The Feet in Human–Computer Interaction: A Survey of Foot-Based Interaction

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Foot-operated computer interfaces have been studied since the inception of human–computer interaction. Thanks to the miniaturisation and decreasing cost of sensing technology, there is an increasing interest exploring this alternative input modality, but no comprehensive overview of its research landscape. In this survey, we review the literature on interfaces operated by the lower limbs. We investigate the characteristics of users and how they affect the design of such interfaces. Next, we describe and analyse foot-based research prototypes and commercial systems in how they capture input and provide feedback. We then analyse the interactions between users and systems from the perspective of the actions performed in these interactions. Finally, we discuss our findings and use them to identify open questions and directions for future research.

CCS Concepts: • **Human-centered computing → Pointing devices**; **Pointing**; **Gestural input**; *Accessibility technologies;*

Additional Key Words and Phrases: Foot interaction, feet tracking, gestural interfaces

ACM Reference Format:
Eduardo Velloso, Dominik Schmidt, Jason Alexander, Hans Gellersen, and Andreas Bulling. 2015. The feet in human–computer interaction: A survey of foot-based interaction. ACM Comput. Surv. 48, 2, Article 21 (September 2015), 35 pages.
DOI: http://dx.doi.org/10.1145/2816455

1. INTRODUCTION

In December, 1968, Douglas Engelbart delivered what later became known as *The Mother of All Demos*. In this famous 90-minute presentation, Engelbart introduced the world to the mouse, amongst other prototypes of the fundamental elements of graphical user interfaces (GUI). Whereas it is widely known that Engelbart and his team created the mouse, it is often forgotten that, before reaching this design, they explored different prototypes operated by the feet [English et al. 1967; Engelbart 1984]. Since then, research in human–computer interaction (HCI) and other fields has given rise to a large variety of computer interfaces operated by the feet, right through to work that employs the feet in mobile and wearable contexts, on interactive floors, and in smart

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DOI: http://dx.doi.org/10.1145/2816455

environments. However, in spite of the volume of research conducted on the topic, there is no single reference that comprehensively overviews the literature, despite a few early works attempting to provide a framework for classifying foot interfaces [Pearson and Weiser 1986; Rovers and Van Essen 2006]. This work aims at filling this gap, with a comprehensive review of foot-based interaction.

Work in foot-based interaction emerged from different motivations, for example: the feet provide an alternative to the hands for accessible input [Springer and Siebes 1996; Carrozza et al. 2007]; they can reach areas that are awkward to reach with the hands, such as floors [Augsten et al. 2010] and the bottom part of walls [Jota et al. 2014]; they provide a natural mapping to locomotion tasks [Drossis et al. 2013; Hollerbach 2002]; and they provide additional input channels for assisting other modalities in complex tasks [Göbel et al. 2013; Simeone et al. 2014].

These different motivations have resulted in the development of a large variety of foot-enabled devices and research contributions from different communities. For example, the different foot mice and joysticks explored in accessibility research; the variety of sensor-enabled trainers and insoles created by the wearable computing community; and the diverse ways of tracking the feet unobtrusively with colour and depth cameras that resulted from computer vision research.

This article reviews devices and interactions that involve our lower limbs. Considering that, when we move our legs we invariably also move our feet, for the sake of simplicity, we refer to these as foot-based interactions. To display the breadth of research that has been conducted, the scope of this survey is broad, covering works that describe foot-operated, foot-worn, and foot-tracking devices. Studies that evaluate interactions afforded by the feet are included as well. Also, to put such interactions in context and to give a theoretical background to the understanding of users' capabilities, we review the literature on the anatomy, biomechanics, and psychology of the behaviour of the lower limbs.

Regardless of the input or output modalities involved, HCI involves *users*, *systems,* and the *interactions* between them. Understanding users helps the design of ergonomically optimal, more widely accessible, and culturally appropriate interfaces. Understanding systems provides both an awareness of tools available to capture input and provide output, as well as an appreciation of existing systems that provides inspiration and direction for future work. Understanding interactions provides a common vocabulary for the design of interactive systems as well as an awareness of user performance limitations.

This work contributes an analysis of foot-based interactions based on the following three lenses. From the *user* perspective (Section 3), we analyse the lower limbs' anatomy and movement, as well as the implications for design created by the pose in which users interact with such systems. We also discuss accessibility and cultural issues.

From the *system* perspective (Section 4), we first analyse the different ways of capturing input from the feet—mediated sensing, intrinsic sensing, and extrinsic sensing—and how these systems differ in their properties. We also discuss their output and how they provide feedback to users.

Finally, from the *interaction* perspective (Section 5), we analyse four categories of actions that users employ when interacting using their feet: deictic, manipulative, semaphoric, and implicit actions. These three perspectives overlap substantially, as one perspective depends on the other to create interactive experiences, but they provide a structure for discussing the most important elements for designing interactions that use the feet as an input modality.

For practitioners, this article provides a theoretical foundation for creating foot interfaces and interactions. For researchers, it provides an overview of the research landscape in foot interaction and points out open research questions.

2. RELATED WORK

We are not the first to attempt to classify work on foot interaction. When Pearson and Weiser [1986] began the development of their *moles*, they provided a historical classification of the feet in the interaction with mechanical devices. In the preindustrial era, the function of the feet was to transmit both power and control (e.g., the horseman's stirrup, the farmer hay fork and shovel, the pipe organist's bellows and foot keys, the potter's kick wheel). With the advent of electricity and other means of providing power, their function shifted to control alone (e.g., car pedals, arcade games, gas pressure controls, guitar effects pedals). Finally, they were used for foot-mediated input for computers (e.g., flight controls for aircrafts and simulators, and volume and sustain controls in music synthesisers). Whereas this classification puts the role of the feet as an interaction modality in context, it does not provide a structure for modern devices.

Rovers and Van Essen [2006] classify foot interactions according to their complexity: (1) simple toggle actions (e.g., foot switches), (2) single parameter (e.g., pedals), (3) multiple parameters (e.g., moles) and (4) intelligent footwear (e.g., Adidas "1"). This classification is not ideal for modern devices for two reasons. First, because of the miniaturisation and decrease in cost of electronic components, most systems provide multiple channels of input, hence fall into the third category. Second, there is an overlap between the fourth category and the others, as intelligent footwear may also provide toggle actions and control one or more parameters.

Because of the wide variety of foot-based interfaces found in the literature, rather than trying to find an all-encompassing taxonomy, we analyse the literature under three different lenses in this article: the users, the systems, and the interactions between them. From the user perspective, we draw from the literature in Biomechanics and Kinesiology [Lippert 2011] to analyse specific movements of the lower limbs. Saffer [2008] performs a similar analysis for full-body gestures and touch interfaces.

From the system perspective, we investigate input and output devices. Our classification borrows from general-input device taxonomies, such as Hinckley and Wigdor [2012] and Hinckley et al. [2004]. For certain categories of devices, we refer readers to more specific surveys, for example, on pedals [Trombley 1966] and on locomotion interfaces [Hollerbach 2002].

Finally, from the interactions perspective, we classify different actions that can be performed with the lower limbs. Karam and schraefel [2005] defined a taxonomy for hand gestures in HCI and proposed five categories for gesture styles: deictic, manipulative, semaphoric, gesticulation, and language gestures. For an overview of gesture taxonomies, see Billinghurst and Buxton [2011].

3. CHARACTERISTICS OF USERS

The design of interactive systems is usually optimised for the movement and capabilities of the hands. Therefore, it is essential to understand the strengths and limitations of the lower limbs, especially in comparison with the arms and hands, in order to design interfaces that take their motion range, weight, and speed into account.

We start our discussion of the user perspective by looking at the anatomy of the legs and feet (Section 3.1) and how the movement on each of their joints is used for interaction (Section 3.2). We then analyse how the pose of the user (sitting, standing, or walking/running) impacts interaction (Section 3.3), as well as accessible input (Section 3.4). Finally, we look at the nonverbal, cultural, and cognitive issues associated with the legs and feet (Sections 3.5 and 3.6).

3.1. Anatomy

One of the features that sets humans apart from other primates is upright walking, which could date from the earliest phase of human evolution [Lovejoy 1988]. Whereas our close cousins use all four limbs for locomotion, we only use our legs. This provided an evolutionary advantage, as it allowed us to carry more food, better gather small food from short trees, expose less skin to direct sunlight, free our hands to use tools or carry babies over long distances, spend less energy when walking at reduced speeds, see further whilst walking, and appear more threatening to predators [Weaver and Klein 2006]. The downside is that we not only lost speed and agility, but also have a much more reduced ability to climb trees [Lovejoy 1988]. Also, due to the constant muscle tension applied to stabilise our bodies and to the much shorter length of the toes compared to the fingers, we lost prehensility—the ability to grasp—in our feet. The direct implication for HCI is that graspable interfaces, such as the regular mouse, are unsuitable for the feet. Therefore, interfaces with moving parts often need to provide some way of securing themselves to the foot, for example, by offering straps or high-friction surfaces.

The foot is a complex structure comprising 26 bones (tarsals, metatarsals and phalanges), over 100 ligaments, muscles, and tendons that work together to maintain balance and propel the human body. The bones of the foot are arranged in three arches, two along its length and one across it. These arches stabilise our bodies in the upright position while giving an elastic springiness to it [Dawe and Davis 2011]. The foot can be divided into three parts: the hindfoot (where the heel is), the midfoot, and the forefoot (where the ball and toes are). Because of this structure, the feet have a very distinctive and asymmetrical shape that can be recognised by vision-based systems [Augsten et al. 2010]. In the gait cycle, these parts touch the ground in sequence, a pattern that has been explored in several projects to estimate user movement (Section 4).

The entire human lower extremity weighs on average approximately 31.2% of our body mass, of which 19.4% is from the thighs, 9.0% from the legs, and 2.8% from our feet [Dempster 1955]. Because the lower limbs weigh a lot more than the upper limbs, their movement tends to be more tiring and leads to cramps if used extensively [Engelbart 1984].

3.2. Kinematic Analysis of the Joints

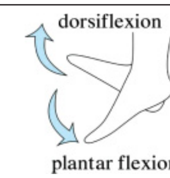
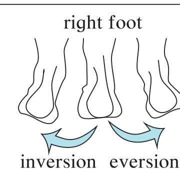
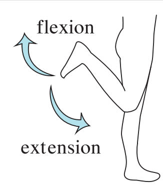
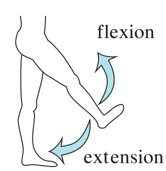
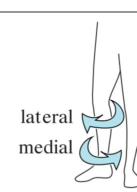
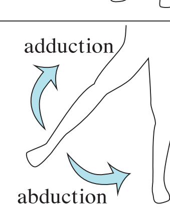
For our purposes, the movement of the lower limbs is mostly performed by three joints on each leg: the ankle, the knee, and the hip. Table I shows the distribution of the ranges of motion for each movement of these joints [Roaas and Andersson 1982].

3.2.1. Ankle. The ankle joint is capable of three types of rotation, each in two directions: dorsiflexion/plantarflexion, abduction/adduction, and inversion/eversion.

Dorsiflexion is the movement that decreases the angle between the top of the foot and the leg. Plantarflexion is the movement that increases this same angle. These are the movements used to operate pedals [Kroemer 1971]. Momentary pedals, which require users to push against a spring, require more force on the plantarflexion, since the spring assists the dorsiflexion, but rocker pedals require the user to push in both directions. Depending on where the foot is anchored, these movements can be interpreted as two separate gestures. If the foot is anchored at the ball, it is considered as heel tapping and if it is anchored at the heel, it is considered as toe tapping. Pedals typically anchor the foot at the heel, but in the control of English et al. [1967], its vertical movement was anchored at the ball.

Inversion is an inward twisting movement, whereas eversion is an outward twisting movement. The range of motion along this axis is very limited. These movements are often combined with other rotations into supination (a triplanar movement in which the foot moves down and towards the center of the body, combining inversion, plantarflexion, and adduction) and pronation (a triplanar movement of the subtalar joint in which the foot moves up and away from the centre of the body, combining eversion, dorsiflexion, and abduction). Supination and pronation are the movements

Table I. Normal Range of Motion of the Right Hip, Knee, and Ankle Joints in Male Subjects, 30–40 Years of Age

		Range of Motion (°)		
Joint	Movement	Mean	SD	
Ankle	Dorsiflexion	15.3	5.8	
	Plantar flexion	30.7	7.5	
	Inversion	27.7	6.9	
	Eversion	27.6	4.6	
Knee	Flexion	143.8	6.4	
	Extension	1.6	2.8	
Hip	Flexion	120.3	8.3	
	Extension	9.4	5.3	
	Medial rotation	32.6	8.2	
	Lateral rotation	33.6	6.8	
	Abduction	38.8	7.0	
	Adduction	30.5	7.3	

Source: Roaas and Andersson [1982].

typically used to move foot joysticks horizontally, as they allow for a shift of weight of the foot with little movement.

Abduction is the movement of the foot away from the centre line of the body and adduction is the movement towards it. As a gesture, these movements are interpreted as heel rotations (if pivoting around the heel) or as toe rotations (if pivoting around the toe) [Scott et al. 2010]. An example of an interface that is controlled by abduction and adduction is Zhong et al.'s *FootMenu* [Zhong et al. 2011], in which the user pivots the foot around the heel to control the horizontal movement of the cursor.

3.2.2. Knee. The knee has two degrees of freedom: rotation and flexion/extension. Because knee rotation assists foot abduction/adduction, we will not treat them separately. Knee flexion is the movement that decreases the angle between the leg and the ankle, whereas knee extension is the movement that increases it. As a gesture, these movements combine into a "kick" [Paelke et al. 2004]. Han et al. [2011] investigated user accuracy in the direction and speed of kicks. The authors found that targets should cover at least 24° and that users have difficulty in controlling the velocity of the kick, but can remember two broad ranges of velocity. The knee has also been used directly to operate mechanical controls, such as the lever [English et al. 1967]. Early pianos also contained knee levers instead of pedals [Rosenblum 1993], an idea that has since been revived to allow users with below-knee amputation to play the piano [Odom et al. 2006].

3.2.3. Hip. The hip rotates in three directions: flexion/extension, abduction/adduction and outward/inward rotation. Because rotations around the hip involve moving the whole leg, they are usually tiresome to be used for HCI, but they often assist the movement of other joints. For example, when standing upright, kicks can be enhanced by using the force from the leg [Paelke et al. 2004; Han et al. 2011]. Abduction and adduction are used when moving foot mice or for free gestures horizontally [Velloso et al. 2015a]. The hip can also be moved to shift the centre of mass of the body, which is used in pressure-sensitive interfaces, such as the Wii Balance board [Williams et al. 2011; Xavier et al. 2011]. An example of a mechanical interface that directly uses the hips is Beckhaus et al.'s *ChairIO*, an augmented stool that acts as a joystick as the users move their hips [Beckhaus et al. 2005a, 2005b, 2007].

3.2.4. Toes. Because the toes are harder to control than the fingers and are often covered by shoes, they are very seldom used for interaction. The exceptions are toe switches embedded into shoes, such as the one described by Thorp [1998] and the ACHILLE insole, that contains a toe switch for controlling a prosthetic arm [Carrozza et al. 2007].

3.2.5. Multiple Joints. Different combinations of knee and hip movements allow the foot to move in different topologies. Pearson and Weiser [1986] presented four topologies for surface-based foot interaction that illustrate these movements when constrained by a desk well (i.e., the space under the desk) whilst seated. A planar topology is defined by a plane that might be tilted by a certain angle. A cylindrical topology ideally has a radius equal to the height of the user's knee, with the main axis crossing the knee. A toroidal topology is defined by a minor radius equal to the height of the knee centred at the knee and a major radius equal to the length of the thigh centred at the hip. A spherical topology has a radius equal to the height of the knee centred at the knee.

These different topologies aim at facilitating the movement for specific joints: in the spherical topology, vertical and horizontal movements are optimised for the knee; in the toroidal topology, vertical movement is optimised for the knee and horizontal movement for the hip; and in the cylindrical topology, vertical movement is optimised for the knee. Vertical and horizontal movement in the planar topology and horizontal

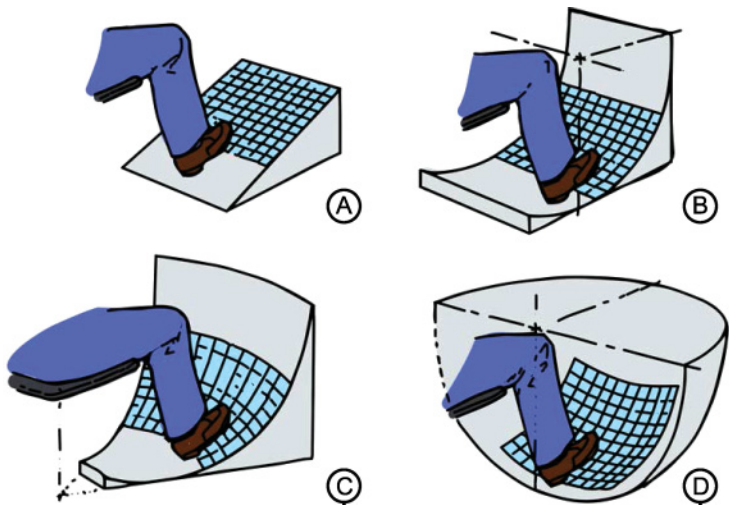


Fig. 1. Topologies for surface-based foot movements in a seated pose (adapted from Pearson and Weiser [1986]): (A) Planar, (B) cylindrical, (C) toroidal, (D) spherical.

movement in the cylindrical topology require combinations of knee and hip movements to reach the whole space, but may be simpler for users to understand.

All these topologies constrain the movement of the foot to a two-dimensional plane existing in the three-dimensional space. When this constraint is removed, we have the free three-dimensional movement common in movement-based interactions, such as in full-body games. These movements use a combination of several joint rotations.

3.2.6. Gait. When walking/running, users will employ combinations of all these movements. The gait cycle (i.e., the pattern of movement during walking) comprises four stages [Morley Jr. et al. 2001; Huang et al. 2006]. It begins when the hindfoot touches the ground (heel strike). Then, the forefoot touches the ground, stabilising the foot and the body (forefoot contact) until the weight of the body is directly over the foot and the opposite foot is swinging from the rear of the body (midstance). Next, the heel lifts from the ground and the weight shifts to the front of the foot, as the opposite foot touches the ground (heel off). Finally, the foot pushes the body forward and enters the swing phase until the cycle restarts (propulsion).

3.3. Pose

The pose in which the system will be used significantly affects the design of the interface. We found in the literature three main poses in which foot-operated systems are used: sitting, standing, and walking/running. We analysed how the poses affect different properties of the interaction: the users' interaction range, the gesture vocabulary, fatigue, challenges for design, and operation of other devices (Table II).

3.3.1. Interaction Range. When seated, a user's interaction range is limited to the feet's reach. While swivel chairs allow for reaching locations beyond that by rotating or pushing the chair, chairs with no moving parts require users to either adjust their pose or clumsily reposition the chair when trying to reach further targets [Velloso et al. 2015a]. Also, targets may be placed on the chair itself, for example, switches mounted on the legs of the chair. By standing upright, users are able to reach farther and by walking towards targets, they can reach indefinitely far targets [Augsten et al. 2010; Bränzel et al. 2013; Grønbæk et al. 2007; Orr and Abowd 2000; Schmidt et al. 2014].

Table II. Properties of Different Poses

	Pose	Range	Gesture Vocabulary	Fatigue	Challenges	Other Devices
Sitting		+	+++	+	Desk well, occlusion	Desktop computers
Standing		++	++	++	Balance, tracked area	Public displays, multitouch tables, mobile devices
Walking Running		+++	+	+++	Limited attention and cognition	Mobile devices, Music players, artistic installations

3.3.2. Gesture Vocabulary. The type of contact between feet and floor in a pose determines the range of possible gestures. The sitting pose allows users to take their feet off the floor simultaneously, thus multifeet and midair gestures are possible [Velloso et al. 2015a; Simeone et al. 2014]. Yet, lifting both feet repeatedly or for a prolonged time leads to fatigue. Standing limits the available vocabulary to single-foot gestures, as the other foot maintains the body's balance. At the same time, however, the increased mobility allows for larger gestures, such as kicking or jumping, and for reaching farther targets. When walking/running, arbitrary gestures are more difficult because the feet are busy in the gait cycle. Instead, the movement itself is often used as replacement, for example, by mapping the real-world movement to movement in virtual environments, or by using different walking patterns to issue commands [Yamamoto et al. 2008].

3.3.3. Fatigue. The pose in which the user interacts with the system will also dictate how long the user may interact with it. Users typically have no problem sitting down and to a lesser extent, standing upright, for long periods of time, but walking and running will be tiresome to different degrees depending on the user's physical fitness. Whereas there are no long-term studies on foot interaction in HCI, piano players and car drivers are able to operate pedal-based interfaces for extended periods of time. However, in pedal-based interfaces, whereas users can minimise fatigue by resting their foot on top of the pedal without intending to activate it–a behaviour called *riding the pedal*–this can lead to accidental activation [Barnett 2009]. In terms of movement direction, Velloso et al. found forward and backward foot movements to be more tiring than left and right ones [Velloso et al. 2015a].

3.3.4. Challenges. When users are sitting, they are often in front of their desks. This spatial configuration constraints the movement in two ways. First, the movement is restricted by the size of the desk well [Pearson and Weiser 1986; Velloso et al. 2015a]. This not only limits the area where users may move their feet, but because the desk well is often cluttered with cables and power plugs, the movement may be affected. Second, the desk occludes the feet, which prohibits direct-input devices, such as Multitoe [Augsten et al. 2010].

When users are standing, movement is usually constrained by users' balance, which will determine how well they can perform midair or floor-touch gestures in a stable manner.

The biggest constraint in walking/running foot interaction is the limited attention and cognition as the user is busy moving through the physical environment. Any deviation of users' normal gait pattern may increase the risk of tripping or losing balance.

3.3.5. Interaction with Other Devices. The pose is also influenced by the choice of other devices with which the foot interface will interact. For example, when sitting down, foot interfaces are usually used to interact with desktop computers, together with mice and keyboards [Pakkanen and Raisamo 2004; Velloso et al. 2015a]. When standing up, they are usually used for interaction with public displays [Saunders and Vogel 2015; Jota et al. 2014], multitouch tables [Richter et al. 2012; Sangsuriyachot et al. 2011] and mobile devices [Han et al. 2011; ur Réhman et al. 2012]. When walking/running, the feet normally interact with music players [Bieber and Diener 2005; Moens et al. 2010], mobile devices [Yamamoto et al. 2008] and artistic installations [Choi and Ricci 1997; Paradiso and Hu 1997].

3.4. Accessibility

Bergman and Johnson [1995] define accessibility as "removing barriers that prevent people with disabilities from participating in substantial life activities, including the use of services, products and information." Together with head-mounted pointing devices and eye trackers, foot-operated interfaces offer an accessible alternative to hand-operated interfaces for people with impairments in their hands, including repetitive strain injury, arthritis, carpal tunnel syndrome, and limb loss. Several works in the literature investigate these devices explicitly for this purpose [Springer and Siebes 1996; Carrozza et al. 2007]. While these interfaces may provide relief for tired wrists, continued use may also strain the ankles, causing further pain and discomfort. They can also be more tiring and lead to cramps if used extensively [Engelbart 1984].

Foot-operated interfaces for accessible input go even beyond computer control. For example, it is now possible to modify cars to allow them to be steered using the left leg through a rotating foot plate. There are also solutions for users with partial impairment of the feet. For example, vacuum-assisted breaking can be installed in cars for users who find it difficult to press down the pedal. Also, foot-slip prevention devices, such as straps and rubber surfaces, can be attached to pedals to prevent the foot from slipping from the device, which can help users with difficulties in performing certain movements.

Interfaces that are exclusively operated by the lower limbs also create new accessibility problems. As with any body-based interfaces, interaction designers must take into consideration limitations for each individual. For people in wheelchairs and crutches or with other disability or impairment of the lower limbs, it will be difficult or even impossible to use such devices. Also, short people might find difficult reaching far targets on the floor if sitting on a high chair. Therefore, it is good practice to provide input alternatives for these users.

In this article, our focus is broader than accessible input, thus we analyse the research space from the point of view of users with no disabilities. However, it is also important to take into account how individual disabilities affect interaction design. For example, users with a motor control disability in their hands will not be able to use certain multimodal combinations of foot-based interaction. In Section 4, we overview different devices that can be used for foot-based accessible input, even when not necessarily designed for this purpose.

3.5. Nonverbal Behaviour and Cultural Issues

Both scientific and anecdotal evidence suggest that the feet give away clues to our internal states. Joe Navarro, an ex-FBI counterintelligence officer and body language expert, considers the feet as "the part of the body that is most likely to reveal a person's true intentions" [Navarro and Karlins 2009]. In social interactions, we tend to focus on each other's faces, thus the legs and feet tend to escape our attention. This makes the lower limbs particularly good at providing clues to how people are really feeling—what psychologists call *nonverbal leakage* [Morris 2002].

In Section 3.1, we explained how our lower limbs evolved to support our bipedalism. As they became our main means of locomotion, our limbic system—the part of our brains responsible for, amongst other functions, our emotions and our fight-or-flight mechanisms—evolved to quickly activate the legs and feet to escape from danger or confront predators. Even though we do not face such challenges today, these hard-wired evolutionary mechanisms still manifest themselves in our nonverbal behaviour.

For example, quick movements of the feet are indicative of anxiety. In a study with students learning foreign languages, Gregersen [2005] reported that anxious students continuously bounced, jiggled, and tapped their feet, whereas nonanxious students only crossed and uncrossed their legs a few times.

We send nonverbal signals not only through feet movements, but also through their overall posture. For example, Mehrabian [1968] relates the symmetry of leg posture to how relaxed the person is: the more asymmetrical the posture, the more relaxed the person. He defines four categories of symmetry in ascending degree of relaxation: symmetrical position of the legs with both feet flat on the floor and the insteps touching; symmetrical position of the legs with both feet flat on the floor and the insteps not touching; asymmetrical stance of the legs with both feet resting flat on the floor, asymmetrical stance of the legs with one or both feet partially lifted off the floor.

The behaviour of our feet is also unconsciously influenced by the behaviour of the people around us—because of the so-called *Chameleon Effect*, we tend to mimic the behaviour of the people we are talking to. In study by Chartrand and Bargh [1999], participants were more likely to tap their feet during a task when their confederate was also tapping his feet. Different leg postures also influence the rapport between people interacting. Harrigan et al. [1985] investigated the nonverbal cues in physician–patient rapport and found that high-rapport physicians were more likely to sit with their legs uncrossed, with their bodies orientated toward the patient, but there was no difference in feet movement between high-rapport and low-rapport doctors. Certain behaviours of the legs and feet vary in different cultures. In several cultures, especially in South Asia, the feet are considered dirty and pointing with the feet or exposing the sole of the foot may be considered rude or insulting [Juckett 2005]. Wagner et al. [2013] investigated the social acceptability of touching on-body targets and found that targets on the lower limbs were significantly less acceptable than on the upper limbs. In China, bound feet used to be considered sexually appealing in women and some men preferred never to see women's feet, which were constantly concealed by shoes and wrapping. This practice was banned in 1949 and the ban remains in effect since.

Some leg postures can also be perceived differently by distinct cultures. For example, certain American men can perceive the way European men cross their legs (with one knee crossed over the other) as slightly effeminate [Morris 2002]. However, with more cultural exchange around the world, these cultural differences tend to be minimised as we can see both Europeans sitting with the ankle over the knee and Americans with one knee over the other [Morris 2002].

These are just a few examples of how people's psychological states and culture are perceived and manifested through their feet. For an in-depth treatment, see Morris [2002] and Argyle [1988]. We return to the topic of how this natural behaviour can be leveraged in HCI in Section 5.3.

3.6. Embodied Cognition

Recent developments in the cognitive sciences and philosophy suggest that "people's subjective, felt experiences of their bodies in action provide part of the fundamental grounding for human cognition and language" [Gibbs 2006]. In other words, our bodily experiences shape the way that we think. This kind of analysis is extremely relevant to HCI, as the bodily gestures used to interact with a given system will significantly impact how we think about the task at hand. Whereas a complete account of embodied cognition is outside the scope of this article, we will discuss a few results that relate to the legs and feet.

Behavioural studies suggest that participants are faster in reacting with the appropriate effector (e.g., hands or feet) when it matches the action in a given sentence. For example, Buccino et al. [2005] asked participants to respond to concrete sentences using the hand or the foot and not to respond to abstract sentences, and found that reaction times were shorter when the effector corresponded to the sentence than when it did not. Similarly, Scorolli and Borghi [2007] asked users whether certain hand and foot actions (e.g., to throw vs. kick a ball) made sense or not and recorded responses with a microphone or a pedal. Again, they found responses to be faster when the effector matched the action.

A possible explanation for this phenomenon is that just thinking about words referring to specific body parts tends to activate areas of the brain that are also activated when actually moving those body parts. For example, Hauk et al. [2004] presented participants with words regarding leg, arm, and face movements and recorded participants' brain activity with fMRI. These authors found a high correlation between the words being read and the body part associated with that action.

In summary, reading and thinking about actions related to the lower limbs, such as kicking and walking, tend to also activate the areas of our brains that are activated when we actually perform those actions. This, in turn, leads to faster reaction times for when we use the body part corresponding to the action we are contemplating. The significance of such findings for HCI is that using the feet for tasks for which we normally think of as being performed by the feet can possibly yield better performance, at least on a neurological and cognitive level. However, these gains can be offset by the generally worse dexterity and heavier weight of the legs, as compared with other body parts (see Section 5.2).

4. FOOT-BASED SYSTEMS

In the previous section, we discussed how users' body pose and movement affect the interaction. In this section, we describe and categorise research prototypes and commercial systems that take input from the feet (Section 4.1) and discuss different ways of providing feedback in foot-based interactions (Section 4.2).

4.1. Input Sensing

Foot-operated input devices exist in a variety of shapes and sizes—from small foot mice, to room-sized augmented floors. In this section, we classify these devices into a taxonomy according to how they capture input from the feet: mediated, intrinsic, and extrinsic sensing (Table III). Mediated sensing happens when the feet are not tracked directly, but rather through devices operated by them. Intrinsic sensing refers to when the feet are tracked through sensors directly attached to them, and extrinsic sensing refers to when the feet are tracked through sensors placed on the environment.

4.1.1. Mediated Sensing. In mediated sensing, instead of tracking the feet directly, sensors track devices operated by the feet. This category comprises mechanical devices such as foot mice, trackballs, and pedals, which contain moving mechanical parts that capture input from the feet. As a result, such devices provide immediate passive haptic feedback on the actual input action. They are usually found in the form of computer peripherals, hence capture input only when the user is directly interacting with the device.

Table III. Categories of Foot Input Sensing

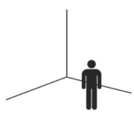
		Instances	Passive feedback	"Always on"
Mediated		Foot switch, pedal, knee control, foot mouse, foot joystick, trackball, moles, balance boards	+++	+
Intrinsic		Augmented shoes, augmented insoles	++	+++
Extrinsic		IR-based trackers, vision- and depth-based trackers, laser range finder, augmented floors and surfaces	+	++

Fig. 2. Mediated sensing using computer peripherals: (A) large trackball [Pakkanen and Raisamo 2004]; (B) Nintendo Wii Balance Board [Daiber et al. 2009]; (C,D) BiliPro foot mouse and keys.

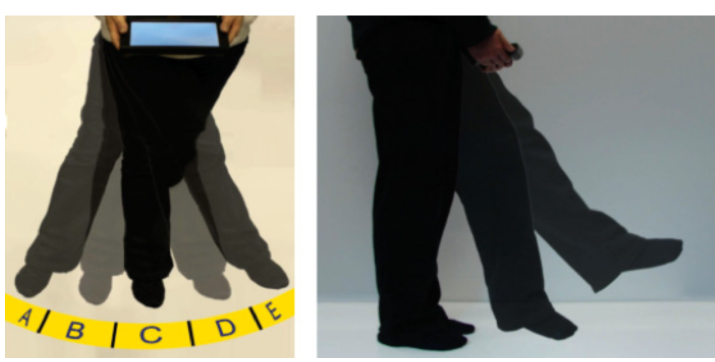


Fig. 3. Example scenario for the use of foot gestures through intrinsic sensing. The user interacts with his tablet by kicking in the air [Han et al. 2011].

The oldest, most widely known, and most thoroughly studied foot interface is the pedal. Pedals are employed in a wide variety of contexts: cars, bicycles, boats, aircrafts, pianos, harps, and guitar effects are some examples from outside the world of computing. Due to the safety-critical role that pedals play in cars and machinery operation, studies looked into finding optimal pedal designs, which go as far back as 1942 [Barnes et al. 1942]. See Trombley [1966] for a review of early work on pedal operation and Rosenblum [1993] for a review of the role of pedals in pianos.

The simplest form of a pedal is a binary switch. Examples include foot-operated light and tap switches and transcription pedals that have multiple switches for controlling playback. As with any switch, they can be latching or momentary, depending on whether they return to their initial state once the user releases them. As Sellen et al. [1992] point out, momentary pedals provide advantages for selecting the mode of operation of software systems because they require users to actively maintain the state by holding down the foot—its kinaesthetic feedback is more difficult to ignore reminding users of which mode they are currently in.

Rather than sensing discrete states, pedals also allow for controlling continuous parameters, such as the acceleration of a car. In this mode, it is necessary to choose an adequate mapping between the pedal and the parameter being controlled: a 0-order control alters the value of the parameter directly, while a first-order control alters the rate of change of the parameter. For example, Kim and Kaber [2009] compared 0-order and first-order pedals for setting font sizes in a text entry task and found the performance of the first-order control to be comparable to the mouse. Similarly to foot switches, continuous pedals can also be momentary or latching.

Pedals often ship in sets of two or three, as they are commonly employed in vehicle simulators. A more complex setup is that of flight-simulator rudder pedals. The pedals in these devices pivot around the centre to control the plane's rudder, offering an additional dimension of control.

Other examples of works that use pedals include controlling a 3D modelling application [Balakrishnan et al. 1999], text entry [Dearman et al. 2010], supporting gaze input [Göbel et al. 2013], and toggling the mode of operation of a piano keyboard [Mohamed and Fels 2002]. Zhong et al. [2011] implemented a pivoting pedal that rotates around the heel in addition to up and down.

Safety-critical applications of pedals should also take into account some problematic issues. First, people seldom scrutinise the floor when they are working, thus they might trip on pedals. Also, "riding the pedal"—which happens when the user stops pressing the pedal, but remains with the foot on top of it—is the most prevalent cause of their accidental activation [Barnett 2009].

Despite the pedal being around for a long time, it was not the first foot-operated interface for a computing system. Among the first alternatives for controlling a cursor, the same team that invented the mouse developed a knee control consisting of two potentiometers linked to a knee lever, which was controlled by the user by pushing the lever side to side or up and down [English et al. 1967].

The term *foot mouse* has been used for different kinds of foot-operated devices. In this article, we restrict the term to devices that work in the same way as the hand mouse while being moved by the foot. Therefore, the physical property that is used as input is the position of the foot. These include commercial products such as the *BiLiPro Foottime Foot Mouse* (2006) and research prototypes such as the puck on a Wacom digitising tablet that Balakrishnan et al. [1999] used to control the camera in a 3D modelling application.

Foot joysticks (also often called foot mice in the literature, e.g., Springer and Siebes [1996]) are controls in which the user nudges the device in a specific direction to control the speed of movement of the cursor in that direction. The *Versatron Foot Mouse* (1984) is the first example of such an interface and was controlled by sliding with the foot a rubber platform spring-loaded to return to the central position. The more recent *No Hands Mouse* uses two devices: one foot joystick to control cursor position and one to control mouse clicks. Such devices are usually mapped as first-order controls, similarly to hand-operated joysticks.

Garcia and Vu [2009, 2011] studied learning effects of users interacting with this device. Research prototypes of foot joysticks include the works of Springer and Siebes [1996] and Göbel et al. [2013].

Large trackballs have also been used for foot-operated cursor control, such as the *BIGtrack Trackball* and the *AbleTrack Trackball*. Mouse clicks are usually operated by external foot switches. Pakkanen and Raisamo [2004] suggest that such interfaces are appropriate for nonaccurate tasks. Some devices use the distribution of the user's weight to control two-dimensional variables. An early video-game controller that used this principle was the *Amiga Joyboard* (1982), which contained the four directional latches of a joystick on the bottom of the board and, by leaning in a certain direction, the user engaged these latches and controlled the game. The *Nintendo Wii Balance Board* (2007) uses four pressure sensors to measure the user's centre of balance and has been used for several purposes beyond entertainment including fitness, navigating maps [Schöning et al. 2009] and navigating 3D environments [Xavier et al. 2011].

Pearson and Weiser [1986] created several early prototypes of foot interfaces, dubbed "moles," as the "beasts are situated under-foot." These authors proposed the term for the category of devices that are operated by the feet in a similar manner to the mouse, but it was not subsequently picked up by other authors. Instead, the term ended up referring to the multiple prototypes that these authors built in the 1980s, which used a rig under the desk to simulate mouse input. In a second work [Pearson and Weiser 1988a], they implemented a planar mole featuring a pedal that slid in all four directions constrained to a plane. In a third study [Pearson and Weiser 1988b], they built two versions of the swing mole, in which the cursor is controlled by the right foot, which slid left and right on a platform that rotated along an axis inside the desk well from the front desk edge.

A final category of mediated sensing input devices are locomotion interfaces for virtual reality. These devices use repetitive movement of the user's limbs to navigate through virtual environments. For a full treatment of this category, we refer the reader to Hollerbach's survey [Hollerbach 2002]. Hollerbach categorises locomotion interfaces as *pedalling devices* (e.g., bicycle simulator [Brogan et al. 1998] and the Sarcos Uniport (1994)), as *walking-in-place devices* (e.g., *Gaiter* [Templeman et al. 1999]), as *foot platforms* (e.g., the Sarcos Biport, *GaitMaster* [Iwata et al. 2001]) and as *treadmills* (e.g., the Sarcos Treadport, the Omni-Directional Treadmill [Darken et al. 1997]).

4.1.2. Intrinsic Sensing. Intrinsic sensing devices contain sensors directly coupled to the legs and feet. These systems are typically wearable and self-contained, requiring little to no instrumentation on the environment, thus allowing users to move freely. Because of this increased mobility, these systems typically monitor users' walking patterns to make inferences about the user. Such systems usually come in the form of sensors and actuators augmenting users' insoles or their whole shoes. They are typically *always on*, meaning that they continuously track users as long as they are wearing the device, without explicit user interference. Among their guidelines for wearability, Gemperle et al. [1998] suggest that the areas of the lower limbs more suitable for mounting wearable devices are the waist and hips, the thigh, the shin, and the top of the foot. The reasons for this are that these are areas that are relatively the same size across adults; have low movement and flexibility, even when in motion; and are large in surface area [Gemperle et al. 1998].

The first documented wearable computer was, in fact, manipulated by the feet. Thorp [1998] describes how, in the 1950s and 1960s, he developed a wearable computer to predict the outcome of casino roulette wheels operated inconspicuously using a toe switch in his shoes. The increased interest in wearable computing in the late 1990s sprung a variety of projects interested in augmenting users' shoes. In an early article on the topic, Mann [1997] mentions building trainers that measured his pace.

Wearable interfaces rely on sensors and devices worn by the user that capture information from the user's feet. Table IV shows the sensors used in previous work. The most common sensors in smart shoes are pressure sensors in the form of force-sensitive resistors. By distributing such sensors on different points of the sole, it is possible to

Table IV. Sensors in Selected Prototypes of Augmented Shoes

Reference	Pressure	Acc.	Gyro.	Bend	Temp.	Humidity	Light	Distancet	Application
In-Shoe Multisensory Data Acquisition System [Morley Jr et al. 2001]	✓				✓	✓			Patient monitoring
Expressive Footwear [Paradiso et al. 2000]	✓	✓	✓	✓				✓	Artistic performance
CyberBoots [Choi and Ricci 1997]	✓								Artistic performance
Shoe-Mouse [Ye et al. 2005]	✓	✓	✓	✓					Cursor control
Shoe Shaped Interface [Watanabe et al. 2005]	✓								Inducing a gait cycle
Intelligent Shoes [Huang et al. 2006]	✓	✓	✓	✓					User identification
ACHILLE [Carrozza et al. 2007]	✓								Control of prosthetics
CabBoots [Frey 2007]		✓	✓				✓	✓	Assisting navigation
Shoe-Shaped I/O Interface [Higuchi et al. 2010]		✓							Artistic performance
Sonic Shoes [Lécuyer et al. 2011]	✓								Auditory feedback
Rhythm 'n' Shoes [Papetti et al. 2011]	✓								Artistic performance
Shoe-Keyboard [Tao et al. 2012]	✓	✓							Character input
ShoeSoleSense [Matthies et al. 2013]	✓								Virtual reality

calculate the weight distribution of the user and infer gait patterns. Bend sensors work in a similar manner, by changing their resistance as they are flexed. These are usually installed at the middle of the foot to detect when the foot is bending, such as in the beginning and end of the gait cycle. In the context of gait analysis, whereas pressure sensors can provide steady-state pressures as the toes bear down, the bend sensors provide a differential sensor that corresponds to the attack and release of the heel [Paradiso et al. 2000].

Another widely employed category of sensors are inertial measurement units, which comprise different combinations of accelerometers, gyroscopes, and magnetometers. With such sensors, it is possible to use movement information to estimate the position and orientation of the foot, which, in turn, can be used for analysing gait and for explicit

Fig. 4. Extrinsic sensing from below with an FTIR floor [Bränzel et al. 2013] and from above with a Kinect sensor [Simeone et al. 2014].

interaction with computers. Whereas such sensors can provide accurate measurements of roll, pitch, and yaw (i.e., the orientation of the foot); their absolute position estimates tend to drift over time [Fischer et al. 2013]. They also work well for detecting relative movements, such as kicks and other gestures [Alexander et al. 2012].

All sensors described so far measure the movement, orientation, and configuration of the foot, but sensors that attempt to make sense of the environment around it—both inside and outside the shoes—have also been explored in the literature, such as humidity, light, and distance sensors [Morley Jr. et al. 2001].

A challenge for wearable devices is how to power all these sensors and processing units. When we walk, we generate kinetic energy, which can be harnessed by augmented shoes using piezoelectric elements. These components convert into electric current the mechanical stress created by the foot when pushing down against the floor. Even though the current generated is not much, it is enough to power active RFID tags [Orecchini et al. 2011] or low-power components.

Paradiso et al. describe several iterations of trainers—dubbed *Expressive Footwear*—augmented with pressure, bend, position, acceleration, and rotation sensors for interactive dance performances [Paradiso and Hu 1997; Paradiso et al. 1998, 1999a, 1999b, 2000] and interactive therapy [Paradiso et al. 2004]. *CyberBoots* was another early work aimed at interactive performances, which consisted of boots that could be worn over the user's shoes to detect walking and leaning patterns from pressure sensors mounted on the insoles [Choi and Ricci 1997]. More recently, other works that used foot-mounted sensors for artistic purposes include geta clogs augmented with a *Nintendo Wiimote* and a pico projector for guitar performances [Higuchi and Nojima 2010], as well as sandals that detect foot tapping to create accompanying drums [Papetti et al. 2011].

By installing sensors on users' shoes, it is possible to unobtrusively monitor their gait patterns anywhere they go. Applications for this kind of technology include detecting abnormal gait patterns [Chen et al. 2008]; identifying users by their gait [Huang et al. 2006]; adjusting music tempo to match the user's pace [Hockman et al. 2009]; navigating in virtual environments [Matthies et al. 2013]; inducing a specific walking cycle [Watanabe et al. 2005]; assisting navigation [Frey 2007]; and even changing the noise of users' footsteps [Lécuyer et al. 2011]. A commercial example is the *Nike+iPod* (2006) line of trainers, which measures and records the distance and pace of a walk or run. From users' gait patterns, it is also possible to infer their trajectories using a technique called *pedestrian dead reckoning*. Fischer et al. [2013]. describe how to achieve this using inertial sensors mounted on the foot.

Augmented shoes have medical applications. Morley Jr. et al. [2001] installed pressure, temperature, and humidity sensors to measure environmental conditions inside diabetic patients' shoes. The commercial product *SurroSense Rx System* also aims at assisting diabetes patients by collecting pressure data on the insole to help prevent foot ulcers. Carrozza et al. [2007] installed switches on the insole of a shoe to control a prosthetic biomechatronic hand.

Motion sensors on the feet have also be used to detect gestures for explicit HCI, including using augmented shoes to emulate a conventional mouse [Ye et al. 2005] and keyboard [Tao et al. 2012]. Gesture-based foot interaction is particularly interesting for mobile devices. Crossan et al. [2010] investigated foot tapping for interacting with a mobile phone without taking it out of the pocket using an accelerometer on the top of the user's feet. Scott et al. [2010] investigated whether such gestures can be recognized using the sensors in a mobile phone inside the user's pockets. Alexander et al. [2012] collected a foot gesture set suggested by users to control a mobile device.

4.1.3. Extrinsic Sensing. Interfaces in this category rely on sensors placed on the environment to capture data from users' feet from the outside. They usually require little or no instrumentation on the user and are *always on* as long as the user is within the tracked area. They typically offer little to no passive haptic feedback.

Several studies of foot interaction rely on passive infrared (IR) motion capture systems to track the feet. These systems use IR cameras to capture the light reflected by markers attached to different points on the user's legs and feet. They are usually very accurate, but require several cameras depending on the volume being tracked and require direct line of sight between the markers and the cameras. Moreover, the need for special markers attached on the users' bodies makes them unsuitable for casual interactions. *The Fantastic Phantom Slipper* was a pair of slippers with reflective markers and vibration motors used for interacting with a virtual environment [Kume et al. 1998]. Quek et al. [2008] used a passive IR system to track users' feet in order to estimate participants' attentional focus from their feet posture.

Vision-based systems use data from one or more colour cameras to extract the feet's position and orientation. The advantage of such systems is that they require little more than a camera, making them easy to deploy. The downside usually comes in loss of accuracy and the need for a direct line of sight. *AR-Soccer* is a football game using the camera in a PDA by extracting the contour of the user's foot and detecting its collision with a virtual ball in order to kick the ball towards the goal [Paelke et al. 2004]. Similarly, ur Réhman et al. [2012] tracked the feet with a mobile phone using template matching. The *Visual Keyboard* used a vision-based approach to extract users' feet in order to play a musical keyboard [Jean and Albu 2008]. Vision methods have also been employed to activate virtual pedals [Shaukat et al. 2010; Yousaf and Habib 2012], predict driver behaviour [Tran et al. 2012], and control a first-person game [Xavier et al. 2011].

Commercial depth cameras, such as the Microsoft Kinect and the Asus Xtion, made it easier to track the feet accurately in three dimensions. These cameras are usually cheap and fairly accurate, but they also require a direct line of sight with the user. Han et al. [2011] used this approach to investigate kick gestures for mobile interaction. At the time of writing, the available SDK of these systems is only able to track legs and feet when the users' whole body is in the field of view. Some works aimed at extending this functionality to be able to track the feet when the rest of the body is not visible. Hu et al. [2011] proposed a method to accurately extract a 3D skeleton of a user's legs and feet with a Kinect mounted on a walker for the elderly (a.k.a. a *Zimmer* frame), but it does not run in real time. *Bootstrapper* recognizes users around a multitouch table by looking at their feet using Kinect sensors mounted on the table edges facing down [Richter et al. 2012]. Simeone et al. [2014] implemented a foot tracker with a Kinect sensor mounted under a desk and used it to support 3D interaction tasks. The same tracking approach has been used to characterise foot movement performance. [Velloso et al. 2015a] and to enable foot-based interaction with games [Velloso et al.

2015b]. Another similar approach is to use a laser range finder. Huber [2013] used such a system to estimate spatial interest at public displays.

As the feet are in contact with the floor most of the time, feet tracking lends itself to using augmented floors, which can be implemented with a variety of sensors. The first few prototypes of interactive floors were built for dance performances: *Magic Carpet* used a grid of piezoelectric wires [Paradiso et al. 1997], *LiteFoot* used a matrix of optical proximity sensors [Fernström and Griffith 1998], and *Z-Tiles* used a modular architecture of hexagonal pressure-sensitive tiles [McElligott et al. 2002; Richardson et al. 2004]. Lopes et al. [2010] used a Dynamic Time Warping algorithm to classify foot gestures on a wooden board from audio data. This approach is simple to deploy, but can only detect gestures rather than positions or orientations, and may suffer from interference from other sources of noise. Other approaches for augmenting floors include pressure sensitive [Sangsuriyachot et al. 2011; Orr and Abowd 2000] and capacitive floors [Jalaliniya et al. 2013].

Camera-based floors sense users' feet positions with computer-vision techniques. *iGameFloor* used four webcams to track users from under a semitransparent floor [Grønbæk et al. 2007]. *Multitoe* is a high-resolution Frustrated Total Internal Reflection (FTIR) back-projected floor that allows for precise touch input [Augsten et al. 2010]. *GravitySpace* used the same technology to reconstruct users' poses in 3D above the floor from pressure imprints [Bränzel et al. 2013]. *Kickables*, in turn, used Multitoe to track tangibles that users manipulate with their feet [Schmidt et al. 2014]. Whereas these approaches are highly accurate and provide output on the same surface, they do not scale very well and are difficult to deploy, as they require a lot of changes in the infrastructure. An alternative would be to track users from above, such as in *iFloor*, but at the price of losing tracking accuracy [Krogh et al. 2007]. A variety of companies sell top-projected interactive floors, including *EyeClick*, *Luminvision,* and *GestureTek*; such installations have been deployed in shopping malls and other public spaces around the world.

The feet have also been used to interact with vertical surfaces. Jota et al. [2014] implemented interaction techniques for interacting with the bottom part of vertical displays, where the hands would not be able to typically reach.

Because augmented environments and surfaces are often able to extract the position and orientation of the whole foot in two or three dimensions, systems can use this information in different ways: as a blob, as a hotspot, or as relative motion. A blob is a set of points that pertain to the foot. When in three dimensions, this is often called a point cloud. For example, FTIR-enabled floors see a 2D blob, whereas depth cameras see 3D point clouds. Using the feet as blobs effectively increases the size of the target, because any part of the foot can activate it. Due to the relatively large size of the feet, this is more prone to accidental activation, thus targets should be large and well spread apart. Examples of works that track the feet as blobs include Paelke et al. [2004] and ur Réhman et al. [2012].

Instead of using the whole blob, it is also possible to reduce it to a single or multiple hotspots. This allows for more precision in the interaction. For example, Simeone et al. [2014] convert a point cloud to two points in 3D representing the tip of the foot and the ankle, and Augsten et al. [2010] convert it to a single point in 2D. Augsten et al. [2010] also investigated which positions users find intuitive for this hotspot. Their results indicate that there is no universal position agreed to by all users, thus in their system they implemented a calibration procedure that allows users to customise the position of the hotspot.

The final approach is to ignore the absolute position and orientation of the feet and take into account only their relative movement. This is often used for gesture recognition, such as in Lopes et al. [2010].

4.2. Output and Feedback

In order to close the interaction loop, interactive systems must provide some kind of feedback or output. Types of output in foot-operated interactive systems include visual, auditory, haptic, and thermal feedback.

Visual feedback is the primary feedback modality for traditional computing systems, thus it is no surprise that a wide variety of foot-operated systems provide some kind of visual feedback. An important issue for visual feedback is the distinction between *direct* and *indirect* input devices. Direct input devices (e.g., a touch-enabled screen) have "a unified input and display surface," whereas indirect devices (e.g., the mouse) do not "provide input on the same physical space as the output" [Hinckley and Wigdor 2012].

Direct input can be implemented by using touch-sensitive floor displays such as Multitoe [Augsten et al. 2010] or by overlaying the interface with the foot, either through Augmented Reality [Paelke et al. 2004] or by projecting the interface on the floor [McFarlane and Wilder 2009]. This presents a challenge because the feet significantly occlude the screen. Moreover, in order to visualise the output, the user must look down, which can be tiring after extended periods of time. In indirect input, the feet and the display are separate. This creates the need for some representation of the feet on the screen, such as a cursor or other parameter that the feet are controlling. Because the input and output devices are separated, special attention must be paid to the mapping between the two, as incompatible mappings may be cumbersome for the user [Chan and Chan 2009]. Saunders and Vogel [2015] investigated indirect interaction with taps and kicks while standing with and without visual feedback.

Audio feedback is usually implemented in mobile systems in order to reduce the cognitive visual overload. Because of the natural rhythmic pattern of our gait, several systems used input from the feet to modulate music, especially tempo, when the user is walking or jogging [Moens et al. 2010; Bieber and Diener 2005]. Another application area in which the feet are used to generate audio output is in artistic performances, by mapping dancers' [Paradiso and Hu 1997] and musicians' [Papetti et al. 2011] feet movements to music parameters. Stienstra et al. [2011] explored how auditory feedback can improve speed skaters' performance by sonifying the data captured from force and acceleration sensors on the skates.

Haptic feedback consists of forces or vibrations applied on the users' skin to stimulate their sense of touch. This has been implemented in a wide variety of augmented shoes in the form of vibration motors [Watanabe et al. 2005; Matthies et al. 2013]. Rovers and van Essen [2005, 2006] presented an investigation and design guidelines for using haptic feedback at different points on the foot sole. Their findings suggest that users understand better vibration patterns in the longitudinal direction than in the transversal direction; users recognise static patterns in the transversal direction, but are confused by moving patterns; and recognising more complex patterns, such as a "zigzag" pattern, is difficult. *CabBoots* [Frey 2007] provides height/tilt actuation to help the user navigate through an environment by using actuators inside the boots to create an angulation on the shoe sole and steer the user in the correct direction. A commercial example of mechanical actuation inside the shoe is the *Adidas 1* (2005) trainers, which contained a motor in the middle of the sole that changed the compression characteristics of the heel pad. The *Vectrasense Raven Thinkshoe* (2004) did something similar but with an air bladder in the sole. One commercial example of haptic feedback on the feet for navigation is the *Lechal Shoe*, which vibrates to guide users on the path that they set on their smartphones.

Thermal feedback can be produced by Peltier elements, which create a temperature differential on each side. Matthies et al. [2013] included one in an insole and suggested that a rising temperature could be used to make the user unconsciously uncomfortable in certain situations, such as to indicate that the player is wounded or bleeding in a game, or feedback on how many missed calls or unread messages the user has received They stress, however, that the human body tends to acclimate to thermal discomfort, becoming less responsive to a constant stimulus. The authors suggest alternating between hot and cold to maintain the sensory response.

5. FOOT-BASED INTERACTIONS

So far, we have analysed previous work in terms of users and systems, relating how different body poses and movements impact the design of systems that capture input from the feet and provide some kind of output. In this section, we deal with the dialogue between users and systems. More specifically, we are concerned with the different actions that users perform with their feet for interaction.

Karam and schraefel [2005] defined a taxonomy for hand gestures in HCI and proposed five categories for gesture styles: *deictic* (gestures involving pointing), *manipulative* ("whose intended purpose is to control some entity by applying a tight relationship between the actual movements of the gesturing hand/arm with the entity being manipulated" [Quek et al. 2002]), *semaphoric* ("any gesturing system that employs a stylized dictionary of static or dynamic (...) gestures" [Quek et al. 2002]), *gesticulation* (gestures that accompany speech) and *language gestures* (such as sign language).

We distinguish four categories of feet actions in HCI: *semaphoric* (Section 5.1), *deictic* (Section 5.2), *manipulative* (Section 5.2), and *implicit* (Section 5.3). We use the same definitions as Karam and schraefel for semaphoric, deictic, and manipulative. Implicit actions comprise the nonverbal behaviour of the legs and feet as well as noncommunicative actions, such as walking.

5.1. Semaphoric

Semaphoric actions are specific gestures belonging to a dictionary. We compiled a comprehensive list of gestures explored in the literature in Table V. In Section 3.2, we showed how gestures derive from the degrees of freedom of the lower limbs. In this section, we look at how these movements and their combinations are used in interactive systems. An important distinction within this category is that, as well as discrete information (i.e., *which* gesture was performed), semaphoric gestures can also carry continuous information (i.e., *how* the gesture was performed). For example, a kick gesture can be used as a simple iconic trigger for a command (e.g., in a music player, a kick advances the playlist to the next song [Alexander et al. 2012]), but the system can also use its direction and speed as parameters for the command (e.g., determining where a football goes in a foot-controlled game [Han et al. 2011; Paelke et al. 2004]).

Touch-sensitive surfaces, inertial motion sensors, and depth cameras made multitouch and midair gestures a reality for consumers [Saffer 2008]. By adapting these technologies for the feet-for example, multitouch floors [Augsten et al. 2010], IMUs on the feet [Han et al. 2011], and depth cameras under the desk [Simeone et al. 2014]—researchers have been incrementing the feet gesture vocabulary as well as understanding what are the appropriate mappings between gesture and functionality.

In a guessability study, Alexander et al. [2012] investigated users' intuitive mappings between feet gestures and controls for mobile devices, compiling a gesture set with corresponding mappings for phone and media control as well as map and browser navigation. They identified two large sets of gestures: discrete and continuous. Furthermore, the authors compared four techniques for implementing continuous mappings for panning actions: displacement-based, rate-based hold, rate-based continuous, and flick. Similar to findings by Kim and Kaber [2009] for pedal operation, Alexander et al. found that users tend to prefer rate-based approaches.

Table V. Dictionary of Semaphoric Feet Gestures

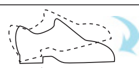
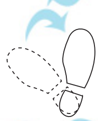
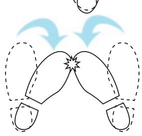
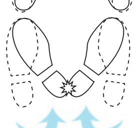
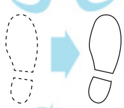
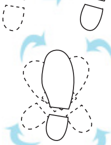
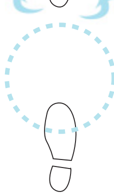
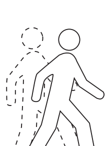
Gesture	Name	Description	Example
	Toe tap	User raises and lowers the toes	[Crossan et al. 2010]
	Heel tap	User raises and lowers the heel	[Tao et al. 2012]
	Toe rotation	User pivots the foot around the toes	[Scott et al. 2010]
	Heel rotation	User pivots the foot around the heel	[Scott et al. 2010]
	Toe click	User touches both toes together	[LaViola Jr et al. 2001]
	Heel click	User touches both heels together	[LaViola Jr et al. 2001]
	Swipe	User slides the foot in a certain direction	[LaViola Jr et al. 2001]
	Shake	User moves the foot with short, quick, irregular vibratory movements	[LaViola Jr et al. 2001]
	Shape trace	User draws the outline of a shape with the toes	[Alexander et al. 2012]
	Kick	Vigorous movement of the foot in a certain direction	[Han et al. 2011]
	Step	User puts one foot in front of the other as if walking	[Drossis et al. 2013]

Table V shows the gestures that emerged from our literature review. Toe tapping is the most common gesture across papers [Chan et al. 2010; Crossan et al. 2010; Papetti et al. 2011; Augsten et al. 2010; LaViola Jr. et al. 2001; Scott et al. 2010]. We attribute its popularity to its low effort, to its historical operation in pedals and to it being analogous to a finger touch. A variation is the heel tap [LaViola Jr. et al. 2001; Scott et al. 2010]. The disadvantage of the heel tap is that it requires users to lift the weight of the leg if sitting or the whole body if standing, which can be demanding on the calf muscle. These gestures are often mapped to selecting an option or activating a certain functionality.

In toe and heel rotation, the user pivots the foot with an abduction or adduction movement at the ankle. When performing this action, the foot remains anchored at the heel or toe, thus it is usually more comfortable than the swipe, which involves moving the whole foot in a certain direction, requiring some leg effort [Velloso et al. 2015a; Scott et al. 2010].

Toe and heel clicking gestures require users to use both feet at the same time. Clicking the heels in Western culture is often associated with the film “The Wizard of Oz” (1939), in which Dorothy, the main character, clicks her heels to go back home. For this reason, heel clicking has been used to invoke the system (the interface’s home) in LaViola Jr. et al. [2001].

Shaking the foot involves an irregular movement across multiple movement axes. The dismissive semantics associated with the gesture led participants in the study by Alexander et al. [2012] to map it to ignore an incoming call. Because it is an easy gesture, with a very distinctive pattern—unlike tapping, for example, which can be mistaken for natural walking—it can be used as a *Whack Gesture*, that is, inexact and inattentive interaction techniques that require minimum cognitive processing from the user [Hudson et al. 2010].

As immortalised by Daniel Day-Lewis’s performance of the real story of Irish painter Christy Brown in *My Left Foot* (1989), some people are able to paint with their feet. Whereas this may sound incredibly hard for most users, it is still possible for them to trace basic shapes with their feet. In the study by Alexander et al. [2012], the shape being traced was a circle, but it would also be possible to devise interaction techniques that use other shapes, such as a square or a triangle.

A foot gesture that has been particularly well studied is the kick. Han et al. [2011] investigated how well users can control the direction and velocity of their kicks in selecting radial targets. The authors recommend using at most 5 targets with an angular width of 24°. In Jota et al. [2014], kicks are used to transfer objects on a vertical screen between the foot-operated area and the hand-operated area. Schmidt et al. [2014] proposed tangibles for feet that users push and kick across a large interaction surface.

Stepping is the basic unit of the *Walking-in-place* (WIP) interaction technique [Slater et al. 1995]. The technique is commonly use for walking around virtual environments, as the proprioceptive information from the body movements makes the user feel more immersed in it. This technique has been used extensively in the Virtual Reality (VR) community and implemented in a wide variety of ways, including sensing in the head-mounted display [Slater et al. 1995], the Wii Balance Board [Williams et al. 2011] and the Kinect depth camera [Zheng et al. 2012]. Because this technique is often used for VR locomotion, controlling speed and direction is critical. Among the solutions for smoothing the speed are the *Gait-Understanding-Driven* (GUD-WIP) [Wendt et al. 2010], *Low-Latency, Continuous Motion* (LLCM-WIP) [Feasel et al. 2008], and *Speed-Amplitude-Supporting* (SAS-WIP) [Bruno et al. 2013] walking-in-place techniques. Whereas WIP techniques are able to set the movement speed, other modalities are still required for setting the direction, including the head, the torso, hand gestures, or other devices such as wands and gamepads [Slater et al. 1995; Templeman et al. 1999]. For a complete treatment of interaction techniques for walking in virtual environments, see Steinicke et al. [2013].

The gestures described so far sprung mostly from research prototypes, but are starting to appear in commercial products. For example, the *Lechal* footwear line uses foot gestures to tag locations, set destinations, and control navigation.

5.2. Deictic and Manipulative

Deictic actions are commonly understood as pointing gestures. When we use our foot to tap on a target on an augmented floor [Augsten et al. 2010] or move a trackball over a target on a GUI [Pakkanen and Raisamo 2004], we are using deictic actions. Manipulative actions map elements of the physical configuration of the foot, such as position or orientation to properties of system objects. When we drag a foot to rotate a virtual cube [Simeone et al. 2014], push a tangible object across the floor [Schmidt et al. 2014] or move a foot mouse to control the orientation of a scene camera [Balakrishnan et al. 1999], we are using manipulative actions. As both types of action involve getting the foot from an original configuration to a target configuration, although for different purposes, we examine them together. More specifically, in this section, we review the literature on the movement times, accuracy, reaction times, and learning effects of such actions.

5.2.1. Movement Times and Accuracy. The most widely adopted model of human movement is Fitts's Law, which was originally developed to predict movement times for hand pointing, but has been proved applicable in a wide variety of situations [Fitts 1954]. Its most common form is the Shannon formulation, proposed by MacKenzie [1992], where MT is the time in seconds to reach the target, D is the distance to the target, and W is the width of the target:

$$MT = a + b \times \log_2\left(\frac{D}{W} + 1\right). \quad (1)$$

Early work on measuring movement times for the feet was concerned with pedal operation—for a review, see Kroemer [1971]. In this context, Drury applied Fitts's Law to find optimal pedal positions [Drury 1975]. He proposed a variation of Fitts's Law that takes into account the width of the user's shoe (S):

$$MT = a + b \times \log_2\left(\frac{D}{W+S} + \frac{1}{2}\right). \quad (2)$$

This modification is due to the fact that Drury considered a target hit whenever any part of the participant's shoe touched it, effectively increasing the size of the target. Hoffman argued that ballistic and visually controlled foot movements should be modelled differently [Hoffmann 1991]. He proposed that, while Fitts's Law provides a good fit for visually controlled movements, ballistic movements are better modelled by the square root of the distance:

$$MT = a + b \times \sqrt{D}. \quad (3)$$

Despite being originally created to model movement times, Fitts's Law can also be adapted to incorporate accuracy measurements. If end-point scatter data is available, this can be accomplished by using the effective distance (D_e) and effective width (W_e), where D_e is the mean movement distance from the start position to the end points and W_e is 4.133 times the standard deviation of the end points:

$$MT = a + b \times \log_2\left(\frac{D_e}{W_e} + 1\right). \quad (4)$$

Table VI. Performance Comparisons between Hand and Feet

Reference	Foot device	Hand device	Participants	$\frac{\text{Foot time}}{\text{Hand time}}$	$\frac{\text{Foot error}}{\text{Hand error}}$
[Hoffmann 1991]	None	None	10	1.95[1]	
[Hoffmann 1991]	None	None	10	1.7[2]	
[Springer and Siebes 1996]	Joystick	Mouse	17	2.32	1.56
[Pakkanen and Raisamo 2004]	Trackball	Trackball	9	1.6	1.2
[Dearman et al. 2010]	Pedals	Tilt	24	1.05[3]	1.20[3]
[Dearman et al. 2010]	Pedals	Touch	24	0.98[3]	1.87[3]
[Garcia and Vu 2011]	Joystick	Trackball	16	1.58[4]	

Notes:
[1]Ratio between the reported coefficients of the indices of difficulty for *visually controlled* movements.
[2]Reported ratio for *ballistic* movements.
[3]Ratio between reported means for selection time and error rate in the text formatting task.
[4]Mean ratio between reported task completion times for the foot joystick and the mouse.
Values correspond to ratios of task completion times and error rates for the feet versus the hands.

Velloso et al. [2015a] derived one-dimensional and two-dimensional performance models for foot-pointing tasks in a seated position that take into account this effective index of difficulty.

Research so far has found little influence of foot dominance on movement times and accuracy. Chan et al. [2010] conducted a study in which they found no effect of gender of foot dominance on movement times in a reciprocal tapping task whilst seated. Velloso et al. [2015a] also found no effect of foot dominance on foot pointing with unconstrained foot movements, but found that sideways movements are faster and easier than forward and backward ones.

We summarise pointing performance results for different input devices in Table VI.

5.2.2. Reaction Times. Reaction time is the time elapsed between the presentation of a sensory stimulus and the corresponding behavioural response. A common model for reaction times is the Hick-Hyman law [Hick 1952; Hyman 1953], which predicts that the reaction time for a set of n stimuli, associated with one-to-one responses is:

$$MT = a + b \times \log_2(n). \tag{5}$$

Simonen et al. [1995] compared reaction times of dominant hands and feet and found that reaction times were nearly the same in choice reaction time testing and the hand was slightly faster (125ms) than the foot in simple reaction time testing. Reaction times are also dependent on the spatial mapping between foot controls and visual stimuli [Chan and Chan 2009].

5.2.3. Learning Effects. An often overlooked issue in foot-interaction studies is the learning effect. Since most users seldom use their feet for computing tasks, a significant amount of the performance gap between hands and feet could be explained by the lack of practice. In a study comparing the learning effects of a foot mouse and a hand trackball over ten sessions, Garcia and Vu [2009, 2011] found that, while participants quickly reached a performance ceiling with the trackball, practice with the foot mouse significantly improved performance.

These results indicate that the feet have an unfair advantage in studies comparing hand- and foot-operated interfaces without allowing enough time for practice. In an early evaluation of pointing devices, in a time when users unfamiliar with a hand mouse still existed, a knee control fared comparably to the mouse, outperforming other hand interfaces [English et al. 1967].

5.3. Implicit

Regardless of how the feet are tracked, the input can be used for explicit or implicit interaction. Schmidt distinguishes explicit from implicit interaction in that, whereas in explicit interaction "the user tells the computer in a certain level of abstraction (...) what she expects the computer to do," in implicit interaction, systems understand as input actions performed by the user that are not primarily aimed at interacting with a computerised system [Schmidt 2000].

In Section 3.5, we showed that our lower limbs send nonverbal signals without our conscious knowledge. Analogously, several systems extract information from foot behaviour without us explicitly using this behaviour for interaction.

On an individual scale, several smart shoes implement this kind of interaction. By monitoring users from within the shoes, these systems are able to infer the user's identity [Huang et al. 2006], gait abnormalities [Kong and Tomizuka 2009], and monitor diseases such as diabetes [Morley Jr. et al. 2001].

On a public scale, augmented environments and surfaces are able to infer information about users unobtrusively by monitoring their feet posture. GravitySpace uses an FTIR-enabled floor to distinguish users, recognise poses, and detect objects [Bränzel et al. 2013]. Bootstrapper recognises users by their shoes to personalise the usage of a multitouch table [Richter et al. 2012]. Smart Floor recognises users from their footstep profile [Orr and Abowd 2000].

Some works draw from Hall's Theory of Proxemics [Hall 1966] to make inferences about a user's attention in regard to public displays. With laser range finders, Huber [2013] was able to distinguish users who were seeking information on a public display from those who were not solely based on their foot patterns. Quek et al. [2008] also found a high correlation between gaze orientation and feet position. Considering that tracking the feet is arguably less invasive than tracking the face or eyes, such approaches offer an interesting way to build context-aware public displays.

5.4. Multimodality

The feet serve one of two purposes in explicit interaction: as the main control of an application (primary) or as supporting other interfaces in the interaction (secondary). Typically, the feet are used as the primary modality for input when the user's hands are busy or dirty (e.g., Alexander et al. [2012]), the user has a disability or other accessibility issue that prevents the individual from using the hands (e.g., Springer and Siebes [1996]), or it is awkward to reach the interface with the hands (e.g., Jota et al. [2014]).

Most commonly, the feet are used to support the task being carried out by the hands. Previous research has explored combinations of the feet with several different modalities, including a keyboard [Garcia and Vu 2011], a multitouch table [Sangsuriyachot et al. 2011], gaze [Göbel et al. 2013], tangible interfaces [Balakrishnan et al. 1999; Schmidt et al. 2014], large displays [Daiber et al. 2009], a mouse [Simeone et al. 2014], and a CAVE [LaViola Jr. et al. 2001]. Typical secondary tasks assigned to the feet include acting as a modifier (e.g., guitar effects pedals, transcription pedals, foot switches as hotkeys), manipulation support (e.g., camera control in 3Denvironments [Balakrishnan et al. 1999]) and mode selection (e.g., mode selection in a text editor [Sellen et al. 1992] and in a musical keyboard [Mohamed and Fels 2002]).

6. DISCUSSION AND FUTURE DIRECTIONS

As a basis for our discussion, we use the categories previously assigned to the surveyed works as a framework for analysing the design space of foot-based interaction and

Table VII. Examples of Instances of the Design Space of Foot-Based Interactions

Pose	Sensing	Interaction	Examples
Sitting	Mediated	Semaphoric	Sellen et al. [1992]
		Deictic and Manipulative	Pakkanen and Raisamo [2004], Springer and Siebes [1996], Balakrishnan et al. [1999], Chan and Chan [2009], Dearman et al. [2010], English et al. [1967], Garcia and Vu [2011], Göbel et al. [2013], Kim and Kaber [2009], Pearson andWeiser [1986], Pearson and Weiser [1988a], Pearson and Weiser [1988b], Xavier et al. [2011], and Zhong et al. [2011]
	Intrinsic	Semaphoric	Papetti et al. [2011] and Tao et al. [2012]
		Deictic and Manipulative	Xavier et al. [2011] and Ye et al. [2005]
	Extrinsic	Semaphoric	Simeone et al. [2014]
		Deictic & Manipulative	Chan et al. [2010], Jean and Albu [2008], Shaukat et al. [2010], Xavier et al. [2011], Simeone et al. [2014], and Velloso et al. [2015a]
		Implicit	Bränzel et al. [2013] and Tran et al. [2012]
Standing	Mediated	Semaphoric	Scott et al. [2010]
		Deictic & Manipulative	Daiber et al. [2009] and Schöning et al. [2009]
	Intrinsic	Semaphoric	Alexander et al. [2012], LaViola Jr. et al. [2001], and Crossan et al. [2010]
		Deictic & Manipulative	Choi and Ricci [1997] and Higuchi and Nojima [2010]
	Extrinsic	Semaphoric	Augsten et al. [2010], Drossis et al. [2013], Jalaliniya et al. [2013], Jota et al. [2014], Lopes et al. [2010], and Sangsuriyachot et al. [2011]
		Deictic & Manipulative	Augsten et al. [2010], Grønbæk et al. [2007], Paelke et al. [2004], ur Réhman et al. [2012], and Saunders and Vogel [2015]
		Implicit	Bränzel et al. [2013], Huber [2013], Quek et al. [2008], and Richter et al. [2012]
Walking & Running	Mediated	Deictic & Manipulative	Templeman et al. [1999], Iwata et al. [2001], and Darken et al. [1997]
	Intrinsic	Semaphoric	Yamamoto et al. [2008]
		Deictic & Manipulative	Choi and Ricci [1997] and Paradiso et al. [2000]
		Implicit	[Frey 2007], Gafurov et al. [2011], Hockman et al. [2009], Huang et al. [2006], Lécuyer et al. [2011], Moens et al. [2010], and Morley Jr. et al. [2001]
	Extrinsic	Semaphoric	Han et al. [2011]
		Implicit	Bränzel et al. [2013], Hu et al. [2011], Orr and Abowd [2000], and Watanabe et al. [2005]

provide directions for future work. Table VII shows how the works described in the previous sections populate this design space.

The first thing that is immediately noticeable in Table VII is that the cell with the highest number of works is that of Sitting, Mediated, Deictic, and Manipulative interaction. These works mostly study foot-operated computer peripherals for the desktop setting. Given that this is the most traditional HCI setting, the high popularity of this kind of work is understandable. However, few works look at long-term deployments of these interfaces, thus more research needs to be done on the effects of practice on user pointing performance.

On the other hand, we also noticed some empty cells (omitted from the table for space purposes). We found no works that investigate implicit interaction with mediated sensing, in any pose. Works that use mediated sensing to analyse human behaviour typically aim at understanding usage patterns or emotions, for example, by looking at the trajectory of the mouse [Yamauchi 2013] or how users press the buttons on a gamepad [Sykes and Brown 2003]. Therefore, we attribute the lack of studies of implicit user behaviour when interacting with foot-operated devices to the limited number of use cases for such input devices and the small populations to which they are targeted.

Similarly, even though there are plenty of works that look at implicit interaction with intrinsic sensing when walking and running, we found no such works explicitly aimed at sitting and standing users. This is explained by the fact that the parameter usually being monitored by such smart shoes is the user's gait cycle. Possible directions for future research along these lines include using smart shoes to infer user states from their natural foot behaviour at their desks or even to infer conversation dynamics from interpersonal communication when standing upright.

From the table, we also notice that different poses lend themselves well to certain types of interaction. In the Sitting pose, aside from Mediated, Deictic, and Manipulative interactions, we also notice a large number of works investigating Extrinsic, Deictic, and Manipulative interactions, evidencing a popularity of works investigating explicit control of desktop computers. In the Standing pose, we see a concentration of works using Extrinsic sensing. This shows that sensing the feet from the outside is well suited to applications in which the user interacts with a fixed installation, such as public displays or interactive floors. In the Walking and Running pose, we see a large number of works exploring Implicit interaction, proving that gait monitoring is a topic that has been explored in depth.

Based on the analysis of the papers reported in this survey, we achieved some insights, summarised in the following:

Feet excel at performing simple tasks. Feet lend themselves to performing simple tasks, such as operating a car's brakes. Yet, these tasks are as important as the tasks simultaneously performed by the user's hands. Several works in the literature mention that the feet are suitable for tasks for which the precision of positioning is not of primary importance [Pakkanen and Raisamo 2004], but the feet are also capable of accomplishing highly complex tasks, such as playing the organ's baseline and manipulating three-dimensional virtual objects [Simeone et al. 2014]. However, this requires a substantial amount of practice. The very few occurrences of such use cases suggest that hands—if they are not busy—are preferred for complex tasks.

Feet interfaces can assist the hands, rather than replacing them. Traditionally, foot-based input was successful only in cases in which hand-based input was not a viable option, either because the hands were already busy with other controls or because they were not available for other reasons (e.g., carrying objects, being dirty) [Alexander et al. 2012]. This is arguably due to the feet being less dexterous, incapable of grasping objects the way our hands can, and being busy with locomotion. Therefore, it is not surprising that, for example, we are not using foot mice, but pedals are more widely adopted, such as in gaming or transcription. Nevertheless, a lot of research has been put into comparing the hands and the feet, leading to results in which the hands consistently outperform the feet. Few works, however, explore how they can be used concurrently. We believe that the feet can effectively complement the hands, offering additional input channels with no homing time.

The performance of the feet might not be as bad as people think. Several works explored the possibility of reassigning cursor control from the hands to the feet, but in these experiments, the mouse consistently outperformed all foot interfaces (Table VI). The results of Garcia and Vu [2011], however, suggest that this may not be because the feet are inherently bad for this purpose, but rather, because of lack of training. Future work must take these learning effects into account, allowing users to become sufficiently familiar with the input device for a fair comparison with hand interfaces.

Foot-based input lends itself well to wearable computing. Wearable computing and augmented reality applications will benefit from foot-based input: users are on the go and interact spontaneously, with their hands often busy with other tasks (Section 4.1.2). At the same time, new sensing technology allows for capturing foot interaction with higher fidelity, allowing for both explicit and implicit interaction.

We still lack the understanding of how these interfaces work in the real world. Whereas there is a significant body of work on laboratory studies of foot-based interfaces, we still need to understand how these interfaces work when deployed for extended periods of time. Not only could such *in-the-wild* studies give us a better understanding of learning effects, they could provide insights on user acceptance of such interfaces.

Interactive systems can further benefit from what the feet tell about users' internal states. Even though the majority of the studies in HCI that explore foot interfaces look into explicit interaction by monitoring the feet, it is possible to recognise not only the activity in which the user engaged, but also internal states, such as attention, relaxation, and anxiety (Sections 3.5 and 5.3).

7. CONCLUSION

In this survey, we analysed foot interaction from the perspectives of the user, the systems, and the interaction between users and systems. From the user perspective, we described the anatomy of the lower limbs and how it evolved. We then broke down the movements for each joint and related them to corresponding interaction techniques. We analysed the different poses in which users interact with foot interfaces—sitting, standing and walking/running—and how these poses influence the interaction. We then discussed how internal states are reflected by the behaviour of the lower limbs.

From the system perspective, we analysed how systems can use the feet to capture input and provide feedback to the user. We classified foot-operated sensing as mediated, intrinsic, and extrinsic. We described actual implementations of such devices in the research literature and in commercial applications. We then discussed the different ways that such systems output information to the user.

Finally, from the interaction perspective, we categorised the foot actions into semaphoric, deictic, manipulative, and implicit. We compiled a dictionary of foot semaphoric gestures, aggregated foot-performance results from previous work, and described applications that infer internal states and activities from the posture and movement of the lower limbs. We then discussed applications that use the feet in combination with other input modalities.

Foot-based input substantially shaped the design of many devices and systems that matter to us and that we interact with on a daily basis, from cars to musical instruments. Whereas mechanical systems have employed foot controls for a long time, electronic devices are seldom designed to benefit from this modality. We believe that, by better understanding the role of the feet in HCI, we can better design interfaces that take input from our whole body.

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Received November 2014; revised July 2015; accepted July 2015