Feel-a-Bump: Haptic Feedback for Foot-Based Angular Menu Selection

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***Abstract*— Although diverse foot-based applications have been explored, foot-based menu selection is underexplored given its potential for low-fatigue secondary control input. Here, we are investigating whether the effect of adding haptic modalities can achieve higher performance in a menu selection task. We study the effect of auditory or vibrotactile feedback on selection performance in radial menus consisting of three, six and nine items. We compared no feedback to one auditory and two vibrotactile clicks, one across the foot, one localized to the movement direction. All feedback modalities allowed for rapid completion of menu selections and, while audio was generally preferred and our results suggest a superiority over haptics, the latter are still helpful in increasing selection accuracy. However, we argue that the difference is such that haptics could still be used with comparable performance in noisy environments or by users with auditory disabilities. Finally, we use an analysis of the number of attempts required to select the correct position, coupled with the number of errors, to make design recommendations for foot-based menus.**

I. Introduction

Foot-based interfaces are commonly used in environments where hands and eyes are occupied. They excel at simple control task and assisting the hands [1], such as in control of automobiles, aircraft, or tool speed. As computing increasingly becomes mobile, we are interested in addressing the question of whether interfaces based on commodity sensor technology, integrated into footwear, can be controlled effectively without visual feedback?

Depending on the environment, relying on the auditory channel may not be feasible due to noise or existing signals, such as in medical or industrial settings. Thus, our interest here is to investigate if vibrotactile feedback can provide comparable performance to auditory feedback. Similarly space and user movement may be heavily constrained, as in surgical theatres.

Here, we investigate the selection of items from a radial menu by foot rotation, seeking to determine whether localized haptic feedback serves as a viable alternative to both visual and auditory feedback, based on user performance. Fig. 1 illustrates our 1-D radial menu selection task. To make menu selections, participants relied on natural proprioceptive feedback, and possibly, visual tracking of their own foot position. In certain conditions, they were also provided with augmented auditory or vibrotactile feedback. Here, we compare a simple click sound to two vibrotactile stimuli, the latter rendered on a multi-actuator insole to investigate whether localized feedback can provide benefits at higher menu item counts.

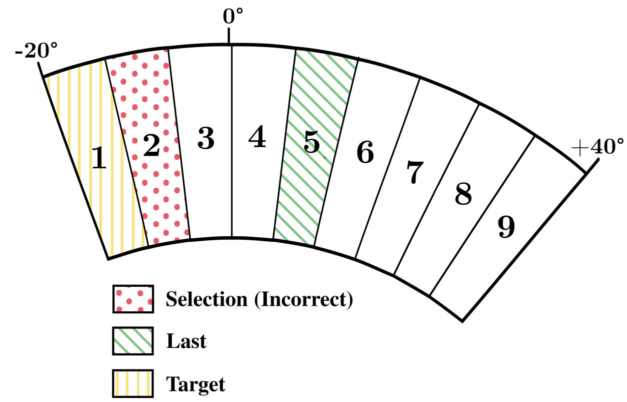

Fig. 1: Example menu for nine items. Starting from the last selection of item 5 (green diagonal hash), the participant has been instructed to select the target, item 1 (yellow vertical hash), but instead makes an incorrect selection of item 2 (red dots).

II. Related Work

Research on foot-based wearables ranges from early instrumented footwear [3], [4], to more recent exploration of haptic actuation, rendering immersive virtual environments [5], [6], supporting rehabilitation [7] and navigation [8], [9]. Foot haptic feedback can also be used to improve gesture interfaces for people with severe motor dysfunction [10]. Velloso et al. provide an extensive literature review of diverse foot interfaces and compared different foot interactions in 1D and 2D based on Fitts' law tasks [1]. Scott at al. presented a system to classify foot-gestures, such as ankle rotation, from a mobile phone in the pocket [11].

Hatscher et al. identified foot rotation and relative as opposed to absolute movement be a suitable gesture for controlling 1-D parameters [12]. Grane et al. evaluated the advantage of haptic feedback in rotary menu selection tasks by adding different haptic texture effects. They found that a combination of visual and haptic feedback is least mentally demanding and offers the highest accuracy [2]. For these reasons, this foot rotational movement has been frequently used an input method. Recently, research on foot-based menu control have studied where range of foot rotation was separated into several areas and assigned either menu items [13] or different functions [14]. These findings motivated our evaluation of a 1-D menu selection task in order to improve our understanding of how haptic feedback should

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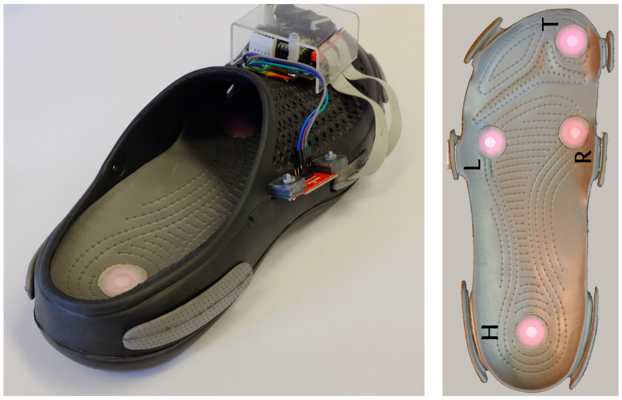

(a) Shoe (b) Insole

Fig. 2: Haptic shoe and insole with actuator placement locations at **t**oe, **h**eel, **r**ight and **l**eft (first and fifth metatarsal head)

be delivered for maximum effectiveness. Specifically, we are interested in its usefulness for wearable devices and assessing the feasibility of using commodity sensor technology for such a system.

III. Methodology

Participants had to choose a highlighted item from a radial menu by rotating their foot. In order to isolate foot interaction to item selection [1] and minimize the risk of parasitic foot movements, users confirmed their menu selections by pressing the space bar on a computer keyboard. Participants were only permitted to advance to the next trial after successfully selecting the indicated target item and could try as often as they needed.

In a pilot study, we found visual feedback on the current menu item to enable near-perfect accuracy. However, since we are interested in supporting users in tasks for which visual attention may be in high demand, we wanted to explore the feasibility of relying on haptic feedback as a substitute for the visual modality. Thus, we chose not to display current menu item during the experiment, but only displayed starting foot position, i.e., the last correct selection, and highlighted the chosen item after it was confirmed.

The menu was placed in the region of comfortable foot rotation, from -20° to 40° [13]. We compared three sizes of menus with three, six and nine items respectively, dividing this range into equal slices. Thus, in menus with three items, the slices subtended 20° per item, 10° per slice for six items, and 6.7° per slice for a menu with nine items. The smallest of these angular displacements is close to the 5° increments we found to be a practical limit for accurate control of foot rotation in a parallel foot control study that relied on visual-proprioceptive feedback. Fig. 1 shows an example of a nine-item menu.

The menu interface was rendered graphically using the Unity game engine, running fullscreen on a desktop computer with a 24" flat panel display. Participants sat comfortably

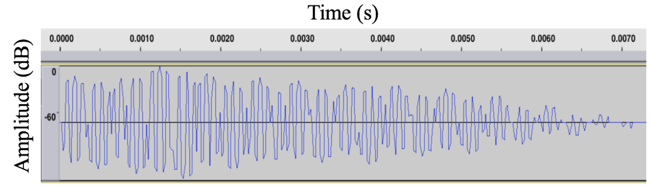

Fig. 3: Auditory feedback: click sound

in front of the computer on a desk, with the foot under the table. Auditory feedback and pink noise to mask audible artifacts from the vibrotactile insole were provided using Beyerdynamic DT770 Pro M headphones.

A. Instrumented Haptic Shoe

Users controlled the menu through an instrumented and actuated shoe, worn on their right foot, pictured in Fig. 2 (a). A Bosch BNO-055 sensor provided us with a stable yaw reading through its integrated fusion of accelerometer, gyrometer and magnetometer readings (at 100 Hz). In order to minimize communication latency, menu item calculation was performed on the shoe's ARM Cortex-M4 microcontroller. Similarly, although the shoe supports wireless communication for future in-situ testing, we opted for a wired connection through USB.

The shoe also contains four vibrotactile actuators. Previous research indicated that vibrotactile stimuli are perceived more reliably when aligned with "anchor points" on the body, anatomical landmarks such as bone structures [15], [16]. For the feet, Hijmans et al. suggested four points that showed the highest pressure and density of mechanoreceptors below first and fifth metatarsal head, big toe and heel [17], [18]. We placed actuators at these locations, as shown in Fig. 2 (b). In the study presented here, only the left (L) and right (R) actuator were used in this study.

We use embedded pancake shaped linear resonant actuators (LRAs) (Samsung DMJBRN0934AA (Ø 9 mm, $f_{res} \approx 205$ Hz, acceleration > 1G @ 100g load), driven by a separate driver chip per actuator (TI DRV2605L). Dished aluminum inserts filled with silicone provide mechanical protection and work as a baffle for the vibration energy, guiding it to the user rather than into the sole and effectively decoupling the actuators from each other. The inserts are embedded in the shaped insole of a foam sandal (size US 10.5) that provides guidance to center the foot in the shoe. In a previous study, we found this to be a suitable coupling enabling good recognition rates for tacton discrimination tasks, especially in stationary scenarios. Users asked to discriminate six tactons delivered through the shoe correctly recognized >92% of the patterns [19].

B. Experiment Design

We evaluated 12 participants (8 male, 4 male) with an mean age of 24.6 years (SD = 4.4 years), with an average US men's shoe size of 9.9 (SD = 0.95), all reporting a dominant right foot. Participants gave informed consent and filled a pre- and post questionnaire.

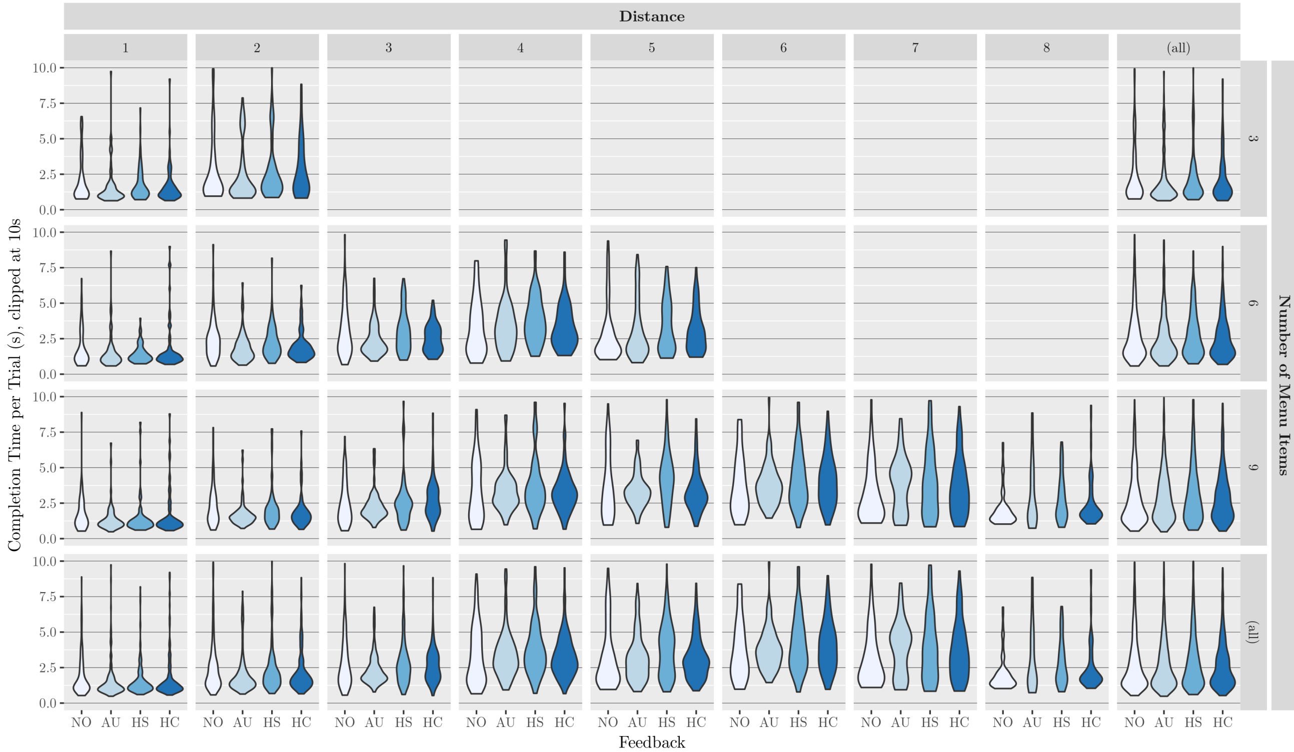

Fig. 4: Completion time: Violin plots with respect to distance, menu size and feedback condition

We compared four conditions for different feedback on the transitions between menu items:

- **NO**: No Feedback
- **AU**: Auditory Feedback
- **HC**: Haptic Click: Simultaneous click, left AND right
- **HS**: Haptic Side: Localized buzzing, left OR right

In the AU/HC/HS conditions, each step between menu items triggered a feedback event, either auditory or haptic. Auditory feedback (AU) consisted of a simple click sound [20], visualized in Figure 3. Haptic click feedback (HC) was a simultaneous buzz of both left and right actuators simultaneously for 50 ms once for every menu item transition. Haptic side feedback (HS) was a localized buzz on the left or right actuator on the side the user rotated their foot towards. Both haptic feedback stimuli were approximately 50 ms in length, as a compromise between being short enough to allow for acceptable foot rotation speed without overlap and ability of pilot subjects to perceive them.

For the order of trials, we followed similar sequences as the multidirectional tapping task described in the ISO9241-9 standard (2002) [21] to cover all possible direction and distance combinations. An example sequence of targets for a three items menu would be 1, 3, 2, 3, 1. Participants carried out a series of ten randomly preselected trials in each of the four conditions, for a total of $10 \times 4 = 40$ trials, with conditions presented in the same order as in the test round.

After a training round for each menu size (3/6/9) and each condition (NO/AU/HC/HS), participants completed blocks of trials for each condition, with conditions ordered by Latin squares. Within each block, trials progressed from the smallest to largest menu size: 12 trials for the three-item menu, 30 trials for the six-item menu, and 48 trials for the nine-item menu, for a total of $4 \times (12 + 30 + 48) = 360$ trials per participant. Although learning effects may have helped participants achieve better performance as the experiment progressed, the results, described below, indicate that difficulty increased as a function of the number of menu items.

IV. Results and Discussion

We compared completion time (time until a correct select was made) by menu size and feedback condition, and also analyzed the number of attempts with respect to distance and menu size according to feedback condition. In the three-item menu, participants achieved similar average completion time in all conditions. Fig. 4 shows the completion times of participants as violin plots. These are similar to box plots but also illustrate the distribution of the data as the width of the "violin body". This allows us to see the multiple peaks corresponding to repeated attempts at hitting the correct target, e.g., for a distance of seven steps.

The percentage of trials correct on the first attempt decreases with the number of menu items, and, as expected, is the worst for the no-feedback condition (see Table I). Interestingly, participants performed better in the clockwise direction. Given that all participants reported a dominant right foot, this may have anatomical reasons and should be investigated in future work. Required attempts, along with completion time, increased with increasing menu size.

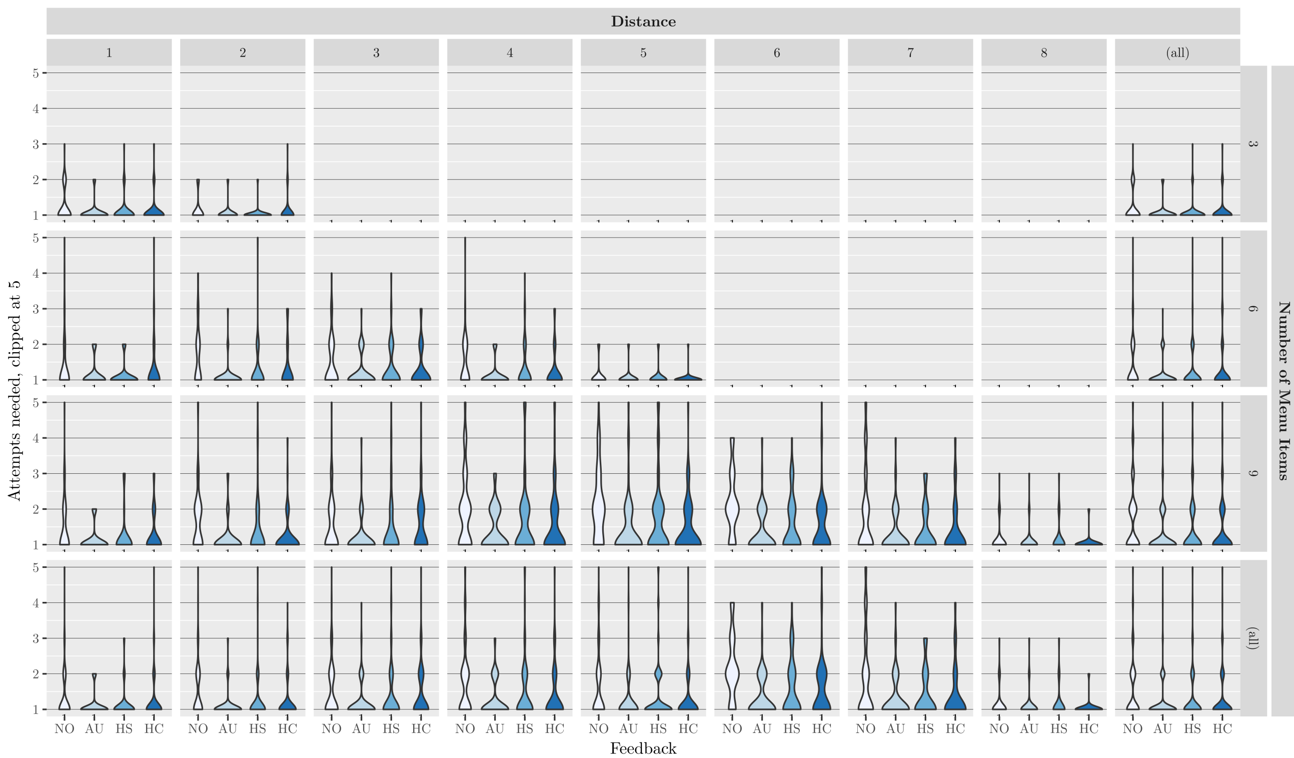

Fig. 5: Attempts needed: Violin plots with respect to distance, menu size and feedback condition

TABLE I: Percentages of trials correct on first attempts, by condition, movement direction and menu size

Size	**AU**		**HC**		**HS**		**NO**	
	↻	↺	↻	↺	↻	↺	↻	↺
3	94.4	93.1	90.3	93.1	97.2	91.7	83.3	79.2
6	92.2	86.7	86.7	82.8	83.9	84.4	80	60.6
9	81.2	79.2	75	70.8	71.5	69.1	55.2	48.6

As is evident from the plot of needed attempts in Fig. 5, moving to either the left or right extreme of the menu was performed easily, because of the infinite target width of an "edge" menu item. However, smaller step sizes proved to be more difficult, even with feedback. Movements within the larger menu required more attempts to reach the target item. 9 of 12 participants preferred audio feedback as modality, and all but one reported the system to be comfortable and easy to use.

Audio feedback outperformed both haptic feedback conditions, and HC exhibited slightly better performance than HS as the number of items increased. However, the effect size was small.

V. Conclusion and Outlook

We investigated whether audio or haptic feedback would improve performance in menu selection when carried out by rotating the foot. Although audio was found to be the most effective modality, it may not be suitable for many potential applications, and the haptic alternative's drop in accuracy would not be meaningful in all applications. Localized haptic feedback did not show a benefit in our experiment, but may be helpful in real-world environments with relatively strong distractors or high loads on the somatosensory system. The system worked well despite employing only an inexpensive motion sensor for angle determination. We conclude that radial foot-menus with non-visual feedback on menu position show promise to be implemented effectively in a mobile context, which could enable many potential use cases of control input where the hands and eyes are occupied. Future studies should both employ a distractor task, as well as haptic or audio noise to better represent real-world conditions.

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