# Free the Hands! Enhanced Target Selection via a Variable-Friction Shoe

**Daniel Horodniczy, Jeremy R Cooperstock**
Centre for Intelligent Machines, McGill University
Montreal, Canada
danielh | jer@cim.mcgill.ca

## ABSTRACT
While several foot-controlled pointing devices have been explored as alternatives to conventional interfaces, we are interested in whether such devices can achieve higher performance with the addition of variable friction. Users wore our variable-friction prototype shoe on their right foot, which they slid on a low-friction surface to control a mouse cursor. Two interface modes were evaluated: constant (CF) and variable friction (VF), under the ISO 9241-9 standard for pointing device evaluation. For the variable-friction modality, target regions were high friction to provide sliding resistance cues. Our findings confirmed that variable-friction foot-controlled pointing can achieve throughput competitive with a range of hand-controlled devices. This suggests the potential for taking advantage of foot input for simple pointing tasks, in particular when the hands are overloaded. With respect to other foot-controlled pointing systems, our implementation offered improved performance and comparable error rates. In addition, the analysis provided further insight into the design of foot-controlled input devices.

### Author Keywords
Variable Friction; Haptic Feedback; Foot-Controlled Input; Fitts' Law.

### ACM Classification Keywords
H.5.2 User Interfaces: Haptic I/O; Input devices and strategies; Interaction styles.

## INTRODUCTION
The foot is an underutilised resource as an interaction tool or peripheral manipulator. There are numerous situations where our feet are left to act as a simple supporting mechanism while our hands are overloaded. In such situations, the feet could perform secondary tasks, thereby relieving load on the hands and potentially achieving greater efficiency. Ultimately, the question we address is whether pointing performance of the foot, manipulated on a 2D plane while sitting, can be improved by friction modulation applied on the contact face of the shoe sole. Target pointing is a common and essential task in the desktop environment. When such pointing is done by foot, previous studies reported a lack of fine-grained dexterity [17]. However, the literature indicates that variable friction can be used to augment pointing performance on touch screens in a sliding context [9]. This motivated the study reported here, investigating whether variable friction, applied to the foot, might allow for effective pointing performance when the hands are overloaded.


CHI 2017, May 6–11, 2017, Denver, CO, USA
 ISBN 978-1-4503-4655-9/17/05 $15.00
DOI: http://dx.doi.org/10.1145/3025453.3025625

## RELATED WORK

### Variable Friction
The literature shows that the objective of variable friction, in general, is to augment simulations or interfaces by adding a degree of controlled tactility, specific to slippage [3, 9]. However, variable friction has not yet entered the mainstream of commercial devices (e.g., smartphones), as have vibration feedback and 3D touch capabilities. Applications include virtual environment augmentation and haptics-driven enhancement of user experience, usability, and pointing performance.

From a haptics standpoint, variable friction has been demonstrated to improve pointing performance [1, 5, 4, 9] and may be used in conjunction with vibration stimuli to further enrich perceptual experiences [10]. Haptic feedback is quite common in mobile devices and we anticipate that the porting of variable friction to these interfaces is simply a matter of time.

### Foot-Controlled Pointing
The foot has been studied from an HCI perspective as early as the 1960s [6]. Early work investigated the ideal ergonomic and functional design of foot-controlled interfaces intended to augment pointing performance and experience in the desktop environment [6, 13, 14]. However, given the greater dexterity of fingers than toes, it comes as no surprise that hand-controlled devices significantly outperform their foot-controlled counterparts, as demonstrated in Table 2. The difference in performance is manifested in both movement time and accuracy, since it takes the foot approximately twice as long as the hand to complete equivalent movements [12, 8].

Garcia and Vu compared the performance of a hand-controlled trackball and a foot-controlled mouse in word processing tasks over ten sessions to investigate the effects of learning.

Trackball performance was superior, but performance quickly plateaued, whereas foot mouse performance continually improved over the sessions. This suggested an inherent bias in comparisons between hand- and foot-operated pointing devices due to experience with hand pointing. It also suggested that further practice may help to meet or exceed conventional mouse pointing performance, necessitating further research on the topic [7, 18].

### A Variable-Friction Shoe

The prototype friction-varying mechanism used in this work (shown in Figure 2) attaches to one's shoe sole at the heel [10]. Both high- and low-friction materials are used on a single face of contact between the mechanism and the floor. Friction is modulated by controlling the position of the high-friction material, thereby regulating the normal force experienced at the heel. To facilitate relative continuity in friction variation, an elastic element is placed between the high-friction material and the position control element. Low-friction material is used at the shoe sole face and in regions where the high-friction material may protrude. When the elastic element is uncompressed, the high-friction material does not contact the floor, resulting in an experience of low-friction. The concept is illustrated in Figure 1. The prototype has a mass of approximately 850 g.

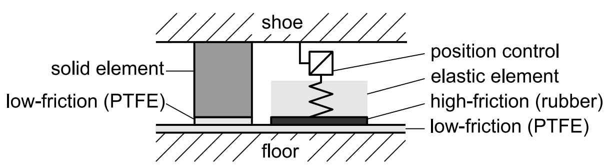


**Figure 1. A diagram illustrating the mechanism of friction variation employed by the prototype.**

Assuming Coulomb's model of dry friction and that the mass of the device is negligible with respect to a user's mass, the effective COF is described mathematically as follows [10]:

$$F_{\text{human}} = F_{\text{lf}} + F_{\text{hf}} \tag{1}$$

$$F_{\text{hf}} = E_{\text{el}} S_{\text{el}} \varepsilon_{\text{el}} \tag{2}$$

$$\mu_{\text{eff}} = \frac{\mu_{\text{lf}} F_{\text{lf}} + \mu_{\text{hf}} F_{\text{hf}}}{F_{\text{lf}} + F_{\text{hf}}} \tag{3}$$

$$\mu_{\text{eff}} = \mu_{\text{lf}} + (\mu_{\text{hf}} - \mu_{\text{lf}}) \frac{E_{\text{el}} S_{\text{el}} \varepsilon_{\text{el}}}{F_{\text{human}}} \tag{4}$$

$F_{\text{human}}$ is the downward force applied by the user on the shoe sole. $F_{\text{lf}}$ and $F_{\text{hf}}$ are the ground reaction forces experienced by the high- and low-friction materials. $E_{\text{el}}$ is Young's modulus of the elastic element, $\varepsilon_{\text{el}}$ its percentage strain and $S_{\text{el}}$ its cross-sectional area (of the high-friction material). The COFs of the high- and low-friction materials are $\mu_{\text{hf}}$ and $\mu_{\text{lf}}$, respectively. When the elastic elements are uncompressed (i.e., $\varepsilon_{\text{el}} = 0$), then $\mu_{\text{eff}} = \mu_{\text{lf}}$. Compression of the elastic element increases the force applied to the high-friction material $F_{\text{hf}}$ by an amount equal to the decrease of force applied to the low-friction material $F_{\text{lf}}$. If $F_{\text{hf}}$ reaches the total force $F_{\text{human}}$, the low-friction material is no longer in contact with the floor and $\mu_{\text{eff}} = \mu_{\text{hf}}$.

The prototype mechanism consists of a set of brake pads, composed of a rigid element (aluminum), elastic element (EVA foam) and high-friction material (Santoprene rubber), which are translated orthogonally with respect to the sole to modulate friction. The sole of the shoe is polytetrafluoroethylene (PTFE) because of its low self-contact COF. The actuator driving the brake pads is a thin-profile stepper motor. Rotational motion from the motor is transferred by a gear train to lead screws, which are fastened by thread on to the rigid element of the brake pads. Brake pad extension was tracked by an optical rotary encoder sensing the rotation of the gear train. The brake is controlled by simple thresholding, i.e., actuation ceases when the desired position is reached. On the bottom of the mechanism, PTFE tabs protrude as the supporting low-friction material. Preliminary tests determined that the shoe could render COFs over a range of approximately 0.11–0.4 for a mass range of 0–11.4 kg.

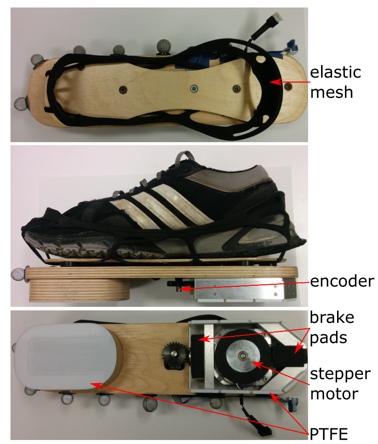


**Figure 2. Top, side and bottom pictures of the prototype with annotations. The prototype fastens to subject's shoes using an elastic mesh.**

## FOOT-CONTROLLED POINTING

### Method

Our experiment used Wobbrock et al.'s *FittsStudy*,[1] where subjects were evaluated using constant low friction (CF), and with high friction over target regions, but low friction elsewhere (VF), to complete 1D and 2D tasks for nine movement conditions. The movement conditions had amplitudes $A = \{300, 600, 1000\}$ and widths $W = \{20, 60, 128\}$, which gave an index of difficulty range of $ID = \{1.74 - 5.67\}$. Each movement condition included a total of fifteen trials, of which the first four were discarded to mask learning effects, resulting in 396 recorded movements per subject. To ensure suppression of learning effects, a number of other measures were taken. The presentation of each combination of interface and dimensionality was based on a Latin squares design and the order of movement conditions within each task was randomized. Before each subject began, they would complete three trials for each combination of interface, task dimensionality and movement condition. To mask the sound of motor actuation, subjects listened to pink noise, played through earbuds, and in addition, wore sound suppression earmuffs during all phases of the experiment.

[1] https://depts.washington.edu/aimgroup/proj/fittsstudy/

In order to guarantee that target regions were high-friction, both proximity and velocity thresholds were used to determine the point in time to extend the shoe's brake pads. Actuation time lasted approximately 180 ms and resulted in an estimated change in COF of approximately 0.25.

### Apparatus and Procedure

The apparatus consisted of the prototype, a slanted PTFE surface, three motion capture cameras (OptiTrack Flex:V100R2), a 24-inch 1920 × 1080 LCD monitor and an ASUS TP500LN laptop computer (Intel® Core™ i7-4510U CPU @ 2 GHz, 8 GB RAM, Windows 10) with a mouse. The motion capture cameras, sampled at 100 Hz, tracked the position of the subject's right foot during the evaluation, which was streamed via USB to a modified version of *FittsStudy* as cursor position input. Subjects wore the prototype on their right foot, which they slid on the slanted PTFE surface to control the mouse cursor. The position of the foot on the PTFE surface was mapped directly to screen coordinates (i.e., absolute positioning). Subjects used a conventional mouse left-click to indicate a selection since our interest was specifically focussed on the human ability to control cursor position. Subjects were instructed to move the cursor to each target as quickly and accurately as possible, with emphasis on speed.

Before each subject's participation, the PTFE surface and prototype sole were sanded with 600 and 1000 grit sandpaper and subsequently cleaned with isopropyl alcohol. Between each of the four blocks experimental conditions, i.e., the pairing of interface (CF or VF) and dimensionality (1D or 2D), the prototype sole and the PTFE surface were wiped clean of PTFE flakes. Figure 3 shows the physical layout of the experimental setup. Before and after the experiment, subjects were required to complete a questionnaire. The pre-experiment questionnaire collected personal data (i.e., age, gender), while the post-experiment questionnaire enquired about interface-specific information such as the subject's levels of comfort, effort, fatigue, perception of variable friction, dimensionality preferences, strategies employed, and difficulties encountered.

**Figure 3. Apparatus used in the foot-controlled pointing Fitts' characterization. The PTFE surface was set on an incline to facilitate a greater range of motion when sliding the foot while sitting.**

### Results

A total of twelve subjects (6F / 6M) aged 20–33 ($\mu = 24.3$, $\sigma = 3.8$), voluntarily consented to participate in the study, which received approval from the McGill Research Ethics Board. Experimentation lasted an average of 45 minutes and subjects were compensated \$10. The pre-experiment questionnaire revealed that eleven of the subjects were right-foot dominant, while the other was ambidextrous. Three of the subjects encountered foot-operated interfaces (e.g., car driving, piano/organ playing) less than once per week, but the remaining nine dealt with them on a consistent basis (i.e., more than twice per week). Table 1 summarizes the Fitts' models and their associated coefficients of determination as well as the mean throughputs (TP) and percentage errors for each combination of interface and dimensionality.

**Table 1. Fitts' law movement time models, their coefficients of determination and associated TPs and error rates.**

| Interface | Movement Model | $R^2$ | TP (bits/s) | % Error |
|---|---|---|---|---|
| 1D CF | $MT = ID \times 341 - 7$ | 0.74 | 3.04 | 6.38 |
| 1D VF | $MT = ID \times 271 - 156$ | 0.74 | 3.22 | 6.40 |
| 2D CF | $MT = ID \times 619 - 363$ | 0.76 | 2.09 | 10.93 |
| 2D VF | $MT = ID \times 470 - 22$ | 0.80 | 2.21 | 8.19 |

A two-factor repeated measures ANOVA was used to analyze the TP data, revealing significant effects of both friction interface ($F_{1,11} = 21.31, p < 0.001$) and task dimensionality ($F_{1,11} = 350.40, p < 0.001$). No interaction was found between these two factors ($F_{1,11} = 0.53, p = 0.48$). Application of Mauchly's test confirmed that the assumption of sphericity had not been violated ($F = 0.72, p = 0.68$). Further inspection, comparing the TPs of constant and variable friction with respect to task dimensionality reveal significant differences between the interfaces for the 1D ($F_{1,11} = 10.87, p < 0.01$) and 2D tasks ($F_{1,11} = 5.07, p < 0.05$). Graphical illustration of the TPs can be seen in Figure 4.

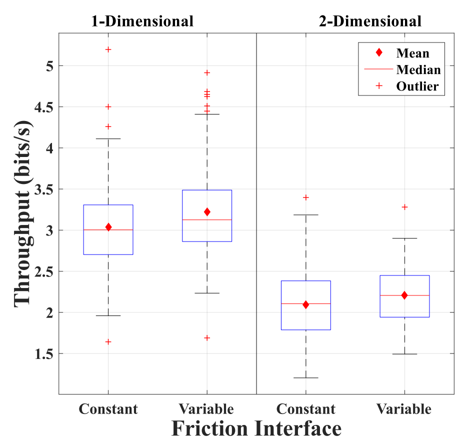


**Figure 4. Box plots of all four combinations of friction interface and task dimensionality.**

### Discussion

#### *Movement Models*

As is apparent from the slopes of the 1D and 2D models, the additional dimension nearly doubles the required movement time for pointing tasks with the same ID. We note that longer movement times are especially prevalent for small target widths. A peculiarity seen in the 2D CF case is its low intercept, which we believe to be attributed to the inherent difficulty of accurate 2D foot-pointing on a slippery surface. While reduced friction minimizes the effort required to move the foot, a lack of accurate fine motor control was observed.

Subjects had the tendency to overshoot targets by a small distance, and subsequently attempt correction, only to overshoot again, spending considerable time in the process of repeated corrections. The same characteristic is not seen in the 1D CF case, most likely due to heel rotation, which subjects often employed.

### *Throughput*

Although this is, to our knowledge, only the second foot-controlled pointing system analyzed using ISO 9241-9, a clear difference in performance is seen between our implementation and that of Velloso et al. [17]. We note that while our foot-based interface cannot achieve the same performance as the best hand-controlled devices, it is nevertheless competitive, as shown in Table 2. Similarly, observed error rates are comparable to that of conventional pointing devices. We attribute the relatively strong performance of the foot-based interface primarily to the inclined, low-friction surface used in our experiment. Minimal effort in sliding, and the use of sticky targets, greatly simplify foot-controlled pointing. We hypothesize that with practice, improved TPs and reduced error rates would be seen and establish the system as a clear competitor with touchpads and trackballs.

**Table 2. Reported throughputs and error rates of hand and foot-operated pointing devices evaluated using ISO 9241-9 on 2D tasks.**

| Hand-Controlled Device | Throughput (bits/s) | Error (%) |
|---|---|---|
| Mouse [16] | 3.7 – 4.9 | 11.0 |
| Trackball [16] | 3.0 | 8.6 |
| Touchpad [16] | 0.99 – 2.9 | 7.0 |
| Wiimote [11] | 2.59 | 10.2 |
| Joystick [16] | 1.6 – 2.55 | 9.6 |
| Wii Classic Controller [11] | 1.48 | 6.58 |
| **Foot-Controlled Device** | **Throughput (bits/s)** | **Error (%)** |
| **2D VF** | **2.21** | **8.19** |
| Depth Camera [17] | 1.16 | 7.64 |

### *Post-Experiment Data*

#### *Likert Scales*

With regards to ease of use, comfort, and smoothness, users indicated a clear appreciation for the interface. We believe this was owed largely to the low-friction surface and possibly the use of familiar mouse clicks as a selection modality. The midrange values of physical effort scores can be explained by the lengthy duration of the experiment and lack of experience with the body kinematics associated with foot pointing. We attribute the mental effort scores to the inherent concentration required when performing Fitts' tasks. Lastly, we note that subjects only indicated initial fatigue, at a low level, after more than thirty minutes of continuous pointing activity. This result is likely helpful for the adoption of new peripherals.

#### *Perceptions, Preferences, Strategies and Challenges*

Seven of the subjects reported perceiving the friction modulation, five of whom felt vibration in addition to increased sliding resistance. Only two of these subjects actually preferred the variable-friction interface, despite its superiority in performance. Those who disliked variable friction complained

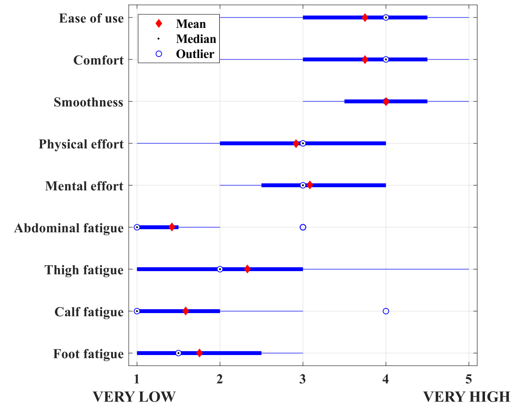


**Figure 5. Box plots of the Likert scale data collected in the post-experiment questionnaire.**

of feeling a lack of control and difficulty in manipulation as desired. Given the improved results of the variable friction modality, we hypothesize that subjects merely perceived a lack of control, due to the increased sliding resistance, rather than having actually experienced one. Four subjects preferred the 2D task for its challenge, while the remainder enjoyed the simplicity of a single dimension. The most preferred direction of movement was diagonal, along the *northwest/southeast* axis, where north is located at the toe and south is located at the heel. We presume this preference can be credited to a physiological predisposition, as similar findings are seen in other publications [2].

Fine motor control, with respect to small-target pointing, was reported as the most challenging aspect of the experiment. Two specific strategies were noted: firm placement of the left foot for superior control, and heel rotation for improved accuracy. Only two of the subjects cited firm foot placement, but all utilized heel rotation. Subjects generally employed heel rotation in low amplitude 1D tasks because of the ease of this movement.

Subjects' recommendations were widely varied, but consisted mostly of suggested physical improvements, described below.

- Subjects wanted to configure the device's friction levels to their preference. This would negate the feeling of lacking control and allow users to fine tune the device as desired.
- Adding vibration feedback was suggested by a number of subjects. Given the inconsistency in sliding friction perception, we hypothesize that this feedback may cause users to overcompensate and perhaps undershoot their targets.
- Modification of the mapping type from an absolute one to a rate-based implementation (i.e., first-order control) may be assistive in low-amplitude movements due to the smaller displacements for reduced speeds.

### *Potential Applications*

A number of potential applications have been envisioned for use with our current implementation. Primarily, these employ variable friction to indicate a change in gradient, e.g., a volume slider whose friction increases with volume, or modulated friction to create virtual "bumps", e.g., detents in a rotational menu, similar to the alarm clock of Levesque et al. [9], but driven by foot. High-friction borders around grouped regions, e.g., individual paragraphs, could facilitate movement through text documents by foot, leaving the user's hands free to manipulate the keyboard as desired. Simeone et al. [15] offer at least two scenarios where variable friction would be beneficial, such as during a swipe gesture to create a bump indicating that the user has passed over an object or menu item, or to create a friction gradient providing feedback of a parameter level during a control operation.

## CONCLUSION

Constrained, low-friction surfaces are comfortable, easy to manipulate and generate little fatigue when used for foot pointing over extended periods of time. We found further evidence that the foot may compete with traditional hand-operated pointing devices. The notion that the foot is better suited to coarse grained, non-accurate tasks is supported by evidence from this experiment, but the analysis clearly indicates that assistive techniques (i.e., variable friction), can make our feet effective in tasks requiring precision.

Evaluation of foot-controlled pointing systems against other pointing devices should be performed with tasks requiring simultaneous cursor control and keyboard manipulation to demonstrate the improved efficiency foot pointing may offer. In addition, the effects of practice require further exploration [18]. Lastly, variable-friction pointing systems should be evaluated with distracting targets [9] to ensure their effectiveness in more realistic use cases.

## REFERENCES


1. Motoyuki Akamatsu and I Scott MacKenzie. 1996. Movement characteristics using a mouse with tactile and force feedback. *International Journal of Human-Computer Studies* 45, 4 (1996), 483–493.
2. Jason Alexander, Teng Han, William Judd, Pourang Irani, and Sriram Subramanian. 2012. Putting your best foot forward: investigating real-world mappings for foot-based gestures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1229–1238.
3. Olivier Bau, Ivan Poupyrev, Ali Israr, and Chris Harrison. 2010. TeslaTouch: electrovibration for touch surfaces. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*. ACM, 283–292.
4. Andy Cockburn and Stephen Brewster. 2005. Multimodal feedback for the acquisition of small targets. *Ergonomics* 48, 9 (2005), 1129–1150.
5. Jack Tigh Dennerlein, David B Martin, and Christopher Hasser. 2000. Force-feedback improves performance for steering and combined steering-targeting tasks. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*. ACM, 423–429.
6. William K English, Douglas C Engelbart, and Melvyn L Berman. 1967. Display-selection techniques for text manipulation. *Human factors in electronics, IEEE Transactions on* 1 (1967), 5–15.
7. Fredrick P Garcia and Kim-Phuong L Vu. 2011. Effectiveness of hand-and foot-operated secondary input devices for word-processing tasks before and after training. *Computers in Human Behavior* 27, 1 (2011), 285–295.
8. Errol R Hoffmann. 1991. A comparison of hand and foot movement times. *Ergonomics* 34, 4 (1991), 397–406.
9. Vincent Levesque, Louise Oram, Karon MacLean, Andy Cockburn, Nicholas D Marchuk, Dan Johnson, J Edward Colgate, and Michael A Peshkin. 2011. Enhancing physicality in touch interaction with programmable friction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2481–2490.
10. Guillaume Millet, Martin J-D Otis, Daniel Horodniczy, and Jeremy R Cooperstock. Design of Variable-Friction Devices for Shoe-Floor Contact. *submitted for publication to Mechatronics* (????).
11. Daniel Natapov, Steven J Castellucci, and I Scott MacKenzie. 2009. ISO 9241-9 evaluation of video game controllers. In *Proceedings of Graphics Interface 2009*. Canadian Information Processing Society, 223–230.
12. Toni Pakkanen and Roope Raisamo. 2004. Appropriateness of foot interaction for non-accurate spatial tasks. In *CHI'04 extended abstracts on Human factors in computing systems*. ACM, 1123–1126.
13. Glenn Pearson and Mark Weiser. 1986. Of moles and men: the design of foot controls for workstations. In *ACM SIGCHI Bulletin*, Vol. 17. ACM, 333–339.
14. Glenn Pearson and Mark Weiser. 1988. Exploratory evaluations of two versions of a foot-operated cursor-positioning device in a target-selection task. *ACM SIGCHI Bulletin* 19, 3 (1988), 70–75.
15. Adalberto L Simeone, Eduardo Velloso, James Alexander, and Hans Gellersen. 2014. Feet movement in desktop 3D interaction. In *3D User Interfaces (3DUI), 2014 IEEE Symposium on*. IEEE, 71–74.
16. R William Soukoreff and I Scott MacKenzie. 2004. Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI. *International journal of human-computer studies* 61, 6 (2004), 751–789.
17. Eduardo Velloso, Jason Alexander, Andreas Bulling, and Hans Gellersen. 2015a. Interactions under the desk: A characterisation of foot movements for input in a seated position. In *Human-Computer Interaction–INTERACT 2015*. Springer, 384–401.
18. Eduardo Velloso, Dominik Schmidt, Jason Alexander, Hans Gellersen, and Andreas Bulling. 2015b. The Feet in Human–Computer Interaction: A Survey of Foot-Based Interaction. *ACM Computing Surveys (CSUR)* 48, 2 (2015), 21.