Chapter 16
Usability of Foot-Based Interaction Techniques for Mobile Solutions

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Abstract Although hand-based interaction dominates mobile applications, this can be unsuitable for use by motor-impaired individuals or in situations such as musical performance or surgery, where the hands are otherwise occupied. The alternative of foot-based interaction, the subject of this chapter, has been shown to offer reasonable performance in such conditions and offers benefits in terms of diversity of input techniques, wide applicability, and social acceptability. This chapter also describes potential applications of foot-based interfaces, with an emphasis on factors related to usability. We aim to inspire designers and developers to consider the potential for leveraging interaction through the feet as a replacement for, or complement to, more traditional application designs.

16.1 Introduction

Hand-based input is a dominant interaction method of interacting with mobile devices. However, the hands are often occupied with various activities such as operating a tool or playing a musical instrument, and manual input interfaces are often unsuitable for use by populations with hand-motor impairments [47]. We regularly and comfortably use our feet in daily life, whether for walking, playing sports, or control of machinery, e.g., driving a car. These factors motivate the development of foot-based interfaces, whether for scenarios in which the hands are fully occupied, or for supporting, extending, or replacing hand-based interfaces.

Usability of foot-based interfaces has been a major topic of exploration, related both to the use of the foot as a means of providing input to a computer, and of the approaches for providing feedback to the user via the foot. With regard to the former, input gestures must be designed or selected in such a manner as to minimize fatigue, which depends on an awareness of physiological constraints and the achievable

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accuracy of foot motor control. Effective performance limits may be determined with measurement tools such as Fitts' Law [14] and used in the design of appropriate interfaces for parameter control. When used for conveying information to the user, foot-based interfaces can be compared on the basis of quantitative measurements of signal values and on the qualitative effects of their perception by the user. A significant body of work has considered the design of haptic icons [11], or "tactons" [9, 10], for which unique challenges arise when delivered to the feet as discussed further in Sect. 16.3.

In this chapter, we discuss the main foot interaction approaches, including foot-controlled input and sensing through the feet. Our aim is to convince the reader of the usability, usefulness, and effectiveness of foot-based interaction.

16.2 Foot-controlled Input

Significant research efforts have been invested toward supporting and replacing hand-based interfaces with foot-controlled systems. The feet have been shown to have great potential as an interaction tool to handle secondary tasks [21, 28] or as the main source of information [15, 33] in situations where the user's hands are occupied or unavailable. These interfaces usually take advantage of one or more of the many gestures and actions available via the feet, e.g., distributed pressure, 3D motion and positioning, pointing, flexion, etc.

Here, one of the first key issues that need to be addressed with foot-based interfaces is how to capture input from the feet. For detecting position and motion, some of the most common approaches rely on shoe platforms equipped with a battery of sensors (e.g., inertial measurement units, pressure sensors, proximity sensors, etc.) [13, 15]. Video-based tracking that relies on traditional camera technologies [33] as well as highly accurate motion capture systems [21] are also used for capturing position. Position and motion data are most often used in spatial tasks since they are better than more constrained approaches (e.g., using force sensors) at capturing the full degrees of freedom of the foot and leg. As a result, systems can be trained to recognize precise gestures and associate them to software-specific functionality. Due to the relative strength of the lower body limbs and the frequently limited extent to which they are occupied with other tasks (e.g., while sitting or standing in place), the addition of instrumentation in custom or conventional shoes is often less cumbersome and more comfortable than equivalent systems installed on the users' hands.

Foot gestures that are based on foot-pressure or foot-force data are called foot rocking gestures. To detect rocking gestures, sensors are typically embedded in a shoe's insole [15] or into the floor itself [29] and detect the foot pressure distributions at strategic anatomical positions. An obvious advantage of rocking gestures in comparison to their motion-based relatives is that they offer a discrete and natural interaction [15]. They lend themselves particularly well to selection and scrolling tasks. In the following subsections, we summarize a variety of foot gesture studies and applications.

16.2.1 Foot Gesture Research

While each application has its own set of constraints, fundamental studies exploring the general properties of foot movements have been and are still being reported. For example, Velloso et al. recently reported a performance comparison between (1) the dominant and nondominant foot, (2) preferred foot movements, and (3) interaction techniques and visualization [40]. First, employing the ISO 9241–9, one- and two-dimensional tasks based on Fitts' law (Fig. 16.1), they compared the performance of the dominant foot versus nondominant foot. In their experiment, each participant performed a total of 468 Fitts' law trials with both feet under nine difficulty levels that varied the width (W) of the targets and the distance between them (which the authors refer to as "amplitude" so is marked "A" in Fig. 16.1). They concluded that there is no statistically significant difference between the dominant and nondominant foot, with regard to the throughput in one- and two-dimensional Fitts' law tasks. In addition, after the second round of trials, the average throughput of horizontal foot movements (2.11 bit/s) was found to be significantly superior to that of the vertical movements (1.94 bits/s) in two-dimensional space.

Second, they compared five different foot gestures: dragging in horizontal/vertical directions, lifting, and heel/toe rotation, to find which input modality was preferred by participants in a targeting task. Their findings determined that the heel rotation movement was the most comfortable and preferred by the users. Participants reportedly experienced significant fatigue while performing the dragging and lifting

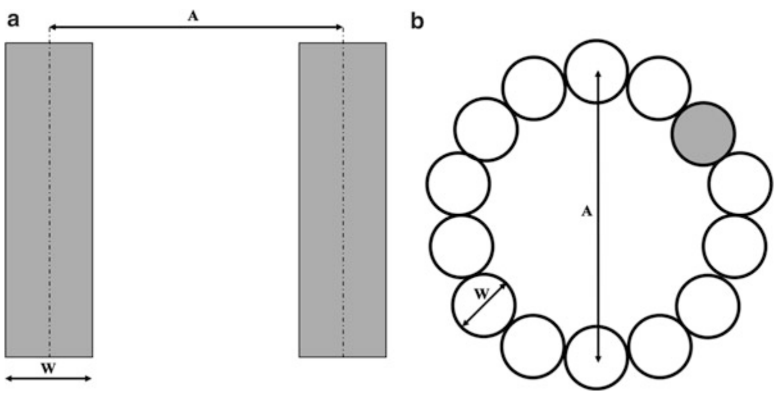

Fig. 16.1 Fitts' Law task (ISO 9241-9). (**a**) One-dimensional Fitts' law task. (**b**) Two-dimensional Fitts' law task

gestures because of the friction observed between the shoe and the floor and of the constant need to work against gravity.

Lastly, they studied how interaction and visualization techniques can influence performance in tasks involving the control of two parameters. Three interaction methods were designed, with a range of options involving one or both feet, and using horizontal and/or vertical foot motion to control multiple parameters in a software simulation. After participants performed tasks that involved different visualizations of the data, they determined that visualization has a significant impact on the performance of multiple variable entries in foot-based interfaces. For example, they observed the worst performance when participants controlled two vertical sliders by using the horizontal and vertical axes with a single foot. However, the same mapping allowed an effective and efficient method for resizing virtual rectangles. This highlights the importance of consistency between users' actions and the effect in the interface. These performance comparisons of different gestures and techniques by Velloso et al. would help to design improved foot-based mobile solutions by considering performance of each gesture and the effect of visualization.

Scott et al. explored the performance of foot lifting and rotation gestures with regard to their axis of rotation [35]. Participants performed a target selection task using gestures informed by anatomical characteristics of the human foot (e.g., dorsiflexion from 10° to 40°; Plantar flexion from 10° to 60°; and heel and toe rotation from −90° to 120°). Their findings showed that plantar flexion exhibited the lowest average selection error at 6.31°, followed by the heel rotation (8.52°), toe rotation (8.55°), and dorsiflexion (11.77°). Unlike the other gestures whose error rates varied as a function of the target angle, plantar flexion had relatively consistent error across the input space. Based on their findings, they proposed to discretize the angle range into three sections to account for the limited accuracy of the gestures. They proposed that the toe/heel zones span from 0° to 25°, 25° to 60°, and more than 60°. For plantar flexion, ranges from 0° to 20°, 20° to 50°, and more than 50° were chosen as optimal. Therefore, the range of each foot gesture and its properties should be considered according to targeted foot-based interactions for mobile solutions.

Finally, Han et al. explored the feasibility of kicking gestures for mobile use cases [16]. In this study, participants used a kicking gesture to specify either direction or velocity. The gesture was detected by a depth camera (Xbox Kinect) using the Open Natural Interaction (OpenNI) library, and all experiments were performed with participants viewing the scene on a 7inch display. To investigate the human ability to control the direction of a kick, they first designed a football game where participants had to kick a virtual ball into a target area. The target area was ranged according to the number of angular divisions where a provided area (from −60° to 60°) was divided into 3–10 divisions. In their result, three divisions showed the highest performance as 96% whereas 10 divisions achieved only 46% accuracy. They determined that five-division condition is the best division since it has reasonable performance a 88% and a suitable number of segments for selection applications. As a second step, they measured the users' ability to control the velocity of the kicking gesture by placing the ball in a fixed location in front of the player and asking them to adapt their motion to match the visually displayed velocity range.

Their results showed that the two-division condition achieved around 87% overall velocity accuracy. However, the three- and four-division conditions did not exhibit significant differences with observed accuracies of 60% and 50%, respectively. Overall, undershooting was observed and participants had difficulty controlling their velocity to match the target ranges when more than two divisions were provided. Thus, the kick gesture for mobile solutions can controll up to five directions, and two kicking velocities. Therefore, to design improved mobile solutions with foot-based interactions, the characteristics, performance, and constraints of each gesture should be considered.

16.2.2 Mapping Foot Gestures to Functions

In the previous section, we discussed several examples of how gestures are constrained by the limits of the human body but covered only limited examples of how those gestures were mapped to specific functionality in the application itself. This section discusses this mapping in greater detail.

Because of our experience with using our feet in the real world, foot gestures are often interpreted in specific ways, which can be used to design more intuitive mappings. For this reason, assigning a suitable foot gesture to a specific function is as important as accurately capturing the foot gesture in the first place. Recent research has pursued finding an optimal gesture set suited to functional aims. For example, Alexander et al. conducted an elicitation study to generate a set of foot movement-based gestures for mobile applications [1]. They observed 537 commands by 19 participants and then extracted 30 commands and mapped each gesture to a specific function by evaluating participant agreement and gesture generalization. After these processes, they selected 13 commands for a follow-up experiment, such as media control and map navigation, and measured the recognition accuracy using a pseudo-wizard-of-oz method. Similarly, Fukahori et al. collated a set of foot pressure-based gestures appropriate for diverse functions [15]. First, they collected 563 gesture concepts in 29 operations from 20 participants and after observation of the gestures performed by participants proposed 29 gestures. The suggested foot gestures aimed at functions, and also the experimental designs in these works would be helpful to design a gesture for a specific function for further mobile solutions.

Whereas most studies limit themselves to mapping a foot gesture to a single function, Saunders et al. [33] explored how a single set of gestures could be mapped onto functions across multiple applications. Although this approach reduces the number of gestures to be memorized, it was confusing to users when they switched between applications, even with access to an integrated help function. For a diverse set of applications, a one-to-many mapping of gestures to functions across different applications may be criticized as risking inconsistency. So, considering both how many gestures and how to map them to functions is required when designing specific solutions.

Although the inconsistency inherent in mapping gestures to diverse applications is difficult to entirely avoid, an approach, based on observations of ordinary foot movements and social acceptability can help to design gestures that have common meanings across applications. The tapping gesture is one example that has a high level of social acceptability and is considered a subtle and everyday gesture [31]. Using tapping gestures effectively has been investigated by many previous works. Crossan et al. compared single tapping with double tapping and observed that single foot tapping was preferable to, and more robust than, both feet tapping, where the user tapped both feet at the same time [13]. Tapping could be accomplished either by toe tapping or heel tapping. Toe tapping is generally preferred to heel tapping due to its relatively low effort and historical operation of pedals [41].

16.2.3 Foot Pointing: Spatial Data

Significant literature exists on the topic of foot-controlled interfaces applied to spatial manipulation tasks. The vast majority explored the performance of foot-based interfaces in comparison with hand-based interfaces and their ability to transfer spatial information. Pakkanen et al. investigated the usability of foot interaction for non-accurate spatial tasks [28]. In their study, participants were given four tasks with different complexity levels, controlled via a trackball operated by either the dominant hand or foot. In each task, participants were required to move toward a target point where the range of movement was set as under 300 pixels. Overall, the hands outperformed the feet for average completion times, accuracy, and user satisfaction. Furthermore, the foot showed limitations for fine manipulations that needed less than ten pixels.

However, recent literature has shown us that while hand-based interfaces using mice and track pads remain dominant, foot-based devices are becoming increasingly accurate. Indeed, Horodniczy and Cooperstock have recently shown that the foot can compete with traditional hand-based interfaces in a pointing task based on a Fitts' law task (ISO 9241–9), by using variable friction to assist users in reducing pointing overshoot and increasing selection accuracy [21]. In their recent experiment, users wore custom shoes (Fig. 16.2) that allow the system to increase the friction between the user's foot and the sliding surface as they approached the targets. Variable friction was achieved by controlling the vertical position of a high-friction material located under the sole, leading to an increase or decrease of the normal force at the point of contact (Fig. 16.3).

They found that the variable friction interface showed significant performance effects on the throughput. In the one/two-dimensional foot interaction, the throughput was increased from 3.04 (bits/s) to 3.22 (bits/s) and from 2.09 (bits/s) to 2.21 (bits/s), respectively, when the friction was added. Additionally, significant differences were shown between the performance of one-dimensional and two-dimensional tasks, with two-dimensional tasks requiring around double the time for pointing tasks at the same index of difficulty. Although this foot-based variable

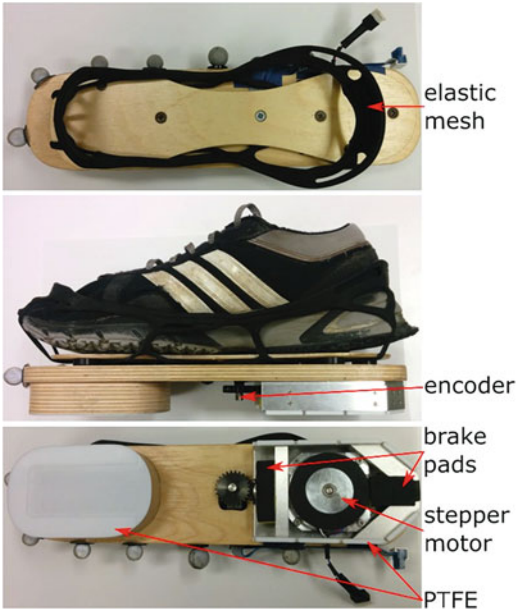

Fig. 16.2 Top, side, and bottom pictures of the prototype. The prototype fastens to participant's shoe using an elastic mesh [21]

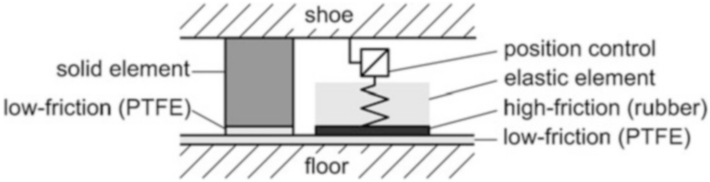

Fig. 16.3 The variable friction mechanism employed by the prototype [21]

friction interface did not achieve performance competitive with the best hand-based interfaces, it demonstrated comparable error rates to traditional pointing devices as well as relatively strong performance (Table.16.1). For example, they observed that on a low-friction surface, participants can perform foot-pointing tasks comfortably and with low fatigue.

Although exploring direct comparisons of hand versus foot interfaces is valuable and illustrates the strengths and weaknesses of each, they need not be exclusive. Foot-based interfaces can be combined with hand-based interfaces. Schoning et al. combined hand and foot control to effectively perform spatial data tasks [34]. The hand gesture showed benefits for precise input, whereas the foot gesture was adequately suited for continuous data collection within comfortable movement ranges and could control a specific function with simple movement, such as zoom/panning. For these reasons, the combined hand and foot outperformed on both throughput and comfort, reducing fatigue and effort.

Table 16.1 Reported throughputs and error rates of hand- and foot-operated pointing devices evaluated using ISO 9241–9 on 2D tasks [21]

Hand-controlled device	**Throughput (bits/s)**	**Error (%)**
Mouse	3.7–4.9	11.0
Trackball	3.0	8.6
Touchpad	0.99–2.9	7.0
Wiimote	2.59	10.2
Joystick	1.6–2.55	9.6
Wii classic controller	1.48	6.58
Foot-controlled device	**Throughput (bits/s)**	**Error (%)**
2D variable friction shoes	2.21	8.19
Depth camera	1.16	7.64

Further, hand and foot interfaces can be augmented with additional control mechanisms. For example, researchers have investigated how to incorporate additional mechanisms, such as eye gaze, to form a more complete solution. Klamka et al. compared performance of hand-based interfaces with performance of foot-based interfaces combined with eye gaze [24]. In this research, participants navigated the spatial data using gaze input in coordination with pedal-based interfaces. Compared to the hand-based interface (mouse) condition, the performance of the gesture combination (foot and gaze) condition did not outperform. However, the gaze-supported gesture was a promising with respect to comfort and ease of control. So, using foot-based interactions to manipulate spatial data, such as controlling a cursor in mobile solutions, could not outperform hand-based interactions, but still they can developed to achieve the better performance by changing frictions by incorporating additional mechanisms.

16.2.4 Menu Interactions

A specific application for foot-based interfaces that has been heavily explored is navigating menu structures. A menu can have different styles in terms of direction of motion, such as linear or radial, and foot gestures can be can be designed to work well in either case. For example, Zhong et al. explored foot-based ergonomics for radial pie menus [47]. Radial movement, as explained in Sect. 16.2.1, is a more comfortable and preferred foot movement, in comparison with horizontal and vertical movements. However, when radial movements are used to navigate menus, they have significant limitations with respect to the ergonomic and comfortable range of motion. From this research, they found the heel rotation movement of the right foot has a usable range from $-20°$ to $40°$. As the number of menu items increases, the angular span of each item is reduced. For this reason, although rotational motion showed advantages in terms of comfortable movement, the radial menu style cannot incorporate sufficient menu items.

Another method for controlling a menu is position tracking, where the menu layout is represented on a 2D display, and the cursor is controlled with the foot. Saunders et al. [33] have explored foot tracking-based interaction techniques to control diverse applications. In their system, users can see the position of their foot as a dot on a display and select an application by foot tapping the area of the virtual target layout, which was represented on the display.

An additional menu design by Crossan et al. implemented hierarchical style menus [13]. They focused on hands-free and eyes-free situations where mobile devices remain pocketed. The primary situation they considered is when the user wants to respond to an event and would typically need to take their mobile device out of their pocket or bag to do so. To mitigate these inconveniences, a foot-tapping technique with audio feedback was used to navigate menu items. They compared user performance while interacting with a two-level hierarchical menu system using either a foot-based or hand-based method. One of the findings was that if the target could be reached with few operations (e.g., less than five taps), the tapping technique was faster than hand-based operation when the phone was in the user's pocket. Thus, they confirmed the advantages of foot interfaces as an alternative method when the device is not held in the hand. These menu interactions based on foot gestures could be developed easily to control diverse parameters in mobile solutions, such as media manipulation, but due to ergonomics and properties of foot gestures, interaction designers need to spend some time on finding and researching suitable gestures for their targeted solutions.

16.3 Sensing Through the Feet

Although the feet can be used for input and manipulation, as described earlier, feet also offer several advantages for the reception of haptic information. They are well separated from other areas of the body, such that it can be easier to localize vibration or other haptic information being delivered to the foot area versus more traditional areas such as the wrist (e.g., smartwatch) or pant pocket (e.g., smartphone). Generally, such haptic information can be similar to that on other portions of the body, used for perceiving simple notifications or more complex haptic patterns (tactons [8]). The feet directly perceive the ground surface while walking and are thus the primary area to use for modifying or simulating the perception of different ground surfaces. This stimulation can come from portions of the foot coming into contact with a stationary or mobile surface with vibration actuators [42] or stimulation may be rendered through actuators coupled via a wearable interface to the foot itself. The latter can be used for mobile systems, by placing actuators in the shoes [3], or else attached to the top of the foot or ankle with straps.

The feet also bring their own set of unique challenges. First, haptic sensitivity is somewhat lower on the feet than on the most perceptive areas of the body such as the fingers and face, but still better than other parts of the body such as the legs and belly [45]. The feet are also a mechanically difficult area to situate haptic actuators, especially on the foot soles, since a high proportion of the user's entire weight presses on the sole of the foot with every step, causing significant repetitive mechanical strain that requires robust electronics and mechanical design to overcome. For example, with health organizations calling for 10,000 steps each day [38], this would result in over million stress cycles each year and potentially more for devices used in athletic training or rehabilitation. On the other hand, the shoes also provide a robust area to attach or embed the actuators, e.g., in the sole of the shoe itself. However, the changes in haptic coupling as the user's foot moves through the gait cycle mean that predicting what the user actually perceives in terms of intensity and duration, or even if they perceive a given stimulus at all (masking), can be more difficult than on other areas of the body. Sensors can be used to partially address these general haptic issues [7], but the ergonomics of haptic coupling for the foot nonetheless represent a significant challenge to be addressed versus haptic coupling on other areas on the body. Specific sensors such as accelerometers and proximity sensors that detect the gait cycle and trigger haptic feedback at appropriate times is a promising approach to overcoming foot-specific perception and masking issues [3]. To produce haptic stimuli, various actuators can be used, including the following types most often found in commercial devices:

- Eccentric Rotating Mass (ERM): An unbalanced weight on a motor, causing it to shake when spinning. Force is along two axes. The ERMs' stimulation amplitude and frequency are strongly correlated and dependent on the voltage being applied to the motor.
- Linear Resonant Actuator (LRA): A mass and spring system that resonates best at a particular frequency. Force is along a single axis. Although its frequency and amplitude can be controlled independently, an LRA's effectiveness will drop significantly when deviating from its recommended operation peak frequency.
- Voice Coil: Shares the mechanical structure of a speaker, with the exception that it does not have a membrane to produce air pressure differentials. It instead moves a mass that produces a rich haptic signal. Force is along a single axis. Since it can be controlled with arbitrary waveforms, frequency and amplitude can be modulated independently.

Hijmans et al. [20] investigated diverse types of actuators and compared their properties, such as dimensions, available frequency, and portability. They compared six different actuators, including the C2 Tactor, C1026B200F Vibration motor, B5A11W vibration motor, P-289 Piezo actuator, APA400M Actuator, and VBW32 Skin Transducer. They pointed out that the input source is also an important consideration when choosing an actuator for a specific application. For example, to activate Piezo actuators, a high voltage and low amperage is required, but conversely for C2 tactor and the VBW 32 skin transducers, a lower voltage and higher current is necessary.

Vibrotactile feedback using ERM, LRA, or voice coil actuators is not the only way of providing haptic information to the foot. Because the foot is in motion and applies pressure while stepping down, passive elements can be incorporated into haptic systems, such as giving the feeling of stepping into snow using potato starch that compresses and cleaves inside a boot as the wearer takes steps [46]. Many of these applications, however, move away from information delivery to instead unconsciously modifying the user's gait or foot position, and are therefore discussed in greater detail in the following sections.

16.3.1 Information Delivery with Vibrations

In comparison to hand-delivered vibrotactile feedback, foot-based studies have received significantly less attention. Early perception studies of the foot measured its tactile sensory characteristics. Kennedy et al. explored glabrous cutaneous receptors in the human foot sole and mapped out the distribution and behavior of each type of haptic receptor [22]. Their study is premised on a model of the foot having four different mechanoreceptor types: slow-adapting (SA) types I and II and fast-adapting (FA) types I and II [22]. For a fuller description of the mechanoreceptors in the skin, see Choi and Kuchenbecker [12]. Given that sections of the foot present different tactile properties depending on mechanoreceptor distribution and type, Hijmans et al. [20] developed a vibrating insole by placing vibration actuators at four locations where the most crucial mechanoreceptors are located (Fig. 16.4b).

Based on these prior works, Anlauff et al. [3] investigated rendering vibration patterns through haptic shoes (Fig. 16.4) for mobile applications. Participants were exposed to six different vibration patterns (Fig. 16.5) during either standing or walking situations, with each tacton composed of three buzzes, each of 250 ms duration, which were generated by pancake-shaped linear resonant actuators (LRA). In their work, the walking condition had significantly lower performance than the standing condition, with a recognition rate of 92% while standing and 62% while walking. They pointed out that when haptic pattern signals were delivered to the user while walking, the haptic artifacts were distorted by gait because the contact points between the actuators and foot sole kept changing. Overall, among the six patterns,

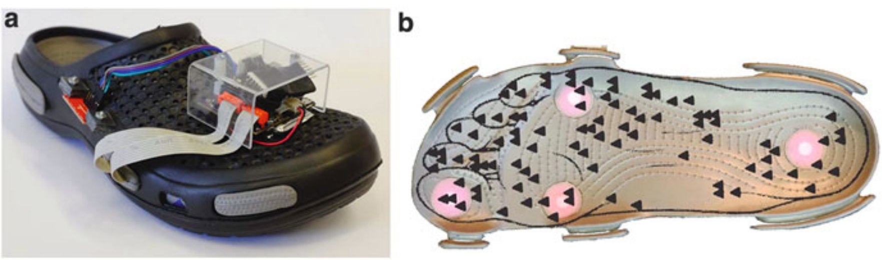

Fig. 16.4 Portable haptic shoes [3]. Left: Shoe, Right: Insole. (**a**) Haptic Shoe Platform. (**b**) Insole with actuator inserts and mechanoreceptor afferent units. (Adapted from Hijmans et al. [20])

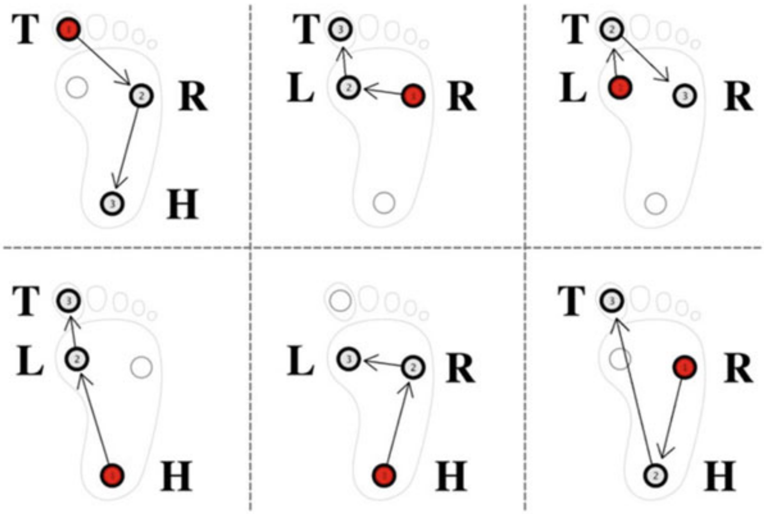

Fig. 16.5 Foot tacton study. Red circle indicates starting actuator position [3]

patterns that spanned the entire foot, such as Toe-Right-Heel or Heel-Left-Toe, had the highest overall accuracy.

Although recognition performance is higher while standing, the perception of vibration feedback while walking has been explored in both general [44] and navigation-specific contexts [25]. Watanabe et al. adjusted cyclic vibration feedback to guide walking-pace [44]. In their experiment, participants were trained to walk according to various vibration intervals, provided through the shoes. A small disk-shaped vibrating motor (FM23A, Tokyo Parts Industrial Co., Ltd) generated vibration at a frequency of 160 Hz. In their work, they found that participants could easily change their walking pace to match that of the vibrotactile cueing. Promisingly, modifications were made unconsciously by the users in response to gradual modification of the feedback pattern's pulsing frequency, which would be adjusted for mobile solutions, such as rehabilitation.

Although we commonly navigate while looking at our phone screen, this can be dangerous. Applications have therefore been developed to send vibrotactile patterns to the feet, freeing the user's vision so that they can remain better aware of their surroundings. Meier et al. [25] evaluated vibrotactile feedback for navigation tasks by attaching actuators to different parts of body. First, they compared the navigation performance with actuators on the foot, wrist, or waist, measuring both accuracy and level of concentration. Each participant was given 104 vibration signals, which were generated by four actuators in four different directions. Among the parts of body, the foot outperformed the other locations. The foot showed 100% accuracy, followed by waist (94.24%) and wrist (86.54%). For the required level of concentration, the foot (−3.63) needed half the concentration of wrist (−1.88) and waist (−1.38). Based on these results, they implemented four different patterns (forward, right, backward, and left), using eight actuators positioned around the foot evenly, and examined the navigation performance across three speed levels: standing, walking (∼3 km/h), and jogging (∼5 km/h). In their work, as speed increased, participants achieved lower pattern recognition accuracy, reported the vibration strength as lower, and required greater concentration to feel the stimuli.

To summarize, in this subsection we described various means of delivering information, including from tactile sensory characteristics to vibration feedback perception studies. Those who want to design mobile solutions based on foot-based information delivery need to carefully consider their experimental designs, vibration patterns, and recognition accuracy in order to implement better solutions.

16.3.2 Foot Interfaces for Medical Settings

Critical care units in hospitals are filled with an overwhelming number of loud and obnoxious alarms originating from patient-monitoring devices, mobile medical equipment, background music in the operating room, and verbal conversation between the staff. The high sound levels in these environments result in disrupted sleep for patients [4] as well as increased ambient stress levels for clinicians [37]. In addition, the composition of the existing auditory alarms is not generally informative of, or associated with, the urgency of the situation. Mondor et al. showed alarms associated with a patient condition to be perceived as less urgent than alarms associated with an equipment technical failure [27].

This makes a hospital setting an excellent case study for illustrating some of the advantages of foot-based interfaces as an interaction method for surgeons and nurses whose hands are occupied during a medical procedure. For example, in order to reduce the auditory burden and improve the information delivery of the alarms, several studies investigated the possibility of including privately delivered vibration as part of the alerts. Complementary tactile displays offer the possibility to reduce the noise level, decrease reliance on visual displays, and deliver information selectively to those who are responsible for responding to a particular alarm [5, 32]. In order to compare information delivery via different modalities, Sanderson et al. reported a comprehensive comparison between characteristics of visual, auditory, and haptic modalities of information presentation [32].

Since haptic stimuli can be rendered simultaneously with that of other modalities, some studies have investigated how simultaneous haptic signals can be used to augment the perception of other modalities. This is an instance of the Principle of Inverse Effectiveness (PoIE), which occurs when stimuli from two modalities are simultaneously presented, causing the overall neural response to be enhanced [26].

To choose a location for delivering the simultaneous vibration, the environmental factor of hospitals should be considered. In order to maintain sterile conditions and reduce the spread of infection, clinicians' hands are typically kept free of external devices. Therefore, positioning actuators on the feet is advantageous in comparison to the arms or wrists because of handwashing and cross-contamination concerns.

Fig. 16.6 Position of the vibration motor on the ankle for exploring the differences between unisensory and multisensory perception of medical alarms [2]

Fig. 16.6 shows the positioning of the vibration motor in the study comparing the perception of auditory alarms with and without vibration [2]. Alirezaee et al. studied the perception rates of participants, responding to high priority alarms when receiving either audio-only or multisensory audio-haptic high-priority alarms. The findings did not support the additive effects of sub-threshold vibration on the threshold of perception of alarm sound, yet introduced an experimental setup to explore the employment of haptic foot-interfaces for patient monitoring purposes by investigating ecologically valid parameters such as clinical performance and preference [2].

Although notifications alone would be an excellent use of the foot region, the user interface input and manipulation techniques discussed in earlier sections also have obvious applications in the medical environment. For example, a closed loop interaction between the clinician and the patient monitoring system could be implemented by using a haptic shoe. Such a system could, for example, render vibrotactile effects to communicate information about patients' vital signs, which the clinician could navigate using gestures as introduced in Sect. 16.2.4. For example, Hatscher et al. implemented foot-based interfaces for successfully reducing the workload of the hands, which are commonly occupied, particularly in an operating room environment [19]. In their experiments, three interaction techniques were designed to select target images from a series of medical images displayed on a monitor. They compared all three options in terms of task completion time and responses to the NASA-Task Load Index questionnaire [18]. The three tested designs were:

1. Discrete button: The angle ranging from −40°to 60° in front of the foot was segmented into five sections (called buttons) where each button occupied 20°. Rotating the foot changed the rate at which the medical images changed to move forward or backward in a list. When the foot was located in the leftmost/rightmost buttons, the image was changed every 0.2 s, while in next inner buttons (from

−20° to 0°or from 20° to 40°), the image was changed at a slower rate of every 0.8 s. The button in 0°–20° left the current image displayed.

2. Foot scrolling: In this interaction, every 10° of foot movement triggered an image change to the previous/next image, depending on direction. The user could raise their foot from the floor to reposition it and scroll further, since images were only changed when the foot was in contact with the floor.
3. Step and scroll: This concept combined foot scrolling with discrete button interactions. In the middle range of −20°–40°, the foot scrolling concept was implemented and the discrete button concept was applied in the outermost areas, covering from −40° to −20° and from 40° to 60°ranges.

They found that the foot scrolling method (#2) outperformed the others, with the shortest completion time and lowest overall workload, followed by discrete button (#1), and with step and scroll (#3) having the poorest results. The authors conclude that even though the scrolling method required repeated operations, the gesture's similarity with sliding hand gestures on touch screens offered performance benefits.

Aside from medical personnel receiving and manipulating information with their feet, it is important to note that patients themselves can also benefit from foot-based interfaces. For example, although seemingly counterintuitive, introducing noise to improve detection and transmission of weak signals was shown to be effective [17]. Accordingly, several studies demonstrate that administering appropriate haptic noise to the foot during rehabilitation results in systems that enhance balance control. For example, Priplata et al. studied the effects of rendering vibrations using instrumented insoles. Their results showed improved balance control for patients suffering from diabetic neuropathy or stroke, and more generally in geriatric populations [30]. In their study, participants were required to close their eyes in order to remove visual cuing. A white noise signal, low-pass filtered to 100 Hz, was delivered by three C-2 actuators on the bottom of each foot. The degree of sway was measured by a motion analysis system (VICON) for 30 s while standing. Five trials were performed with the haptic noise, and five without. They found the noise condition significantly reduced postural sway with respect to a range of sway parameters, such as the anteroposterior and mediolateral axes. They attributed these findings to the noise promoting the detection of bodily pressure changes, as indicated in previous literature [30].

16.3.3 Virtual Feedback Through the Feet

Beyond conveying information or interacting with applications through the feet, much prior work focuses on how to provide virtual immersive experiences. Although the foot has been less explored compared to the hands, tactile stimulation of the foot presents considerable potential for improving the fidelity of virtual reality (VR) experiences. In current VR systems, despite the dominance of audio and visual stimuli, additional modalities are used to convey compelling immersive sensations, including via haptic feedback. VR applications that rely on the feet include feeling diverse surfaces [39, 43], walking simulations [36], and collision detection [6]. To examine the importance of haptic stimuli through the feet in virtual environments, Visell et al. simulated virtual surfaces, such as soil or ice, through an augmented floor [43]. In their work, participants walked on a 6 × 6 array of 30.5 × 30.5 cm rigid tiles, each with four force sensors and a vibrotactile actuator embedded. By estimating the foot pressure distribution applied to the tiles, different audio and tactile feedback was rendered (Fig. 16.7). For providing immersive visual feedback, the floor was surrounded by overhead projectors (Fig. 16.8).

Use cases for virtual reality applications, including immersive walking experiences, have also been extensively investigated. People can be provided diverse sensations while walking. For example, when they step on the ground, many variables determine the varied tactile and sound feedback from the ground, such as their weight, pressure, and foot speed. Terziman et al. simulated each virtual step by rendering tactile vibration through the feet [36]. They conveyed the vibration using low-frequency loud speakers on tiles and designed different vibrations according to the contact position, physical model, and force of the feet on the tiles. In

Fig. 16.7 Still images from the frozen pond scenario [43]

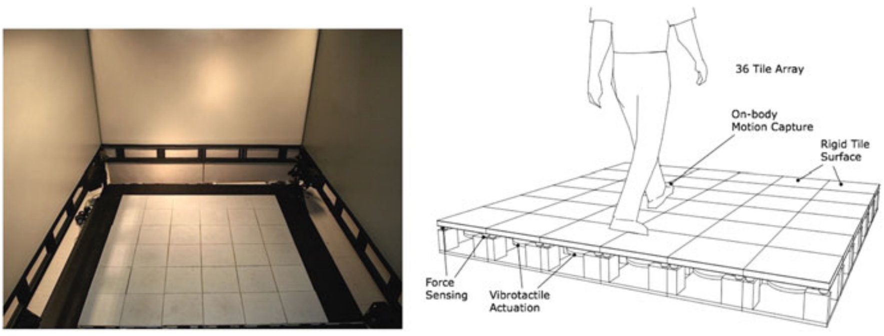

Fig. 16.8 Left: Distributed floor interface situated within an immersive, rear projected VE simulator. Right: illustration showing sensing and actuating components [43]

Fig. 16.9 Haptic shoes and positions of foot pressure sensors [23]

their experiments, to generate immersive stepping effects, they examined diverse factors, such as vertical versus lateral oscillations, physical versus metaphorical patterns, and heel strike versus heel and toe strike. Vertical vibration outperformed horizontal vibration when generating effects, based on the results of performance questionnaires. For the study of vibration type, the physics-based vibration (Rigid Contact Model), where the user's feet were considered as rigid objects, showed similar effects with those of the metaphorical-based model (Ground Reaction Force Model), which simulated the force generated by footsteps. In addition, they determined that only heel contact was suitable to be stimulated for conveying walking effects in virtual environments.

However, these tile-based architectures exhibit difficulties in scalability and mobility due to their significant hardware requirements and space limitations [23]. Thus, shoe-based architectures are beginning to emerge to overcome these limitations. Turchet et al. implemented interactive feedback experiments [39] where the participants were provided audio and visual stimuli with and without haptic feedback through the shoes. Vibrotactile actuators were embedded in the shoes and used to render virtual surfaces, such as snow and sand. Overall, participants preferred the added haptic effects with respect to enhancing the realism of the experience. To improve immersion, Kim and Cooperstock integrated foot-pressure sensing and vibration actuation into shoes [23]. Foot pressure was measured by four force-sensitive resistors (FSR), and the centroid pressure value of the foot was calculated by normalizing the locations of the four FSRs, such as Left $(-0.5,0)$, Right $(0.5,0)$, Toe $(0,1)$, and Heel $(0,-1)$ (See Fig. 16.9). Delivering haptic feedback based on pressure distribution of the feet could play an important role in designing mobile VR/AR solutions, including immersive VR/AR experiences, gaming, balance control, or rehabilitation applications.

In addition, as another foot based experience, as opposed to walking on different virtual surfaces, a foot-based virtual collision study has been developed to render immersive experience to the user. Blom et al. explored collision notification methods based on haptic feedback for virtual reality environments [6]. In their experiments, the participants were tracked by an optical tracking system (ART AR-Track2) and received vibration feedback through the floor or through a wand, where nine different collision effects (only visual: 1, only sound: 3, only vibration: 1, sound and vibration: 2, and other: 2) were rendered to the participants. The vibration feedback generally outperformed other feedback with respect to user preferences. Among vibration feedback modalities, the floor-based vibration outperformed the wand-based vibration. They also indicate collision recognition performance could be enhanced via multi-modal feedback.

Due to the advantages of the foot-based interactions, such as usable space for actuators in the shoes, and sensitivity to stimuli as described in Sect. 16.3, diverse experiences and techniques to render virtual feedback through the feet have been studied in many fields. We expect that foot-based mobile solutions will expand more broadly to improve virtual experiences, such as mobile gaming experiences or immersive virtual/augmented environment for rehabilitation.

16.4 Conclusions

Even though most interaction design is focused on the forearms and hands, in this chapter, we discussed various scenarios where using the feet can be an effective alternative or improvement. We explored multiple studies focused on foot interfaces and their promising future directions, both as foot-gesture-based interaction methods by detecting foot movement or toe/heel pressure as well as sensing-based techniques through delivering information to the foot. We provide and discuss examples that demonstrate scenarios where the hands are frequently occupied or body limitations were considered, and thus where foot interaction is promising for use cases such as doctors performing a medical procedure or a machinist operating a tool. These foot-based interactions and solutions for augmenting the communication of information are a cutting edge human–computer interaction method and offer potential benefits to mobile applications. Based on the literature and examples we have discussed, we hope that future researchers and developers are inspired to consider the feet as a viable alternative to mobile interaction techniques that occupy the hands.

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