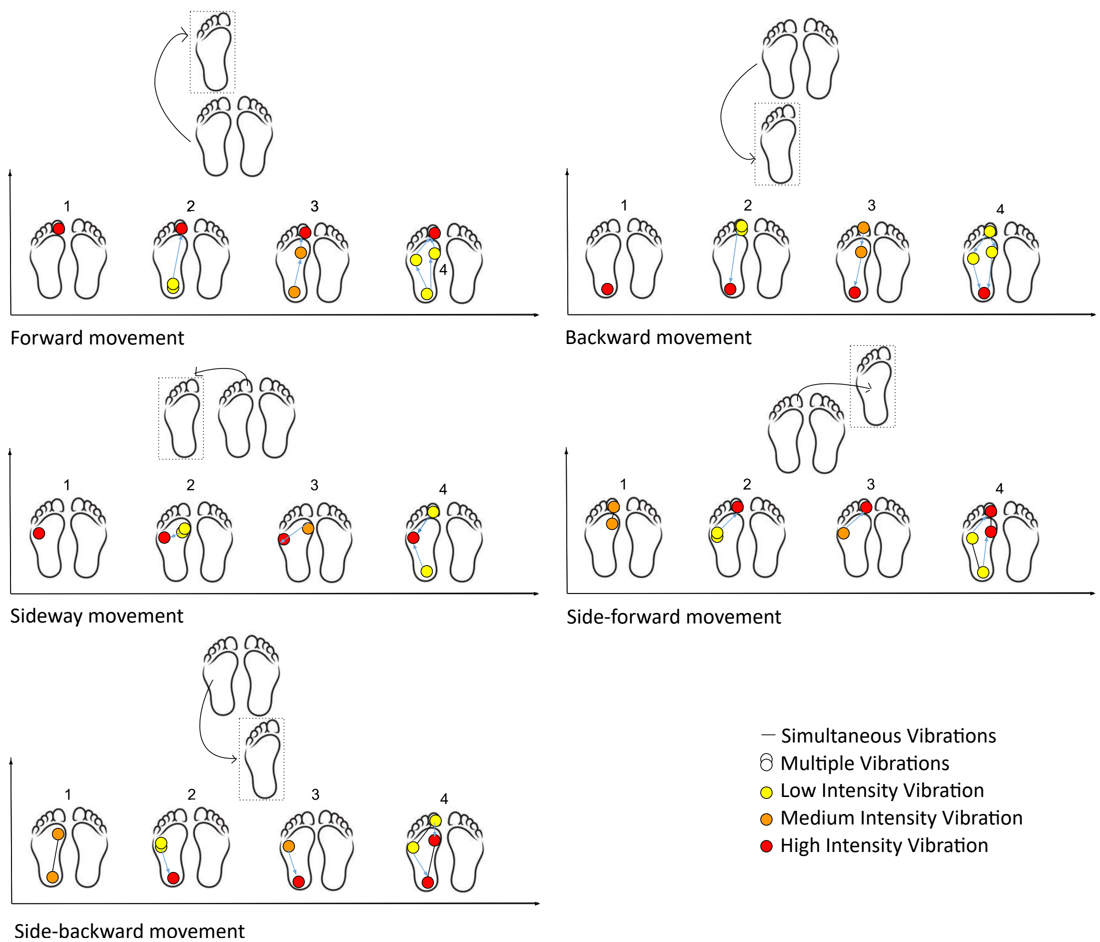

Fig. 5.4: Sample haptic patterns to convey basic steps of Salsa. Pattern 1 has vibrations directly mapped to the direction of foot movement. Patterns 2 and 3 have vibrations that lead to a particular direction from the opposite side and hint movement along a line. Pattern 4 creates a gradient vibration using almost all the actuators for conveying a direction; this might have a sweeping effect.

5.3.4 Developing a High-Fidelity User Interface

Santos *et al.* [88] have presented a prototype mobile application for dance training systems. In the future, we can develop such an application that interacts with the shoes and presents personalized summaries, visualization and narratives based on the learning process. A detailed user interface research taking the dance learner and the instructor in the loop can give us insights about the necessary functionalities.

5.4 Challenges

To achieve the goal of facilitating novice dancers during the learning process, we need to overcome several design and research challenges.

- We have suggested an alternative placement of actuators based on our preliminary pilot study. Although we tested our actuator placement for walking conditions, we still have to perform extensive testing for dancing. It might be the case that the vibrations get dampened during dynamic stance and the dancers do not perceive them effectively.
- Dancing is an art and is very qualitative in nature. Based on the procedure of traditional learning, we plan to model several aspects of dancing quantitatively. However, multiple variations and styles originate from a particular dance genre, and it could be challenging to capture all these crucial elements in our model.
- The notion of correctness in dancing is vague. Based on prior work, we assume that we could gain understanding of performance parameters from comparing sensor data of expert and novice dancers and provide relevant feedback; however, we are not sure how dancers' diversity and their variations of movements and styles will effect the evaluation algorithm.

5.5 Conclusion

In this chapter, we proposed a haptic-based guidance system for dance learning. We aim to design this system for novice dancers to assist them in learning fundamental movements effectively. Although the core contribution of this work is the design and assembly of haptic-augmented shoes; we have also discussed the research questions and design challenges, which will inform the development of the overall system. The process of dance learning consists of several elements, out of which we have focused on spatial foot-work, rhythm, and weight transfer. The scope of our project is limited to lower-body dance movements. However, our system can be combined with sensors and actuators on the upper body to develop a full-body guidance technique. Moreover, this architecture can be adapted to design training methods for related physical activities such as martial arts, yoga, and weight lifting. It may later contribute to assistive technologies for those with vision or hearing impairments.

Chapter 6

Conclusion

Foot-based interfaces have significant potential in haptic communication. In cases where hands are occupied, and the use of other body locations is not suitable, the feet offer an alternative site for discreet and unobtrusive communication. This thesis broadly discussed two themes relevant to haptics research on feet—the exploration of new locations on the feet for haptic rendering and the application of foot-based haptic interfaces for learning physical activities.

Although there are foot-based wearables that assist in navigation, gait training, and fitness-tracking, they only use specific plantar locations such as the metatarsal arch or heel for haptic delivery via feet and convey limited information. As the feet have ten digits, similar to that of hands, we hypothesized that we could use them as a possible location for rendering information in cases where numerosity is an essential factor. Hence, we explored the toes as a location for tactile communication. It has been reported by prior literature that toes have inferior tactile discriminability as compared to fingers. To mitigate this, we presented a design of tactile encoding. Our method demonstrated performance similar to that of fingers, justifying the use of toes as a suitable location for tactile rendering.

Motivated by these results, we further tested our method for rendering numeric information, which could find use in haptic foot-based interfaces. We presented HapToes, our haptic encoded rendering for conveying numeric information via toes. We evaluated its performance against ActiVibe, a previously reported haptic numeric rendering technique. The results proved that our method performs similar to ActiVibe for rendering a single value and establishes superiority for conveying three values.

There are several ways to use a ten-unit tactile toe display that may facilitate the design of assistive systems and interactive interfaces. For example, in a control room setting, we can map each toe to the alert messages coming from a particular monitored unit or in a navigation system, we can assign each toe to the type of location such as cafe, hospital, or railway station. We can also use toes for conveying Braille messages and, if needed, develop an entirely new tactile language based on the toes. That said, we speculate that numerosity in the egocentric reference frame of one's hands or feet may be comparatively less suited to encode non-ordinal information and likely impose a higher cognitive load if used to represent items having either a different spatial layout in the exocentric environment or no spatial association at all, for example, alphabets, phonemes, or words. However, we still believe that testing the tactile toe display for such use cases would be crucial to gain concrete evidence.

Another research direction that we discussed in this thesis was the application of foot-based wearables in dance learning. The human feet are responsible for locomotion and balance control, which makes them a natural location for providing guidance to learn lower-body motor skills for any physical activity. Dancing is a particularly complex activity that involves aspects of directional movements, rhythm and weight transfer. Novice dancers often struggle with these aspects and can be helped with a well-designed guidance system. We presented a design of haptic-augmented smart shoes and proposed new locations to place the haptic actuators on the feet. The sites used by previous researchers were on the plantar side of the feet, which often experienced the weight of the body and allowed for dampening of vibrations. As we needed locations that are widely separated and not affected by the propagation of vibrations, we experimented with the sites on both the dorsal and the plantar side of the feet. Our pilot experiment proved that a hybrid placement considering both sides of the feet performs better than the plantar placement of actuators; hence we used this design for our haptic-augmented smart shoes. We further discussed the design of a haptic-assisted guidance system for dance learning and reported several research questions and design challenges relevant to this system.

Currently, as an initial stage, we proposed this system specifically for novice dancers and focused on training for fundamental movements. However, in the future, such a system can offer several possibilities for facilitating individual as well as group dance learning. With an extended network architecture involving several pairs of instrumented shoes, this system can assist a group of dancers by recording their movements, analyzing their motion, and giving them individual as well as comparative feedback.

We presented proof of concept prototypes for tactile toe display in Chapters 3 and 4 and a pair of haptic-augmented shoes in Chapter 5. These prototypes were developed to test our research hypotheses and might not represent the final form factor of the product. As the adaptability of any smart wearable relies on comfort and familiarity, further work would be needed on the design and hardware assembly of these prototypes. In that respect, the tactile toe assembly can be embedded in shoes or insoles. Similarly, the microelectronic assembly currently placed on the arch of the haptic shoes can be embedded in the shoe fabric or sole. We can further use flexible electronic circuits and a newer version of vibrotactile actuators that are directly coupled with the skin such as *Tacttoo* [53] or *Springlets* [54].

Although there are different ways in which we can render haptic stimuli, we only experimented with poking and vibration because of their familiarity and ease of use. As the results of our study suggested that there was no significant difference between these two methods of stimulus delivery, we chose vibrotactile actuators because of their smaller form factor as compared to solenoids, the actuators used for poking. In the future, experiments can be done with different types of tactile input on feet such as electrotactile stimulus, skin stretch, or temperature.

In the scope of this thesis, we only discussed applications for the general user base; however, as the haptic modality augments the sense of vision and hearing, these systems can also prove useful for communities with vision and hearing impairments. As a use case of haptic numeric rendering on the feet—a foot-based navigation system designed for the visually impaired can not only guide them to the bus stop but also convey the information about the bus number or the time when the next bus arrives. Similarly, a pair of haptic-augmented shoes can help novice dancers with vision or hearing impairments to learn several aspects of dance movements effectively.

Our research suggests that foot-based haptic interfaces have much potential, both in the domains of information delivery and guidance systems. Although it is challenging to overcome imperfect coupling of actuators and dampening of haptic stimuli in mobile conditions such as walking and running, it is still interesting to explore the possibilities of haptic communication through the feet and develop methods to tackle these challenges.

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