FingerPad: Private and Subtle Interaction Using Fingertips

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ABSTRACT
We present FingerPad, a nail-mounted device that turns the tip of the index finger into a touchpad, allowing private and subtle interaction while on the move. FingerPad enables touch input using magnetic tracking, by adding a Hall sensor grid on the index fingernail, and a magnet on the thumbnail. Since it permits input through the pinch gesture, FingerPad is suitable for private use because the movements of the fingers in a pinch are subtle and are naturally hidden by the hand. Functionally, FingerPad resembles a touchpad, and also allows for eyes-free use. Additionally, since the necessary devices are attached to the nails, FingerPad preserves natural haptic feedback without affecting the native function of the fingertips. Through user study, we analyze the three design factors, namely posture, commitment method and target size, to assess the design of the FingerPad. Though the results show some trade-off among the factors, generally participants achieve 93% accuracy for very small targets (1.2mm-width) in the *seated condition*, and 92% accuracy for 2.5mm-width targets in the *walking condition*.

Author Keywords
Instant-available, private input, subtle interaction, eyes-free interaction, nail device, finger-mounted device.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

General Terms
Design, Human Factors

INTRODUCTION
Recent developments have seen new proposals for glass-mounted displays for use in mobile computing. Though similar to head-mounted displays, glass-mounted displays (e.g., Google Glass) are specially designed to be lightweight, attachable, non-obstructive to natural vision, and with increased social acceptance.

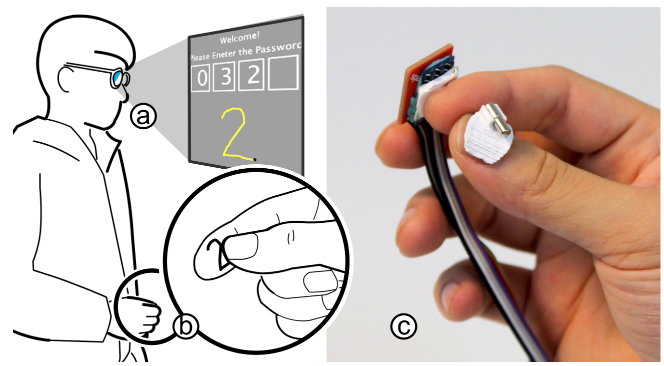

Figure 1. FingerPad enables touchpad function through pinch gesture. The user can (a) enter passwords to the private glass display (b) by drawing numbers with the thumb tip on the index fingertip. (c) The proposed technology is realized through magnetic tracking by adding a magnet and Hall sensor grid on the fingernails.

Although these types of displays permit personal and private visual outputs, their input methods may not offer the same privacy. For example, voice input is commonly used for glass-mounted displays because it is expressive and effective. However, voice input can be problematic in loud environments, and privacy issues arise with its use in public spaces (e.g., password input)[11]. Gesture input suffers from similar privacy concerns because input actions are easily observable.

To permit private input, recent research proposes subtle interactions [2, 10, 15], which are based on implicit movements and generally considered socially acceptable. For example, muscle interface [10] allows input through unobservable muscle movement. Foot gesture [12] detects subtle foot motions. Ring devices [1, 9] and fabrics [6] have been developed to support tap, spin, and slide inputs. Although these methods allow subtle inputs (and thus allow for privacy and social acceptability), they generally suffer from limited input space.

This paper presents FingerPad, a nail-mounted device that turns pinched fingertips into a touchpad, allowing private, and subtle interactions. As illustrated in Figure 1, the user treats the tip of their index finger as the touchpad, and their thumb as the touch stylus. FingerPad enables touchpad function using magnetic tracking, by adding a magnet and Hall sensors on the fingernails. Functionally, FingerPad resembles a touchpad that users can easily learn to use. Allowing for 2D touch input, FingerPad is suited for rich interactions, including pointing, menu selection, and stroke input.

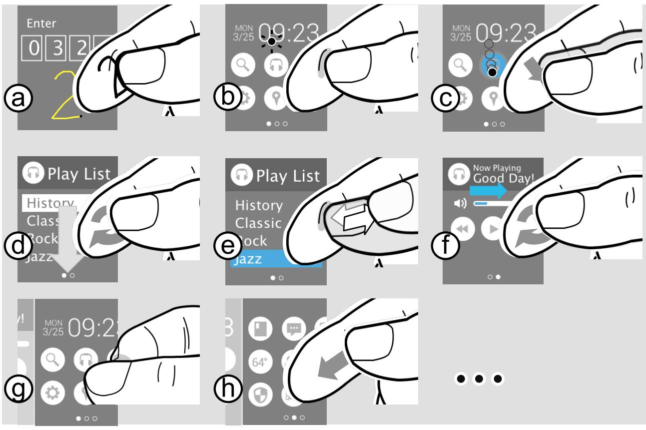

Figure 2. The walkthrough illustrates the use of FingerPad for glass displays. The graphics on the left of the subfigures are GUIs presented in the glass display view. Meanwhile, the graphics on the right of the subfigures are the suggested gestures that can be enabled using the proposed technique.

Benefits

Enabling touchpad functions through the pinch gesture suggests several benefits. (1) Private and socially acceptable: since the subtle movements between pinched fingers are naturally hidden by the operation hand, FingerPad is appropriate in contexts where privacy or social acceptance is a concern. (2) Highly mobile: owing to the dexterity and stability of the hands, FingerPad allows precise 2D input even while users are highly mobile, such as walking as tested in the study. (3) Natural haptic feedback: attachment of the device to the nails preserves natural haptic feedback from the fingertips, and dose not affect their native functions (e.g., griping small objects). (4) Instant availability: allowing for quick access (right under the fingertips), FingerPad can provide instant help between manual works (e.g., switching radio channels during hands on cooking). Additionally, by tracking through magnetism, FingerPad is occlusion-free (i.e., it can be used with the hands in the pocket).

SCENARIO

Figure 2 illustrates a scenario involving the application of FingerPad for private visual outputs, such as glass-mounted displays. Robin wears the glass display while on the train on his way to work. The glass display asks the subject, Robin, to provide an authentication password. Instead of using voice input, he chooses to use the FingerPad input owing to privacy concerns. (a) Robin individually writes four numbers on the tip of his index finger to unlock the glass application. (b) Robin presses on the tip of his index finger to enter the cursor mode, (c) then moves the cursor over the music app, and releases the pressure on his thumb to make a selection. (d) In the music list, he draws a circle on his fingertip to move to the Jazz category, and (e) clicks to enter the player page. (f) He then circles again to adjust the volume. (g) To jump to the home screen, he taps on the very tip of his index finger. Finally, (h) he swipes his thumb leftward, which takes him to the next app page, and plans to check the daily.

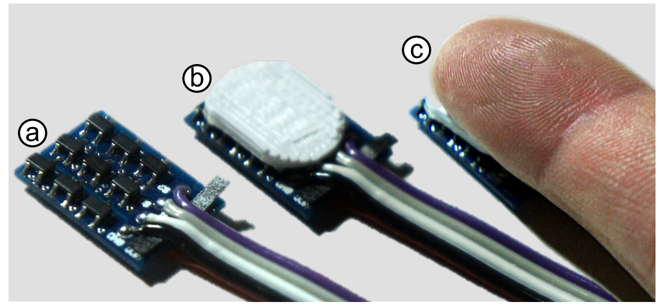

Figure 3. (a) The 3x3 sensor grid, and (b) a nail-shaped plate with a curved surface (c) suggesting fitness to the natural nail.

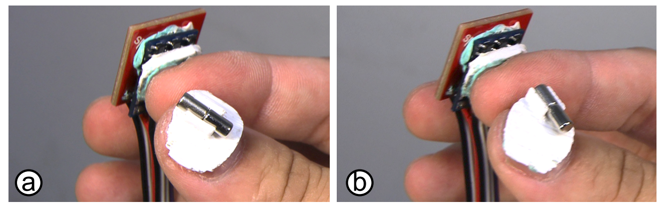

Figure 4. The magnet holder grips the magnet at a specific orientation. (a) The first design of the magnet holder. (b) The magnet orientation is pushed 30 degrees to the right to accommodate the bio-mechanism of the index and thumb fingers.

DESIGN CONSIDERATION

There are several possible methods to install 2D input capability on the fingertips, such as a fingerstall-like device with a touchpad added to the tip side, or a ring device [8] with a tiny optical mouse. Although fingerstalls and rings are reasonable forms, they can affect the native abilities of the fingertips. For example, fingerstalls influence the softness and friction of the fingertips, which are essential for gripping small objects. The ring mouse is a decent alternative, but constrains the finger. In comparison, FingerPad places no constraints on the fingertip, finger, and hand. To the knowledge of the authors, magnetic tracking is the only available solution that preserves the natural haptics of the fingers. However, the downside of magnetic tracking is that the device must be installed on two fingers.

PROTOTYPE

FingerPad is a pair of nail-mounted devices comprising a thin (2mm) magnetic sensing plate, and a plate of neodymium magnet. The sensing plate includes a 3x3 Winson WSH138 Hall sensor grid (Figure 3a), and each sensor is separated from the others by 2mm, which implies a total area of 12(W) x 12(H) mm^2. Each sensor element detects both N- and S-polar magnetic field intensities within the range 0 to 200 Gauss on a 512-point scale. An Arduino board with an ATmega32U4 microprocessor bridges the sensing plate and the computer. Based on the magnetic strength captured by the plate, FingerPad approximates the magnet position, transforms that position into finger-pad coordinates defined through user calibration (see the *Tracking* and *User calibration* sections), and sends these coordinates to the applications.

To attach the sensor plate firmly to the nail, we use a 3D printer to craft a nail piece that suggests the curved surface of a natural nail. As shown in Figure 3b, the sensor plate,

Figure 5. To guide the calibration, a translucent dot pattern is fixed to the index fingertip, thus helping to obtain good homographic transformations.

glued the nail piece, is further glued onto the nail of the user using twin adhesive tape. The use of glue helps users envision future nail devices that resemble artificial nails.

Another nail piece is created that holds the magnet and fixes its orientation. The magnet is placed such that the polar orientation of the magnet is parallel with the normal of the sensor grid when users place their thumb at the center of the tip of the index finger. Figure 4a shows the first design. To adapt the bio-mechanism of the thumb and index fingers, we improve the design by moving the magnet orientation 30 degrees to the right (Figure 4b). The magnet we used is a 3mm-diameter x 8mm-height cylindrical neodymium magnet, which allows effective sensing within 2.1cm using the sensor plate. Notably, this effective distance can be further extended with more sensitive magnetic field sensors, such as magnetometers [5].

Tracking

The finger-pad coordinate is presented as Cartesian coordinate. For the 3 x 3 sensor grid, the sensor at the lower left corner is set as the coordinate origin. The magnet position expressed in sensor-grid coordinates is approximated from bilinear weighting based on the magnetic strength read by each Hall sensor. Because the measured magnetic field strength is in fact a mix of quadratic and cubic attenuation, this approach merely approximates the magnet position. The *User calibration* section further regulates the positioning result.

Two strategies are applied to improve the positioning. First, the polarity of the magnet is positioned in parallel with the normal of the sensor grid, as shown in Figure 4b. Second, we exclude opposite polar values read by the sensors. When users tap on the edges of the index fingertip (e.g., the bottom area), the magnet orientation may deviate from the normal of the sensor grid, which leads some sensors to read opposite polar values.

User calibration

User calibration is performed to regulate the 2D positions calculated in the *Tracking* section, to the finger-pad coordinate in the index fingertip. To account for the non-linear mappings between the sensor-grid and the finger-pad coordinates, the finger-pad coordinate is divided into multiple sub-coordinates, and the nonlinearity is approximated by computing the homographic transformation between each sub-coordinate and the sensor-grid coordinate.

Typically, a homographic transformation can be determined by more than four pairwise correspondent points. To guide the calibration, a translucent dot pattern is fixed on the tip of the index finger. The dots are separated by 4mm in a Cartesian coordinate, and the 3 x 3 dot pattern suggests a normal fingertip size. We stick the pattern on the index fingertip area, as shown in Figure 5. The nine pairs of the correspondent points from the calibration process are then used to compute the homographic transformation for each of the four sub-coordinates. Provided the magnet orientation is correctly positioned, the calibration configuration can adapt well to fingers of different sizes and thickness.

Land-on detection

Although the Hall sensor plate can detect a hover state (e.g., when the thumb is near the index fingertip) based on the strength of the magnetic field, it is hard to determine when the thumb of the user contacts the index fingertip. To detect contact, an accelerometer is added to the Hall sensor plate to detect the impact associated with contact. Specifically, we calculate the derivative in the X-, Y-, and Z-axes, respectively, using a sliding window. Monitoring the values in the sliding window can identify a candidate for land-on when a positive derivative is followed by a negative one. Contact is only reported, when the thumb is simultaneously within the hover range. After contact, touch interactions by the user can be recognized until the thumb moves beyond the hover range.

Flick selection

While the upside of magnetic sensors is 2D tracking, whether users have released the pinch is tricky to determine from the observed magnetic strengths. We implemented take-off selection, which required the user to release the pinch sufficiently fast and far to produce a clear decrease in magnetic strengths. In the pilot, participants reported that fast take-off contradicted the sense of commitment. This problem was resolved by the second design, which used flick. In this design (1) users pushed to overcome the friction from the fingerprints, which better matched the sense of commitment. Additionally, (2) flick-up is more easily detectable because the magnetic-field intensity drops as a result of this motion in an inverse-cubic manner, compared to an inverse-square decrease in take-off selection.

We propose selection by flick, as illustrated in Figure 6. Moving the cursor over a target, the user makes a selection by flicking their thumb up. Upon exit from the hover state, we remove the cursor movement during the last 180 milliseconds (determined from a pilot testing) to eliminate unwanted cursor movement. The final cursor position determines the selection. The side effect of flick selection is that the user may experience unwanted cursor movement before the thumb exits the hover state.

APPLICATION

Based on the touchpad functions provided by the prototype, we implement the touch cursor, gesture input, and stroke input functions to demonstrate the capability of FingerPad. The implemented application is described in the Scenario section. The touch cursor function allows a user to use a long press

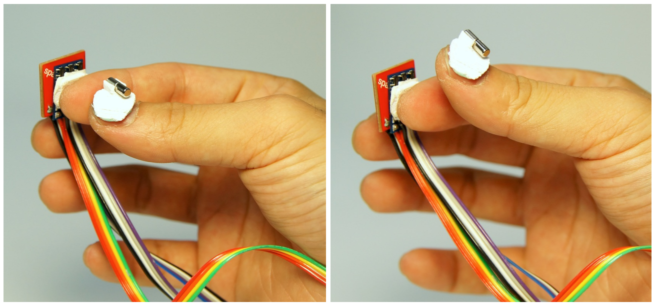

Figure 6. The user makes a selection by flicking the thumb up.

to enter the cursor mode, which reveals the cursor on the display (e.g., the glass interface). Movement of the thumb on the index fingertip allows the user to freely move the cursor. The flick selection then allows the user to make a menu selection. Swipe and circling gestures can be used in the gesture input. In a page view, the user can swipe left or right to view the subsequent or previous page. In a list view, the user can make a clockwise or counter-clockwise circling gesture to scroll down or up through the list. In terms of stroke input, the unistroke recognizer [14] is adapted for numeric input, which allows users to write the password or phone numbers.

USER STUDY

This study seeks to understand user performance in a mobile scenario that included seated and walking conditions. We proposed the flick method as a baseline method, and included the bimanual click method to reveal the upper-bound results. Finally, this study also seeks to determine how small a target users can select to learn the user limitations.

Task and Conditions

The participants are instructed to move the cursor over the target shown in the screen and make the selection using single-handed flick selection method or the bimanual clicker method with the non-pointing hand depending on the conditions. The target color changes when the cursor enters the target square. On successful selection, the target disappears and the next target appears on the screen. We measured task time and error rate for target side lengths of 10mm, 5mm, 2.5mm, 1.2mm and 0.6mm. The 0.6mm case is included to test user limitations. The experiment screen is a 13-inch macbook air. Only a sub-region (3-inch, 4:3) in the center of the screen is used. The cursor is absolute mapping.

In the *seated condition*, the participants sat on the chair in front of the table with the screen facing them. The participants , and were instructed to adjust the chair height such that they could rest their dominant hands on the table for support (Figure 7a). The participants ensured that they could see the smallest (0.6mm) target clearly. The screen was moved closer to the participants if necessary to achieve this. In the *walking condition*, subjects performed tasks on the treadmill. The screen was placed on top of the treadmill control platform, as shown in Figure 7b. In principle, the screen in both conditions was positioned at a normal reading distance (40cm). The treadmill was set to a normal walking speed (3.5 km/hour)

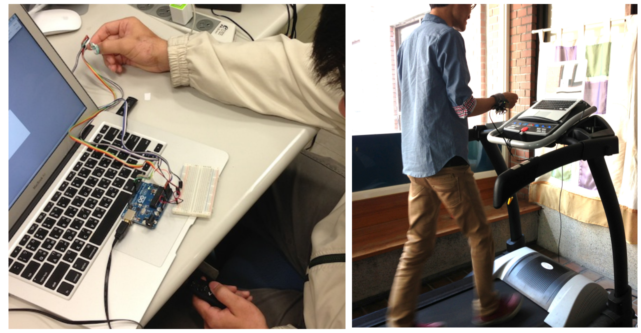

Figure 7. The study setup for the seated condition (left) and walking condition (right).

and participants adjusted this speed by up to 0.5km in either direction according to their preference.

Interface and apparatus

The participants wore the sensor part of the device on the index fingernail, and the magnet part on the thumbnail. Owing to differences in nail sizes and the way participants moved their thumbs on the index finger pads, participants were assisted in wearing the device, and adjusted the magnet holder orientation to accommodate interpersonal tapping habits. The pilot testing found that the thick fingers from some male participants could degrade the tracking performance using the original magnet setting. To avoid tracking errors, the magnet was replaced with a wider magnet (4mm-diameter x 8mm-height) that ensures the tracking performance.

Experimental design

The study design was 2 x 2 x 5 x 12 (Condition x Commitment method x Target Size x Target Position) with three repetitions for each cell. The Condition was the between-subject variable. The target sizes were 10mm, 5mm, 2.5mm, 1.2mm and 0.6mm, and the target positions were the 12 centroids of a regular 4 x 3 grid. For each trial, task completion time and errors were recorded. The different commitment methods were counterbalanced, and the target sizes and positions were randomized.

Participants

22 participants (10 female) with mean age 26.9 years old (*SD*: 3.9), ranging from 22 to 38 years olds, were recruited from the university. Each subject was rewarded by a small gift for their participation. The task took about 30 minutes. All participants were right-handed and had experience of using touch input devices.

Results and discussion

A multi-way ANOVA found there was a significant difference in completion time between different target sizes, and existed an interaction effect between the commitment method and the posture. While for the error rate, it found only [target size x posture] and [commitment method x posture] interactions. To further evaluate how these factors (i.e. the posture, the commitment method, and the target size) affected user performance, we did the following post-hoc tests.

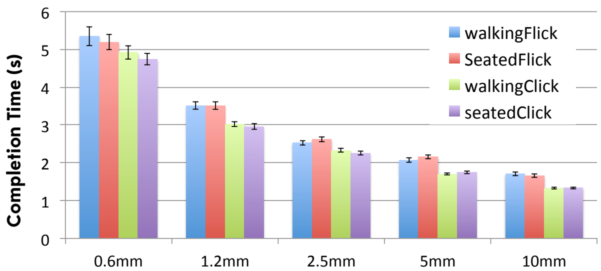

Figure 8. The study completion times, with 95% confidence intervals, of different target sizes in two commitment methods under the seated and walking conditions.

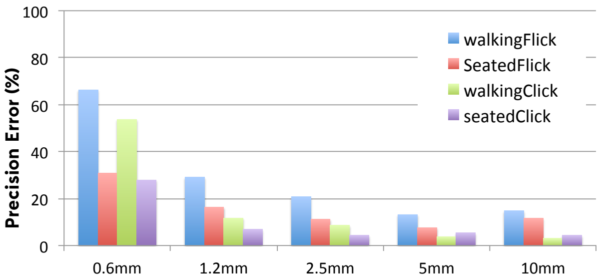

Figure 9. The study error rates of different target sizes for two commitment methods under the seated and walking conditions.

Posture

To analyze the data, we ran the pairwise *t*-test to determine whether posture affects user performance. Completion time did not differ significantly between the seated and walking conditions. However, error rate differed significantly between the two postures when the target size was below 2.5mm. In terms of design insights, if the system can detect user posture, it can adjust UI layout accordingly. For example, the system can provide seated users with a tight layout and compact information, and can provide walking users with a loose layout and abstract information. However, if users want a consistent user experience, the target size should be larger than 2.5 mm.

Commitment method

The pairwise *t*-test was run to determine whether different commitment methods for both postures affect user performance. The results showed that the clicker method was significantly faster than the flick method only for the walking posture. As for the error rate, while in the walking condition, the difference in error rate between the flick and clicker methods, were statistically significant. Regarding design insights, performance can be improved by choosing different commitment methods. However, there exists a trade-off between the two methods. Although the clicker method can perform better, it requires bimanual interaction. Compared to the clicker method, users can perform the task with only one hand, which frees the other hand.

Target size

The pairwise *t*-test was run to learn whether different target sizes affect user performance. For both completion time and error rate, the statistics show that 0.6mm differs significantly compared to all other target sizes for subjects adopting a walking or seated posture. Regarding completion time, 1.2mm differs significantly compared to 5mm and 10mm for subjects adopting a walking or seated posture. Hence, in terms of design, we suggest the control should exceed 1.2mm to maximize user experience.

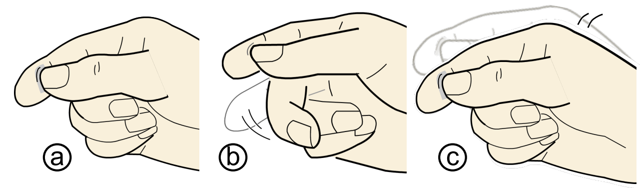

Figure 10. Other commitment methods described by the participants are as follows: (a) press, (b) move the middle finger, and (c) move the wrist.

Based on the results of the user study, we were also impressed by the ability of users in cursor control under the walking condition, even though cursor shaking was inevitable. When working on the smallest target, the participants reported that they reduced shaking by pressing hard during the pinch gesture. Specifically, they first moved the cursor to an area near the target, then squeezed the fingertips, and made minor adjustments to the cursor position to achieve fine control.

Summary

Generally, through the user studies, we can conclude three design insights. First, posture affects performance, but this influence is significantly decreased provided the target size is sufficiently large (e.g., larger than 2.5mm). Second, performance differs with commitment method. Based on considering comfort and convenience, alternative designs of the single-handed commitment methods can also be considered. For example, hard pressing (Figure 10a), moving the middle finger in the air (Figure 10b), or slightly twisting the wrist (Figure 10c) can be adopted. Third, the target size of the control buttons should not be too small, such as smaller than 0.6mm. Nevertheless, the system design should consider the trade-offs among the three factors.

RELATED WORK

This work is related to private and subtle interaction, and finger-worn devices, and magnetic tracking.

Private and subtle interaction

Several subtle interaction techniques have previously been proposed. Costanza et al. [2] used electromyography to sense subtle motionless gestures. Saponas et al. [10] used a similar technique to sense different finger gestures. Furthermore, Scott et al. [12] proposed using mobile devices located in the pocket of the user to sense foot gestures. Pinstripe [6] allows users to perform subtle interactions by pinching and rolling their clothes. Other works [1, 9] used rings as a subtle input device. Still, these techniques could only support limited gesture input. In contrast, FingerPad is functionally equivalent to a touchpad, which implies that it can provide more dimensions for the input space.

Finger-worn input devices

Several technologies have been proposed that use finger-worn devices to sense gestures. FingerRing [3] placed accelerometers on every finger to sense different chord gestures. UbiFinger [13] allowed control of house appliances through finger gestures by placing an IR transmitter and bending/touch sensors on the index finger together with an accelerometer on the wrist. Magic finger [16] extended the dimensions of touching gestures through a finger mounted camera. Since FingerPad uses pinched fingers as the input, it offers more privacy and subtlety than these works.

Magnetic tracking

Magnetic tracking has previously been used to sense gestures remotely. For instance, Han et al. [4] tracked a finger-mounted magnet for handwriting input. Similarly, Abracadabra [5] used a finger-mounted magnet to control a watch. Meanwhile, Nenya [1] used a magnet mounted in a finger ring for device control. Liang et al. [7] used a magnet mounted in a stylus and the Hall sensor array to enable input on arbitrary surfaces. Compared with these works, FingerPad provides more private and subtle input through pinched fingertips.

CONCLUSION

This paper presented FingerPad, a nail-mounted device that enables touchpad functions from users manipulating their index fingertips, allowing for private and subtle interaction on the move. The study shows good user ability to control a cursor using the pinch gesture with FingerPad. The statistics demonstrate that users can achieve 93% accuracy for very small targets (1.2mm-width) in the seated condition, and 92% accuracy for 2.5mm-width targets in the walking condition, which is sufficient for mobile usage. This study makes design insights based on exploration of three factors, namely posture, commitment method, and target size. Despite inevitable trade-offs among these factors, this study still demonstrates that the FingerPad can work well for subtle interactions.

In the future, although the FingerPad is intended for use with mobile glass displays, the technology could also be applied without visual support. Different commitment methods can be explored in the future to create different alternative gestures. Once devices designed for rich private output are invented, users will need to use them privately with a rich input device, and the input method should be sufficiently subtle to achieve social acceptability, as is achieved by the FingerPad.

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