FootUI: Assisting People with Upper Body Motor Impairments to Use Smartphones with Foot Gestures on the Bed

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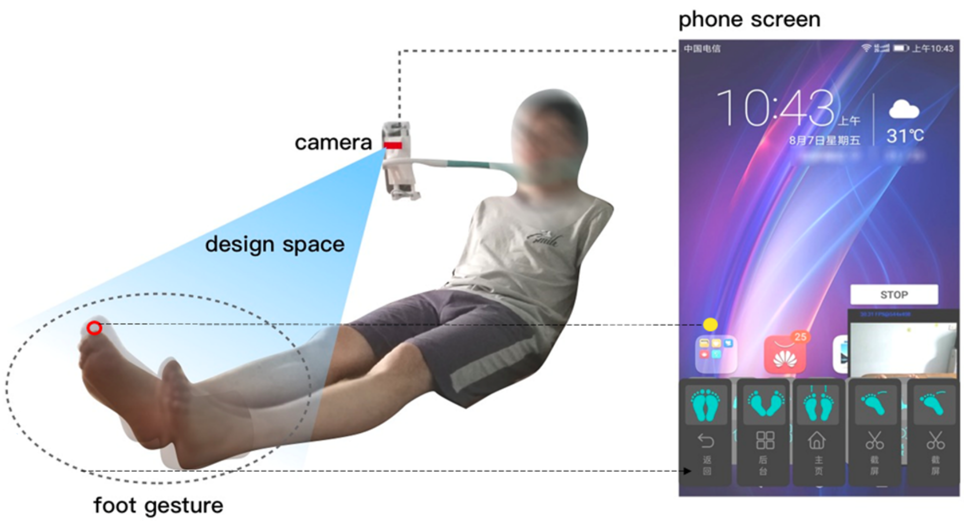

Figure 1: Usage scenario of FootUI

ABSTRACT

Some people with upper body motor impairments but sound lower limbs usually use feet to interact with smartphones. However, touching the touchscreen with big toes is tiring, inefficient and easy to mistouch. In this paper, we propose FootUI, which leverages the phone camera to track users' feet and translates the foot gestures to smartphone operations. This technique enables users to interact with smartphones while reclining on the bed and improves the comfort of users. We explore the usage scenario and foot gestures, define the mapping from foot gestures to smartphone operations and develop the prototype on smartphones, which includes the gesture tracking and recognition algorithm, and the user interface. Evaluation results show that FootUI is easy, efficient and interesting to use. Our work provides a novel input technique for people with upper body motor impairments but sound lower limbs.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility technologies**.

KEYWORDS

accessibility, foot-based interaction, upper body motor impairments, smartphone

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1 INTRODUCTION

Some people with upper body motor impairments but sound lower limbs choose to interact with smartphones with their feet by touching the phone screen [2], which is fatiguing and inefficient. Therefore, providing them with an interaction technique that is suitable for foot input can help them interact with smartphones better.

In this paper, we propose FootUI, a vision-based interaction technique to assist people with upper body motor impairments to interact with smartphones through foot gestures. As such persons are accustomed to using smartphones while sitting on the bed, we define the usage scenario (See Fig 1) as following. A user reclines on the bed and uses a smartphone without hands. The smartphone is fixed on the smartphone holder and the user's feet are within the view of the phone camera. The camera is always on to track the user's feet. The movement of the right toe is mapped to the cursor on the screen, and some special foot gestures can trigger some smartphone shortcuts.

We conducted formative interviews with upper body motor-impaired smartphone users firstly to understand their daily use of smartphones. According to the results of the formative interviews, we designed the usage scenario and created a foot gesture set. After that, we developed the gesture tracking and recognition algorithm, designed the mapping from foot gestures to smartphone operations as well as the user interface of the FootUI. Finally, we evaluated FootUI quantitatively and qualitatively. Result shows that the task completion time of FootUI is about 2.1 times of finger touch. Subjective feedback reflects that FootUI is easy, efficient and interesting to use, and can help the people with upper body motor impairments to use smartphones smoothly and comfortably.

2 RELATED WORKS

There are lots of research proposing interaction techniques to assist people with upper body motor impairments to use their motor-impaired upper limbs to interact with information devices. Cursor based input techniques like PointAsist [11], Steady Clicks [13] and Click Control [5] have been developed for better pointing performance. Wobbrock et al. [15–17] experimented the use of physical edges to assist motor-impaired users and proposed Barrier Pointing [4]. To improve touch accuracy, researchers explored the users' interaction behavior and developed gesture recognition algorithms such as Shared User Modeling Framework [7], Session Specific Models [8], Smart Touch [9] and Cluster Touch [10]. However, these techniques are unavailable to amputees and people with severe upper body paralysis.

Research on foot-based interaction has a long history. Velloso et al. [14] surveyed foot-based interaction from three aspects: characteristics of users, foot-based systems and foot-based interactions. Katsumi et al. [6] compared gaze input, head input and foot input and concluded that foot input is an option for hands-free interaction when seated. As for designing and sensing foot gestures for controlling mobile devices, Scott et al. studied the ergonomic characteristics and design space of four gestures: dorsiflexion, plantar flexion, toe rotation and heel rotation for eyes-free interaction with mobile devices in the pocket [12]. Alexander et al. [1] created a user-defined gesture set for mobile device commands and validated that rate-based techniques are significantly faster, more accurate and result in far fewer target crossings compared to displacement-based techniques. However, accessible foot input research focusing on leveraging foot gestures as the main form of input to support fully hands-free interaction is lacking.

3 INVESTIGATION ON UPPER BODY MOTOR-IMPAIRED SMARTPHONE USERS

To understand how upper body motor-impaired smartphone users use smartphones in their daily life, We conducted formative interviews with three participants. Table 1 shows the detailed information of our participants. They were all female and 39.33 years old on average. All of them reported the daily use of smartphones with feet. One was reported as cerebral palsy with dysphonia, and the others were reported as amputation of both arms. We provided them with some monetary rewards for their participation.

3.1 Procedure

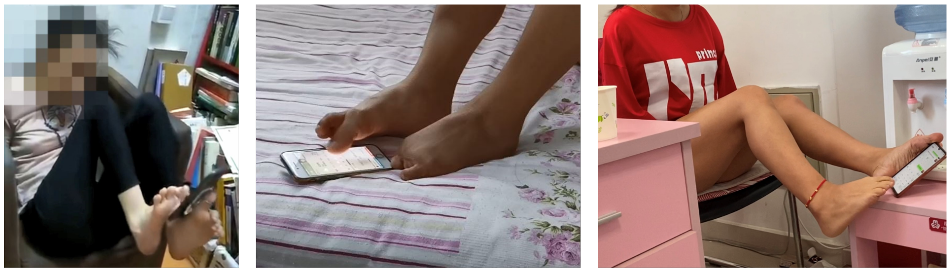
We conducted face-to-face interviews with P2 and P3 in their home and an online interview with P1 who live in another city. During the face-to-face interviews, we asked them to complete the following smartphone operations in their living environment: 1) start a frequently used app, 2) perform a scroll down, 3) take a screenshot, 4) tune the volume, 5) tune the screen brightness, 6) go to the home screen. We observed how participants performed these touchscreen-based and side-button based actions and asked them to think aloud. When they expressed that they were in trouble, we offered some assistance and asked some questions accordingly. After they finished the designated smartphone operations, we asked them some questions about 1) their dissatisfaction with the current way of using smartphones, 2) their ideal way of using smartphones, 3) the most comfortable postures to use smartphones. When some interesting points came up, we explored more details in depth. Finally, to investigate the user's requirement for various shortcuts in smartphones, so that we can match the foot gestures to the shortcuts with commensurate necessity, we summarized nine shortcuts in smartphones and asked the participants' about their need for these shortcuts. For the online interview, we asked the participant to finish the same smartphone operations and film the process with the assistance of a helper. We analyzed the video that she provided and asked her the above questions.

3.2 Findings

Fig 2 shows the participants' daily use of smartphone. We got the following findings during the formative interview. 1) They usually use smartphones on the bed, where they can interact with the touchscreen efficiently and accurately. 2) Sitting is the preferred posture for their using the smartphone. P2 said, "Sitting is the most comfortable posture to use the smartphone. I mean various sitting

Table 1: Summary of study participants

No	Age	Gender	Disability	Smartphone OS	Career
P1	32	F	Cerebral Palsy	Android	Writer
P2	38	F	Arm amputation	iOS	Special education teacher
P3	48	F	Arm amputation	Android	Artist



(p1) (p2) (p3)

Figure 2: Examples of how participants interact with smartphone in daily life

postures, such as reclining on the bed." P3 said, "I only use my phone when I'm sitting, clamp like this or place on a platform." 3) They mainly touch the screen with the right foot big toe in the sitting posture, where the smartphone lies on the bed or is clamped by the left foot, but they are not satisfied with such input method because of the mistouch and the difficulty to perform complex gesture input. P2 mentioned, "Many times, the touch screen is not satisfying. On the one hand, there are mistouches. On the other hand, we need to touch the screen with one foot holding the phone and it isn't easy to zoom in and out when taking pictures. Moreover, using the iOS device to take screenshots requires pressing two buttons, which is difficult for us to perform with our feet." P1 said, "Typing with feet is too tiring, and the phone is not easy to hold. Also, because the toes are too big, mistouch is also very annoying." 4) As for the ideal way of interacting with smartphones, P1 and p2 both expressed the need for additional auxiliary clamping tools to help them fix the phone. P1 said, "I don't want my phone to be like a bar of chocolate. It should have a handler." P2 said, "I want a 'small ear' on the phone because I often make mistouch when holding the phone with my toe." She even expressed that she prefers mouse to touch screen. She said, "I accept each of touchscreen and mouse, but I prefer the mouse." 5) When participants operated smartphones with feet, we found that they usually used ankle-based gestures such as heel rotation and used toe-based gestures seldom. Additionally, they are able to keep their feet in the air for a long time. 6) As for the necessity of smartphone shortcuts we summarized, all participants agree that "Home" is the most necessary shortcut. "Back", "Volume", "Screenshot" "Brightness", "Notice" and "Screen Switch" are of the similar necessity. "Easy Access" and "App Switch" are regarded as the least necessary shortcuts.

4 DESIGN OF FOOTUI

4.1 Usage Scenario and Foot Gesture set

We summarized the characteristics of upper body motor-impaired smartphone users in pilot study and defined the usage scenario. For flexible foot motion, we define that the user reclines on the bed with a smartphone fixed on the smartphone holder. The user's feet are within the view of the phone camera and the camera is always on to track the user's foot gestures. Users can put pillows or cushions under their legs to facilitate their leg lifting (See Fig 1). Based on the usage scenario, we created a foot gesture set which contains 11 kinds of foot gestures (See Fig 3). The gestures were designed based on the kinematic analysis and semaphoric gesture summary in [14] and were divided into two groups: dynamic continuous gestures and discrete gestures. Eight of them were single foot gestures and three of them were double foot gestures. Different gestures may come from the same foot gesture topology, e.g. "Heel Rotation" is dynamic continuous gestures and "Rotate Left/Right" are discrete gestures. We mainly focused on the ankle-based gestures and also included some leg-based gestures according to the findings from investigations on target users.

4.2 Gesture Tracking and Recognition Algorithm

To collect the foot gesture data, we recruited able-bodied participants to perform the foot gestures that we designed and recorded videos of their foot gestures with smartphones. We manually segmented the videos and removed the videos and frames when the participants were not performing the required foot gesture. Video segments have lengths varying from 4 to 96 frames, with a resolution of 960x1280 pixels. The final dataset contains 543 videos, 11920 frames in total.

We segmented the feet from the background by color in HSV (Hue, Saturation and Value) space, detected the contours of the feet and extracted feature points, or the furthest point in different directions on the contours, as in Fig 4. To condense length-varying feature point sequences into low-dimension features, we broke down the continuous fingertip movement into discrete strokes. A stroke was defined as the cumulative fingertip movement within a short period of time, until the fingertip moved backwards or stops

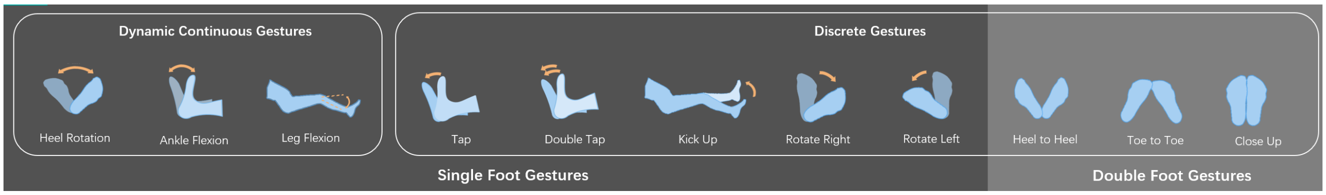


Figure 3: Foot gesture set

Table 2: Confusion matrix in classification.

Foot Gestures	CU	RL	RR	KU	DTap	T2T	H2H	Tap
Close up (CU)	**0.800**	0.067	0.067	0	0	0	0.067	0
Rotate left (RL)	0	**0.929**	0.036	0	0	0	0	0.036
Rotate right (RR)	0	0	**0.931**	0	0	0	0	0.069
Kick up (KU)	0	0	0	**0.931**	0.034	0	0	0.034
Double tap (DTap)	0	0	0	0	**0.900**	0	0	0.100
Toe to Toe (T2T)	0.067	0	0	0	0	**0.933**	0	0
Heel to Heel (H2H)	0.067	0.067	0.067	0	0	0	**0.800**	0
Tap	0	0	0.034	0	0.034	0	0	**0.931**

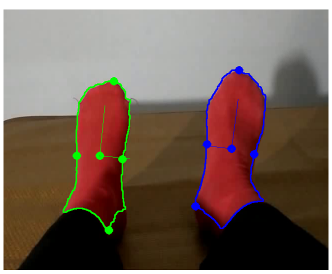


Figure 4: Feature point extracted from foot contours

moving, e.g., a "Tap" is composed of a downward stroke and an upward stroke. The most complex gesture is "Double Tap" which is composed of four strokes. Therefore, four latest strokes of each foot were kept as input feature.

We trained our classifier on the normalized, 32-dimension feature (4 strokes $\times$ 2 dimensional coordinates $\times$ 2 points, fingertip & heel $\times$ 2 feet) to classify the gestures. Leave-one-out cross validation showed an accuracy of 90.53% (SD=6.62) and Table 2 showed the confusion matrix. Our tracking algorithm can smoothly track the fingertips, which means users can use their preferred dynamic continuous foot gestures for pointing.

4.3 Mapping from foot gestures to smartphone operations

We mapped the foot gestures to smartphone operations following the rule of mapping the most user-preferred foot gestures to the most necessary smartphone operations. The smartphone operations were divided into basic operations and shortcuts. Fig 5 shows the mapping from foot gestures to smartphone operations. "Right foot heel rotation" moves the cursor horizontally, the combination of "right foot ankle flexion" (for fine movement) and "right leg flexion" (for rough movement) moves the cursor vertically, and "left foot tap" triggers. When there is a slider on the interface, "right foot heel rotation" slides the slider. For shortcuts, "heel to heel" is mapped to "screenshot", "close up" is mapped to "app switch", "left foot kick up" is mapped to notice, "left foot rotate left" is mapped to "back", "toe to toe" is mapped to "home" and "left foot double tap" evokes shortcut menu. We also mapped the combination of single foot gestures to some shortcuts e.g. both feet tapping evokes brightness slider. The screen scrolls left when the user rotates both feet to the left, and the screen scrolls right, when the user rotates both feet to the right. When the user rotates right foot to the right and left foot to the left simultaneously, the volume slider appears.

4.4 Design of the User Interface

Finally, we designed the user interface of FootUI, as Fig 6 displays. The yellow dot on the interface is the cursor, which is a mapping of the right foot fingertip and moves with the movement of the big toe. There is a floating camera view at the lower right of the interface, which can display the user's current foot motion. To enable users to use feet for scrolling and reduce the fatigue, we also set scroll buttons in the lower right corner of the interface based on the Fitts' Law [3]. Users can tap the button with the cursor instead of scrolling with the foot. The lower left corner of the interface is the shortcut menu button, which will pop up the shortcut menu bar after it is triggered. We bound the foot gesture icon to the tab of corresponding shortcut operation to strengthen the user's memory of foot gestures. Users can trigger the shortcut operation by either clicking the tab in the shortcut menu or performing corresponding foot gesture prompted by the icon. The position of the shortcut menu button is also easy to point.

5 EVALUATION OF FOOTUI

We recruited 14 able-bodied participants (7 female, 7 male) and two both-arm amputees (all female) to evaluate FootUI. To simulate the real interaction process between users and smartphones, we

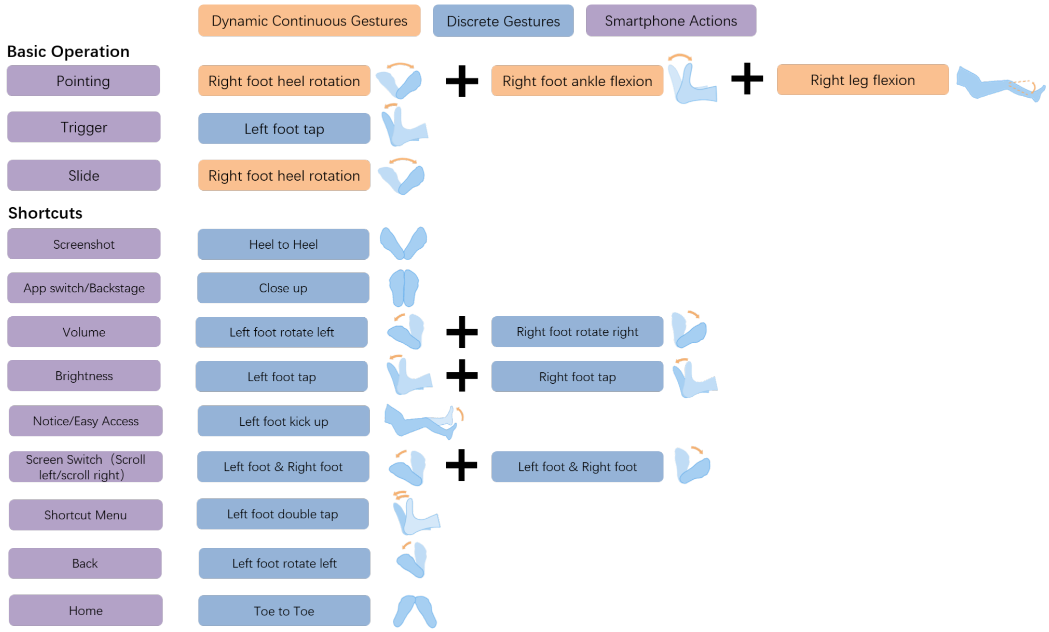


Figure 5: Mapping from foot gestures to smartphone operations

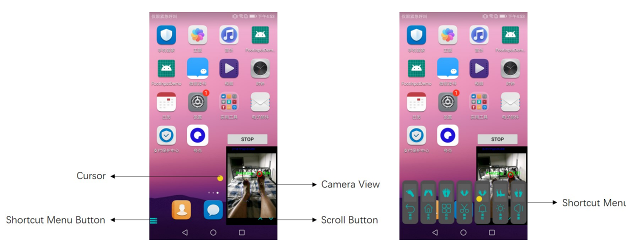


Figure 6: User interface of FootUI

designed an interactive task, reading and listening to an e-book with an e-reading app. This task not only covered the foot gestures that we designed, but also simulated the user's interaction behavior in the wild. We divided the task into ten sub-tasks as following.

- Start the e-reading app
- Listen to a phonetic reading of a book
- Tune the volume
- Suspend the phonetic reading
- Read the title page of the e-book
- Tune the screen brightness
- Take a screenshot
- Go to home screen
- Read the notice and get back
- Get into app backstage and return to the e-reading app

The upper body motor-impaired participants only need to complete one round of tasks with FootUI while the able-bodied participants need to complete the tasks with finger touch and FootUI each. The order of using the finger touch and FootUI was counter balanced. To ensure the continuity of the interaction process, the participants were allowed to ask for hint of sub-tasks and foot gestures, but the query for foot gestures was recorded as a memory error. Post-task questionnaires containing 5-point likert scale on user satisfaction, fatigue, ease-of-use and learnability, and interviewers on user experience were also conducted.

We defined the time from we give the participants a start instruction to they finish the last sub-task as the task completion time and we recorded the task completion time of finger touch and FootUI. The mean task completion time of finger touch is 96.33s (SD=32.04) and is 198.10s (SD=86.07) of FootUI. The task completion time was calculated from participants who completed all the sub-tasks with both finger touch and FootUI (data from 5 participants was removed because they forgot to complete some sub-tasks and didn't finish the whole task).

We labeled the operating steps and errors appeared in the tasks and found that errors were mainly occurred in three ways: 1) The cursor was not moved to the specified position. 2) The algorithm classified the foot gestures incorrectly so that FootUI evoked incorrect smartphone operations. 3) The participant confused some gestures or asked the host for their forgotten gestures. We defined the number of the first type of error as pointing error, the number of the second type of error as classification error and the number of the third type of error as memory error. Accordingly, we defined that 1) pointing accuracy = 1-$\frac{pointingerror}{pointingsteps}$, where pointing steps denotes steps that participants move cursor for pointing, 2) classification accuracy = 1- $\frac{classificationerror}{discretesteps}$ and 3) memory accuracy = 1- $\frac{memoryerror}{discretesteps}$, where discrete steps denotes the number of discrete foot gestures that participants performed. The mean pointing accuracy is 96.75% (SD=8.36), the mean classification accuracy is 84.65% (SD=8.14) and the mean memory accuracy is 92.97% (SD=6.59).

Table 3 showed the average ratings of FootUI and finger touch on four indicators. Wilcoxon signed-rank test revealed that finger

Table 3: Subjective evaluation results of FootUI (from 1 - not good to 5 - good)

Statement	FootUI	Finger touch
user satisfaction	3.63 (SD=0.86)	4.44 (SD=0.70)
fatigue	3.38 (SD=0.78)	4.44 (SD=1.11)
ease-of-use	3.56 (SD=1.00)	4.44 (SD=0.79)
learnability	3.75 (SD=1.09)	4.19 (SD=1.18)

touch got significant higher ratings on user satisfaction, fatigue and ease-of-use with $p<0.01$ but no significant diffenrece between FootUI and finger touch on learnability ($p=0.08>0.05$) appeared, suggesting FootUI is easy to learn.

Subjective feedback from the participants showed that FootUI is easy, efficient and interesting to use. P7 said "Although the requirement for foot postures was a little strict, I felt the using experience was good when I got familiar with it." P3 said "I think this is a good way to help the people with upper body motor impairments use smartphones conveniently. The interaction process was smooth and the learning cost was relatively low." P5, P7 and P11 all expressed that using FootUI for smartphone interaction was novel and interesting. Two upper body motor-impaired participants also expressed positive attitude to FootUI and confirmed its usability. P15 (both-arm amputee) said "when I get closer to the phone for carefully reading, my foot can't touch it and your software really solve this problem." P16 (both-arm amputee) said "I think the people with cerebral palsy and those who just lost their arms due to accident may need this technique much more than me." They also expressed that FootUI brought them much convenience to interact with smartphones especially when they recline on the bed and browse the phone.

6 CONCLUSION AND FUTURE WORK

We present FootUI, a novel interaction technique that enables people with upper body motor impairments but sounds lower limbs to use smartphones reclining on the bed. We designed, developed and evaluated FootUI including foot gesture set, mapping from gestures to smartphone operations, foot gesture tracking and recognition algorithm and foot-gesture-based user interface. The gesture tracking and recognition algorithm achieved an average accuracy of 90.53% for 8 gesture classifications. The evaluation result shows that FootUI is easy, efficient and interesting to use and can help the people with upper body motor impairments interact with smartphones more smoothly and comfortably in such scenario. As far as we know, this work is the first exploration for the method to assist people with upper body motor impairments to interact with smartphones with foot gestures.

There are some limitations that we will address in future work. (i) Because of the difficulty for recruiting upper body motor-impaired participants, we recruited some able-bodied participants to our user study and the number of our target users was small. We will recruit more upper body motor-impaired participants to evaluate FootUI in the future. (ii) The evaluation of FootUI is rough, we will choose an appropriate baseline and evaluate FootUI thoroughly.

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