FingerT9: Leveraging Thumb-to-finger Interaction for Same-side-hand Text Entry on Smartwatches

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ABSTRACT
We introduce *FingerT9*, leveraging the action of thumb-to-finger touching on the finger segments, to support same-side-hand (SSH) text entry on smartwatches. This is achieved by mapping a T9 keyboard layout to the finger segments. Our solution avoids the problems of fat finger and screen occlusion, and enables text entry using the same-side hand which wears the watch. In the pilot study, we determined the layout mapping preferred by the users. We conducted an experiment to compare the text-entry performances of *FingerT9*, the tilt-based SSH input, and the direct-touch non-SSH input. The results showed that the participants performed significantly faster and more accurately with *FingerT9* than the tilt-based method. There was no significant difference between *FingerT9* and direct-touch methods in terms of efficiency and error rate. We then conducted the second experiment to study the learning curve on SSH text entry methods: *FingerT9* and the tilt-based input. *FingerT9* gave significantly better long-term improvement. In addition, eyes-free text entry (i.e., looking at the screen output but not the keyboard layout mapped on the finger segments) was made possible once the participants were familiar with the keyboard layout.

Author Keywords
Mobile interaction; smartwatch; text entry; same-sided hand interaction; thumb-to-finger interaction;

ACM Classification Keywords
H5.2. Information Interfaces and Presentation (e.g. HCI): User interfaces—Input devices and strategies;

INTRODUCTION
The smartwatch is emerging as a major category of personal computing devices after the desktop PCs, laptops, smartphones, and tablets. There are various smartwatch applications, such as checking emails, calling, messaging, and social networking. Among these applications, typing/text entry is essential [36]. Traditionally, text entry techniques for small displays employ QWERTY-like soft keyboards [20].

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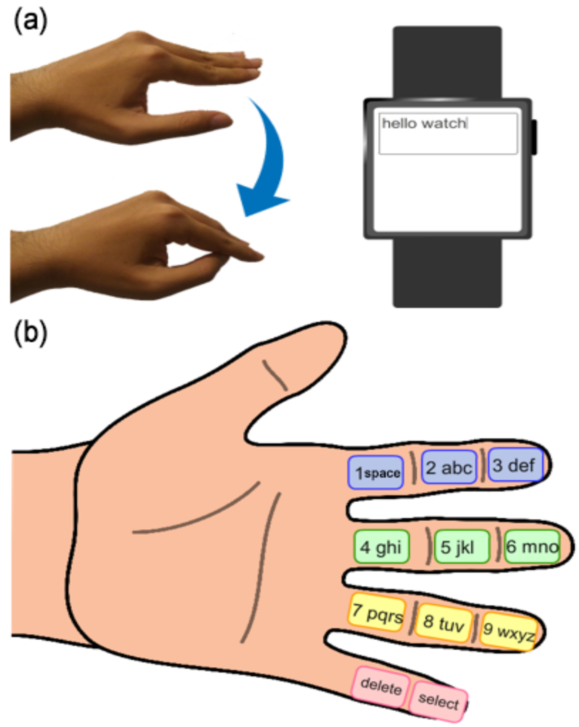

Figure 1: *FingerT9* uses thumb-to-finger interaction (a) on T9 keyboard layout mapped onto finger segments (b) for text entry on smartwatches.

Several novel text-entry methods, such as multiple tap selection [23] and memorization of individual gestures [9], have been proposed to facilitate touch-based smartwatch text entry. However, touching on smartwatch usually requires the input from the non-wearing hand, and this may not be feasible when the non-wearing hand is occupied by other tasks. Voice input is an alternative input method. However, it may become awkward in certain situations, e.g., due to privacy or noisy environment. On the other hand, users often adopt one-handed strategies with their thumbs to interact with mobile devices when his/her other hand is occupied. There is still lack of efficient one-handed (same-sided hand) technique that particularly aims to address the problem of text entry on smartwatches.

Research showed that people can accurately touch their finger segments with their thumbs and thumb-to-finger interfaces support effective eyes-free interaction [16]. In this paper, we introduce *FingerT9*, leveraging the action of thumb-to-finger touching on the finger segments, to support same-sided-hand (SSH) text entry on smartwatches (Figure 1a). *FingerT9* contributes the first design and empirical investigation on the same-sided hand (SSH) smartwatch text entry, an important but underexplored problem. SSH interaction can offer benefits by freeing the other hand for tasks like carrying a bag, and allow users to operate mobile devices in a distracted, multitasking scenario. While the existing smartwatch text input methods are fast, they require the other hand for input and thus cannot be used in these scenarios. In *FingerT9*, a T9 phone keyboard [12] is mapped onto the finger segments (Figure 1b). The T9 layout was chosen due to its common usage especially among feature phone users and the intuitive mapping between the T9 keyboard and the finger segments. We developed an experimental prototype of *FingerT9* by attaching thin capacitive touch sensors to the finger segments (Figure 2) and algorithmically predicting the user's intention based on a series of thumb-to-finger taps.

We conducted a controlled experiment to compare *FingerT9*, a tilt-based SSH interaction method for text entry, and the direct-touch text entry which uses the T9 keyboard layout but requires the input from the non-wearing hand. The results showed that the participants performed significantly faster and more accurately with *FingerT9* (WPM: 3.43, error rate: 11.14%) than the tilt-based text-entry (WPM: 2.45, error rate: 20.73%). While the participants typed significantly faster with the direct-touch input method (WPM: 6.50) than *FingerT9*, there was no significant difference between these two methods in terms of efficiency and error rate, and *FingerT9* could outstand in the one-hand situation. A 5-day user study further revealed that *FingerT9* yielded significantly better long-term improvement than the tilt-based method. With *FingerT9*, the users achieved 5.42 WPM with an error rate of 4.68% after a 5-day training.

Our contributions are two-fold:

1) The integration of thumb-to-finger interaction with text entry on smartwatches;
2) The evaluation that showed the advantages of *FingerT9* over a tilt-based SSH text-entry method.

RELATED WORK

Our research on *FingerT9* is highly related to and motivated by the existing studies on facilitating typing/text entry for smartwatches, and supporting SSH smartwatch interaction which refers to one-handed interaction using device-worn arm/wrist.

Typing/Text Entry on Smartwatches

There have been various techniques proposed to facilitate smartwatch text entry, mostly by customizing the soft-keyboard layouts. Most works utilized 2-step iterative interaction, such as *ZoomBoard* [23], *SwipeBoard* [3], *SplitBoard* [15], *Swipekey* [27], and *ZShift* [20]. They can achieve the typing speed close to 10 WPM (word per minute) on average. Some other techniques incorporated input decoders (i.e. *VelociTap* [31] with 41 WPM, *WatchWriter* [10] with 22 WPM, *Driftboard* [28] with 9 WPM). Yi et al. [34] also showed that a Bayesian decoder could achieve about 26.8 to 33.6 WPM on a tiny QWERTY keyboard with keyboard sizes from 2 to 4 cm. All these techniques adopted a QWERTY keyboard with the input on the touch screen. However, these techniques have a tradeoff between the screen occupation and input precision. Therefore, researchers have also explored alternative non-touchscreen-based text-entry methods using non-touchscreen sensors. Funk et al. [8] used a touch-sensitive wristband to support text entry on smartwatches, but the speed reached only about 3 WPM. Götzelmann et al. [11] presented *InclineType*, a tilt-based keyboard using the built-in accelerometer of the smartwatch (with screen tap for selection confirmation), reaching the speed of 6 WPM on average. Darbar et al. [7] used hall-effect sensors to enable 3D space stroke-based text entry on smartwatches, with 3.9 WPM. Yi et al [33] presented *COMPASS*, a non-touch bezel-based text-entry method by rotating the bezel and pressing physical button on smartwatch.

All these smartwatch text-entry techniques required the input from the non-wearing hands, and are not suitable for the situations that require SSH input, such as the non-wearing hand holding a train handle or carrying a briefcase. In *FingerT9*, we investigated the feasibility of using the same-side wearing hand for text entry, while providing physical feedback by leveraging the finger segments as the input surface.

T9/Ambiguous Text Entry on Smartwatches

Existing works also showed the feasibility of integrating T9 keyboard in smartwatch text entry. James and Reischel's study [5] on mobile phone text entry showed that users can achieve novice 9 WPM to expert 20 WPM for physical phone T9 entry. *Invisiboard* [22] used the entire smartwatch display for both text entry and display at the same time by combining T9 text entry with swiping gestures to reach 10.6 WPM. Besides, Komninos and Dunlop [18] proposed an ambiguous keyboard, having six keys containing three to six letter each, for opposite hand entry with 8 WPM. *UniWatch* [24] used a minimal three-key ambiguous keypad for French typing in smartwatch with 9.84 WPM. *DragKeys* [4] also proposed two levels of ambiguous keys arranged circularly around text cursor and entered characters by dragging. These research works show the possibility of reducing the number of key for smartwatch typing without significantly sacrificing typing performance. Typing with T9 is generally faster than other ambiguous text entry since users are more familiar with the layout. However, all these smartwatch typing techniques require the input form the non-wearing hands and do not support SSH input. In *FingerT9*, we adopt T9 entry to smartwatch for SSH typing with the smartwatch-worn hand by mapping a T9 keyboard layout to the finger segments.

One-handed Smartwatch Interaction

Although most existing smartwatch interaction techniques require the input from the non-wearing hand, namely the *Opposite-Side* Interaction, there is an increasing research

Figure 2: Experimental prototype of *FingerT9*.

interest in SSH interaction [17], leveraging the capabilities of wrist-worn devices using the device-worn arm/wrist. One of the first SSH-operated wrist-worn devices was presented by Rekimoto with the *GestureWrist* [26], which used capacitive sensors and an accelerometer to sense wrist-shape changes and forearm movements for input. *ViBand* [19] hacked the built-in accelerometer in a smartwatch by increasing its sampling rate, to support the sensing of micro-scale gestures of the wearing hand. Guo introduced *ObjectPoint* and *AnglePoint* [13] for no-touch wrist-only interactions on smartwatch using accelerometer and gyroscope in smartwatch. *Float* [29] combined wrist tilting and in-air finger taps detected by the photoplethysmogram (PPG) signal from heart rate monitor and built-in accelerometer and gyroscope, to allow one-handed target selection in smartwatches. Both Guo's method and *Float* introduced one-handed wrist tilting selection for smartwatches. *WristWhirl* [9] utilized the additional proximity sensors around the wrist, and turned the wrist as an always-available joystick to perform one-handed continuous input on smartwatches. Huang et al. presented *DigitSpace* [16], a thumb-to-finger interface addressing hand anatomy and touch precision, and explored the region of finger where interaction can be performed comfortably. Both *WristWhirl* and *DigitSpace* introduced SSH text entry with hand-written stroke path for smartwatches. However, Curran et al. [6] showed users achieved significantly higher speed and lower error rate with keyboard typing than handwriting in mobile text entry. This finding motivated us to investigate SSH keyboard typing for smartwatch.

Furthermore, several user-behavior researches [16, 25, 30] showed that users can achieve a high accuracy while performing the touch gesture from the thumb to different segments of the other fingers. This suggested the possibility of finger segment interaction, which is leveraged in our research for SSH text entry for smartwatches.

FINGERT9 DESIGN

FingerT9 mapped a T9 keyboard on finger segments (Figure 1b). Eleven keys are mapped onto the segments of the index, middle, ring and pinky fingers. Eight keys are responsible for typing letters (A-Z), and three function keys are used for adding space, deleting, and confirming candidate selection. Eight segments on the index, middle, and ring fingers correspond to eight keys, in which several letters are

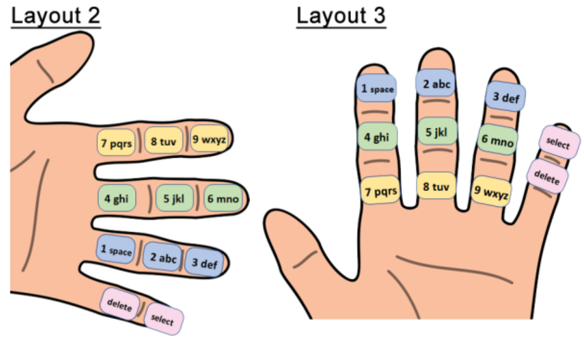

Figure 3: Alternative layouts with different key arrangements

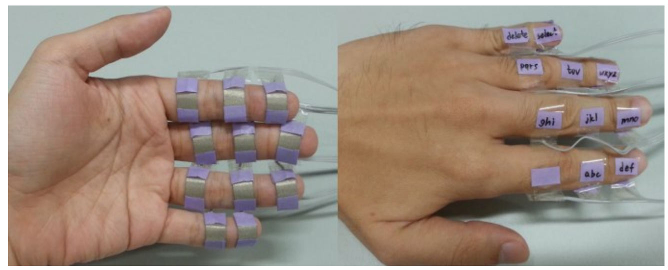

Figure 4: Experimental prototype: hand-up view (Left) and hand-down view with letter hint labels (Right).

associated with each key. Three segments, one on the index finger and two on the pinky finger, are the functional keys.

Layout Design

To design the user-preferred mapping between the T9 keyboard and finger segments, we conducted a questionnaire survey with 22 participants (7 females, aged 20 to 28, all right-handed, and all with T9 input experience). During the survey, we presented three layouts with different key arrangements. Layout 1 (Figure 1b) directly maps the T9 keyboard on finger segments, while Layout 2 (Figure 3) vertically flips the letter keys (for the use when the hand faces down) and the space key, and Layout 3 (Figure 3) rotates the keyboard in Layout 1 by 90°orientation. The participants were asked to perform thumb-to-finger touch with the three layouts and then rate their impression on the ease of use and the ease of memorizing for each layout from 1 to 5 score (1 means hard and 5 means easy). The average ease of use scores for the three layouts were 3.55, 2.59, and 2.86, respectively, and the average ease of memorizing scores were 3.14, 2.32, and 2.64, showing that Layout 1 had the highest score. The ANOVA for ease of use was significant ($F(2, N=22) = 5.126$, $p < 0.05$) while the ANOVA for ease of memorizing was not significant. The non-parametric Friedman test showed that the layouts significantly affected the perceived ease of use ($\chi2(2)=8.95$, $p<0.05$) and the participants' preference ($\chi2(2)=6.91$, $p<0.05$). Wilcoxon Signed Rank Test showed that layout1 was perceived to be significantly easier to use, and preferred. We then asked the participants to choose their preferred layout and 13 participants chose Layout 1, 4 participants chose Layout 2, and 5 participants chose Layout 3. The participants commented Layout 1 had

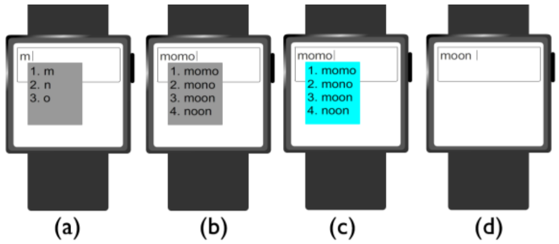

Figure 5: A storyboard illustrating a user entering "moon" with *FingerT9*. (a) Type by tapping a key on finger segment. (b) Type the word letter by letter. Candidate list is displayed. (c) The user taps the "select" key. Candidate list turns to cyan to indicate selection is triggered. (d) The user taps "3" to confirm selection of the third candidate.

the same key arrangement as the traditional T9 keyboard, and is thus easier to remember. For these reasons, we adopted Layout 1 as the layout of *FingerT9*.

System Implementation

In the first prototype, we attached 11 pressure sensors on the finger segments to detect the thumb-to-finger touching. The sequence of the thumb-to-finger touching is collected by the Arduino Mega, and communicated to the computer through a local network. The prototype used a pre-specified pressure threshold to detect the input, meaning that a touch with pressure over the threshold is regarded as a tap. However, our pilot test showed that users found it difficult to apply enough force on some finger segments, especially the segments near the palm. We then improved our prototype by using thin-film capacitive sensors as shown in Figure 4, which are more sensitive and flexible than pressure sensors. The threshold of thumb-to-finger touch was adjusted to achieve stable and sensitive sensing. We admitted that there are alternative implementations, such as using data-glove, or camera-based finger tracking approaches. We adopted thin-film capacitive sensors due to their high robustness and allowance for tactile cues (i.e. skin sensation) of the finger without blocking by glove.

FingerT9 Interaction

The interaction of *FingerT9* consists of two steps: word typing (Figure 5(a)(b)) and candidate selection (Figure 5(c)(d)).

In the **word-typing** part, users perform a thumb touch on a particular finger segment to type a letter. Once users type the word letter by letter, a candidate list of possible words will be shown. The candidate list is generated by a word-prediction algorithm based on a trie-based dictionary containing over 230,000 English words which is sufficient for messaging in daily lives except for specific names. The list ranks the candidates in alphabetical order. To trigger the candidate-selection mode, users can perform a thumb touch on the "select" key on the finger segment at the tip of pinky finger. Users can delete a single letter at the back of input with the "delete" key.

In **candidate selection**, all words in the candidate list are numbered and each finger segment represents a particular number. The candidate list can show at most six prediction results each time which is enough to show all the candidates in most cases. If there are more prediction results, users can perform a thumb touch on the "select" key to show the next six results. Users can perform a thumb touch on a respective finger segment to confirm the selected candidate. In some cases, if the desired candidate is already the first one, users can simply perform a touch on the space key to select the first candidate without triggering candidate selection.

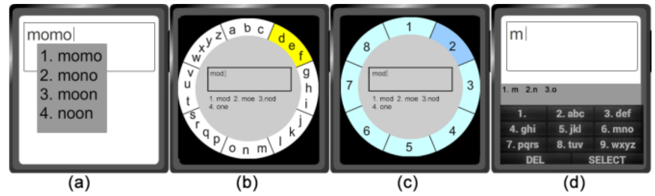

Figure 6: Smartwatch interface: (a) *FingerT9*, (b) tilt-based input with round keyboard layout, (c) tilt-based input candidate selection, and (d) direct touch input with T9 keyboard layout.

EXPERIMENT I: COMPARISON AMONG *FINGERT9*, TILT-BASED INPUT, AND DIRECT-TOUCH INPUT

While there are gesture typing and handwriting methods [10, 16, 35], research showed that users generally preferred typing, and can potentially achieve significantly higher speed and lower error rate with keyboard typing [6]. We thus focus on keyboard typing. More specifically, we conducted a within-subject controlled experiment to compare three keyboard typing smartwatch text-entry methods: *FingerT9*, tilt-based input, and direct-touch input. *FingerT9* and the tilt-based input are SSH text entry methods while the direct-touch input, requiring both hands, is a common text entry method used in the smartwatch. While the direct-touch input is a non-SSH text-entry method, we tested it on the T9 keyboard layout and thus its performance can be considered as the baseline to investigate how *FingerT9* could perform when compared to the commonly used typing method. Although there were many other state-of-the-art smartwatch typing methods, most of them were based on QWERTY-based keyboards and thus directly comparing our technique with them might not lead to any useful conclusion.

Tilt-based input has been proposed for SSH smartwatch interaction but not specifically for text entry. Our implementation is based on the input approach of *Float* [29], which uses wrist tilting for item selection and selection confirmation by mid-air finger tapping. Selection confirmation in existing SSH tilt-based input mostly used finger tap. Long pause is an alternative solution, but slows the typing speed. To achieve faster typing speed, we thus adopted thumb-to-finger tap for confirmation and used the same four functional keys as our method. This design allowed us to have a more direct comparison between thumb-to-finger input and tilt-based input for text entry on smartwatch.

Participants
12 participants (5 males, aged 20 to 34, all right-handed, and all with experience on T9) were recruited from the university; one had experience of using smartwatch for two years. All the participants wore the smartwatch on their left hands during the experiment.

Apparatus
We implemented *FingerT9*, the tilt-based input, and the direct-touch input on a Tenfifteen QW09 smartwatch with a 1.5-inch touchscreen of 240x240 resolution. The same T9 word-prediction algorithm was used for all the three methods.

For the tilt-based input, the absolute tilt level and the position of the watch were tracked by accelerometer and gyroscope. We then mapped the direction to the eight cardinal directions representing the eight letter keys of T9 keyboard in a round layout (Figure 6b) for letter selection. Capacitive sensors were attached to four finger segments, corresponding to four functional keys: space, confirm, delete, and select. Comparing to *FingerT9*, the "confirm" key was added for entering the selected letter in the tilt-based keyboard. We mapped the space, delete, and select keys to the same index finger and pinky finger segments as *FingerT9*, and the finger segment at the index fingertip was used for the confirm key. The participants can type desired letters by tilting at a specific angle range and then confirm by thumb touch on the confirm key. The participants performed word typing and then candidate selection. In candidate selection (Figure 6c), participants select desired candidates by tilting and then thumb-touching on the confirm key.

For direct touch input, we implemented our custom T9 soft keyboard layout on the smartwatch (Figure 6d) by closely following the design guidelines for small screen display [32]. We maximized the button size, and used high contrast, bright color and legible text at a minimum of 14pt for effective viewing. The participants directly tapped on the soft keyboard for word typing and candidate selection. Different from *FingerT9* and tilt-based input, the direct touch method required the input from the non-wearing hand.

Task
The participants were asked to transcribe a total of 20 short phrases chosen from the standard phrases sets for evaluating text [21]. The participants had to complete 4 blocks of short phrases and each block contains 5 randomly chosen phrases for each method. They were asked to correct errors immediately only if they realized that an error occurred, and to proceed as quickly and accurately as possible. The correction can only be done by deleting letters at the back and then retyping the corrected ones. All the words in the test phrases were contained in the prediction dictionary. If the users type the word correctly, they could find it on the candidate list.

Measures
The words per minute (WPM) was calculated based on Equation 1, by considering the time of transcribing text divided by the average length of a word in characters including space [1].

$$WPM = \frac{|T|-1}{S} \times 60 \times \frac{1}{5}. \quad (1)$$

More specifically, let T be the number of transcribed character and S the time measured in second from the first key press to the last including the functional keys. S does not measure the entry of the very first character that refers to "-1" in the numerator, since the time between the beginning of typing and the touching of the first character is not measured, and the entry of first character is never counted. 60 is the number of seconds per minute and the one fifth refers to the factor for the average length of a word in characters.

The efficiency was calculated by the actual keystroke divided by the minimum keystroke during transcription. The efficiency will be 1.0 if a user correctly types all the words in the test phrase without deleting any letter.

The total error rate, considering the cost of error correction during transcription, was calculated to measure the ratio of the total number of incorrect to the corrected characters.

Procedure
The three text-entry methods were introduced and evaluated in a counter-balanced order. The participants were instructed to practice by typing a specific sentence: 'the quick brown fox jumps over the lazy dog' until they were satisfied. They spent 10 minutes practicing each input method. When the participants got familiar with the input method, they started 4 blocks of transcription tasks, with no repeated phrases among blocks. They may take rest after completing one block. After transcribing all 20 short phrases, they were asked to finish a NASA-TLX questionnaire [14], to assess the perceived workload. During the experiment, the task completion time, the efficiency, and the error rate were recorded for each phrase.

Results
We collected in total 3,456 words input in Experiment I. Table 1 showed the results of the three text-entry methods. We first compared the two SSH text-entry methods, *FingerT9* and tilt-based input. Repeated-measures ANOVA showed the text-entry techniques had a significant effect on WPM ($F(2,22)=48.58$, $p<0.001$, $\eta^2 = 0.815$), error rate ($F(2,22)=15.93$, $p<0.001$, $\eta^2 = 0.592$), and efficiency ($F(2,22)=12.99$, $p<0.001$, $\eta^2 = 0.541$). The post-hoc pairwise tests showed *FingerT9* was significantly faster ($p<0.001$), more efficient ($p<0.001$), and less error-prone ($p<0.001$) than Tilt. *FingerT9* had slightly but not significantly less error and higher efficiency than Direct Touch. The error rates of final text after user correction are: *FingerT9*: 0.22%; Tilt: 1.65%; Direct Touch: 0.28%. For a block with average 115.0 letters including space, the average numbers of correction with delete key are: *FingerT9*: 13.4; Tilt: 26.1; Direct Touch: 19.0.

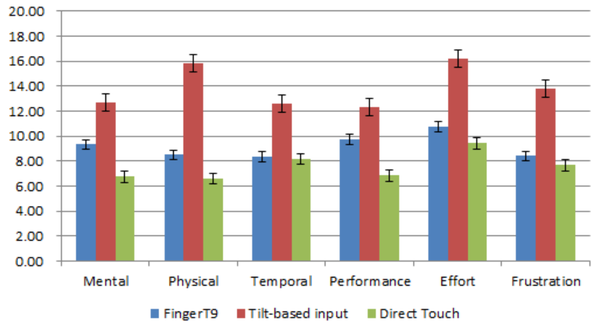

Figure 7: Average NASA-TLX scores from 12 participants. The lower the better.

FingerT9 may perform more accurately than traditional direct-touch input. Although direct-touch was significantly faster than *FingerT9*, it requires two hands for typing. There is no significant difference in terms of the efficiency and the error rate between *FingerT9* and direct-touch, showing that *FingerT9* is feasible for text entry on smartwatches.

The NASA-TLX scores are shown in Figure **7**. One-way ANOVA showed the text-entry techniques significantly affected the user-perceived workload: physical demand ($F(2,33)=15.04$, $p<0.001$, $\eta^2 = 0.477$); effort ($F(2,33)=9.46$, $p<0.01$, $\eta^2 = 0.364$); frustration ($F(2,33)=6.86$, $p<0.01$, $\eta^2 = 0.294$). Post-hoc pairwise tests showed *FingerT9* was rated significantly lower than Tilt in these aspects. All the participants preferred *FingerT9*, and commented that it was easy to learn. There was no significant difference between the NASA-TLX scores of *FingerT9* and Direct Touch. Most of the participants preferred to use direct touch due to its fast text entry speed, and without requiring sensors attached on fingers. Still, four participants preferred to use *FingerT9* since they found it is more accurate and does not occlude the smartwatch screen.

EXPERIMENT II: LEARNING CURVES EVALUATION

From the first experiment, we found that *FingerT9* had similar efficiency and error rate to direct-touch, and the performance of *FingerT9* improved over time (block 1: WPM = 2.99, error rate = 13.97%, block 4: WPM = 3.95, error rate = 9.70%). Therefore, we conducted a long-term evaluation to investigate the learning curves of the SSH text-entry techniques: *FingerT9* and tilt-based input. We focus on SSH interaction techniques and thus the direct-touch method was excluded. Since SSH tapping on finger segments is a new interaction experience for the participants, it was expected that the initial performance would be slow, and gradually increase over time.

Participants

We recruited four participants (all female, aged 20-21, all right-handed, and with experience on T9) for a five-day evaluation. All the four participants had no experience of using smartwatches, and did not attend the first experiment. Although all the participants were female, repeated-measures ANOVA for the Experiment I showed no significant effect of gender on the performance.

	WPM	Error rate	Efficiency
FingerT9	3.43 (SD = 0.87)	11.14% (SD = 0.05)	82.53% (SD = 0.06)
Tilt-based input	2.45 (SD = 0.59)	20.73% (SD = 0.09)	71.83% (SD = 0.11)
Direct-touch	6.50 (SD = 1.91)	13.78% (SD = 0.07)	80.94% (SD = 0.08)

Table 1. WPM, efficiency, and total error rate among the three methods in Experiment I, SD is standard deviation.

Task

The participants were asked to transcribe short phrases chosen from the same set of phrases in the first experiment using *FingerT9* and the tilt-based input. The two text-entry methods were introduced and used in a counter-balanced order. The participants were asked to complete 2 blocks of short phrases transcription per method each day, and each block contained 5 phrases. Phrases were not repeated across days. Each participant transcribed a total of 10 blocks containing 50 phrases per method in five days. They were asked to correct errors immediately only if they realized errors, and to proceed as quickly and accurately as possible.

Procedure

Before starting the transcription tasks, the participants were instructed to practice the input methods by typing the sentence: 'the quick brown fox jumps over the lazy dog' at least once. They then started 2 blocks of transcription tasks, and could take rest after each block. After the tasks in each day, they were instructed to answer the NASA-TLX questionnaire.

In the first two days, the labels containing the letter hints (Figure 4) were attached on the backs of the finger segments, so the participants could looked at the hints when they were not sure which finger segment the corresponding letter is mapped to. The participants were asked to remember the layout for both *FingerT9* and the tilt-based input. Starting from day 3, the hint labels were removed, and the participants could ask for a cheat sheet from the experimenter for 10 seconds if they forgot the layout.

Results

We collected in total 3,440 words input in Experiment II. Figure 8 showed the performance of *FingerT9* and the tilt-based method. Overall, *FingerT9* resulted in higher text-entry speed, lower error rate, and higher efficiency than the tilt-based method.

Repeated-measures ANOVA showed a significant interaction effect of the input techniques and the training time on the typing speed ($F(9, 27) = 2.25$, $p < 0.05$, $\eta^2 = 0.429$), the error rate ($F(9, 27) = 2.12$, $p < 0.05$, $\eta^2 = 0.25$), and the efficiency ($F(9, 27) = 2.18$, $p < 0.05$, $\eta^2 = 0.36$). Post-hoc pairwise test showed *FingerT9* was significantly faster than Tilt (5.42 WPM vs 4.13 WPM, $p < 0.01$) after five-day training, while

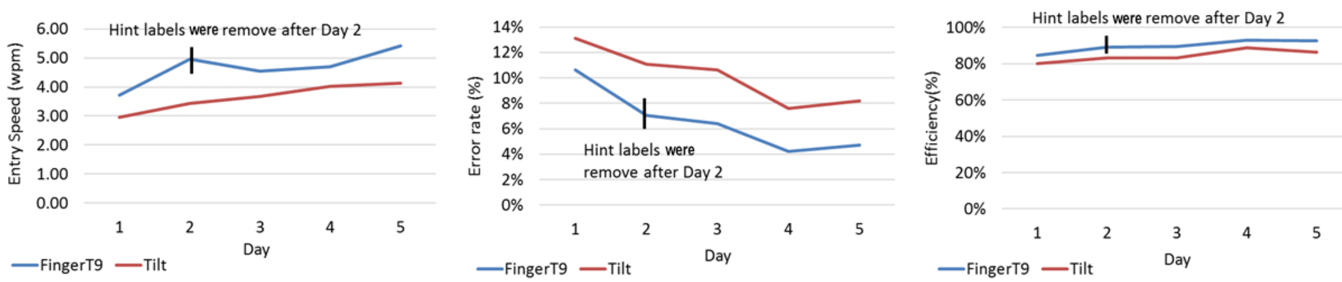

Figure 8. Text entry performance measurements for the two input methods: *FingerT9* and tilt-based input.

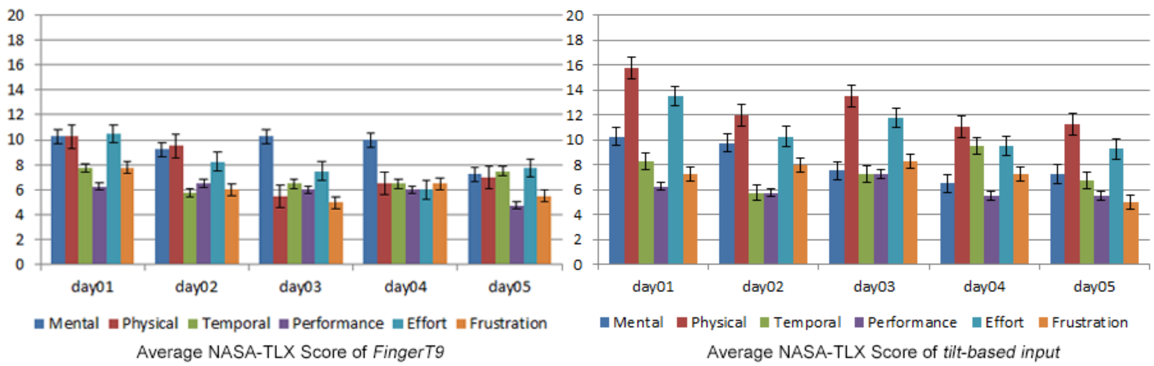

Figure 9. Average NASA-TLX scores of *FingerT9* and tilt-based input for Experiment II.

the difference was not significant in day 1 (3.72 WPM vs 2.96 WPM). Both *FingerT9* and the tilt-based method decreased in error rate and increased in efficiency across days. *FingerT9* error rate dropped from average of 10.6% to 4.68% while that of tilt-based input dropped from average of 13.14% to 8.17% from day 1 to day 5. Post-hoc pairwise comparison showed that participants improved significantly with *FingerT9* from day 3 to day 4 ($F(1,14) = 4.764$, $p < 0.05$) and from day 4 to day 5 ($F(1,14) = 8.176$, $p < 0.05$) in error rate. For efficiency, there was significant improvement from day 4 to day 5 ($F(1,14) = 9.454$, $p < 0.05$). Overall *FingerT9* produced a slightly better improvement in error rate and efficiency. These results indicated *FingerT9* produced a faster learning effect than tilt-based input in text entry speed. The user performance with *FingerT9* dropped (as expected) after removing the hint labels, but the drop was not significant, and it was still significantly faster than the tilt-based method ($p < 0.05$).

All the participants could remember the layout from day 3 and the text-entry speed kept increasing from day 3 to day 5. There was no such drop for tilt-based input on day 3, since the keyboard was still shown on the watch screen. In addition, the participants needed to remember only four functional keys for the tilt-based method, which are fewer than eleven keys, each of which corresponding to multiple letters, for *FingerT9*.

Figure 9 showed the NASA-TLX scores for *FingerT9* and tilt-based input across days. The participants said that it was tiring to use tilt-based input for a long time than using *FingerT9*. Although the participants found that it took time to remember the key mapping on finger segments, all the participants still preferred to use *FingerT9* than tilt-based input. The participants commented that it was confusing to touch on the finger segments on the middle and ring fingers on the first two days but they could perform better after two-day practice. Two participants said that it was faster and required less effort to type with *FingerT9* once they remembered the mapping on finger segments.

DISCUSSION

Azenkot and Zhai showed that index-finger typing was faster than one-thumb typing on smartphone, mainly because of lower degree of movement in thumb [2]. We also expected that *FingerT9*, as an SSH text-entry method, is slower than the T9 text-entry method by the other hand. However, SSH smartwatch text entry would still be useful when the other hand is not available (e.g. carrying heavy items and holding handrails). Our results showed that as the first solution for SSH smartwatch text entry, *FingerT9* already achieved 6.09 WPM in day 5 and can be potentially used for inputting short phrases in practice. We believe our work has opened future directions to design new finger-space text entry and SSH smartwatch interaction.

One of the limitations of thumb-to-finger touching is that the segments on fingertips are easier to touch than the segments near the palm due to the structure of human hand. In addition, users need time to remember and familiarize themselves with the keyboard layout. One future direction worthy to explore would be to optimize the mapping between the keyboard layout and the finger segments. Besides, the current experimental prototype may get charged by moisture and dust from sweat and produces error.

CONCLUSION AND FUTURE WORK

We introduced *FingerT9*, a novel SSH text-entry approach for smartwatch, combining traditional T9 keyboard and thumb-to-finger interaction. We implemented an experimental prototype with the thin-film capacitive sensors attached on the finger segments.

The within-subject controlled experiment showed that *FingerT9* has significant faster typing speed and lower error rate than the SSH tilt-based input, and has lower error compared with the traditional direct-touch input. Experiment II showed that *FingerT9* has significant improvement than the tilt-based input over time and users could remember the *FingerT9* layout. The two experiments revealed that *FingerT9* performed better than tilt-based input in text entry speed, error rate, efficiency, and learnability. These advantages of *FingerT9* over the tilt-based method could be due to the simplified typing procedure (i.e. eliminating the step of letter selection) and the reduced physical efforts.

In the future, we would like to optimize the keyboard layout, and improve the prototype of thumb-to-finger touch sensing ability by attempting possible finger sensing approaches through tracking finger movement with high resolution Electrical Impedance Tomography (EIT). We will investigate SSH smartwatch text entry in more depth with text entry in specific context (such as, walking, standing, and hand holding something), study the performance of SSH text entry with dominant and non-dominant hands and its social acceptance to see how practical SSH smartwatch text entry is in everyday life. Besides, we are interested in exploring *FingerT9* for other language text entry, such as Chinese, Japanese, and Korean, and investigate how it could be applied for eyes-free typing.

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